An evaluation of ground pipe ventilation and overnight radiant cooling to displace air conditioning in Warm Humid South Eastern Nigeria.

A thesis submitted in fulfilment of the requirements for the degree of Doctor of Philosophy

Ogbonnaya Iheanyichukwu Onyeabo

Department of Architecture

University of Strathclyde, Glasgow

United Kingdom

March 2019.

Declaration of Authenticity and Author's Rights

This thesis is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.'

'The copyright of this thesis belongs to the author under the terms of the United Kingdom Copyright Acts as qualified by University of Strathclyde Regulation 3.50. Due acknowledgement must always be made of the use of any material contained in, or derived from, this thesis.'

Signed: Date:

Acknowledgements

From the depths of my heart, I owe special thanks to Almighty God for life sustained, wisdom granted and strength to endure throughout the entire course of my PhD research programme. I am particularly grateful to my supervisor, Dr Stirling. G. Howieson, whose encouragement, guidance and support contributed immensely to the success of this work. A big appreciation goes to the TET-fund and the Department of Architecture at Abia State University, Uturu in Nigeria for sponsoring part of the study. I say a big thank you to my parents, Mr and Mrs Isaac. A. Ogbonnaya, my wife Dr Chiemeka.J. Ogbonnaya, and my children Miss Chimbusonma Ogbonnaya and Master Chimbumnobi Ogbonnaya, to whom this work is dedicated, for their love, patience, and support. Not to be omitted are my siblings and their families, thank you all for your assistance and support. Finally, I am greatly indebted to Mr Michael Agbai a.k.a “Dealer” whose assistance during the field work in Nigeria made possible the measurements in the case study buildings, including sky temperature and soil temperature measurements, and the construction and installation of all the experimental test cells used in this research.

Table of Contents

List of Figures

List of Tables

List of Abbreviations

AC	Air-Conditioning
ACH	Air change per hour
ANSI	American National Standards Institute
ARCON	Architects Registration Council of Nigeria
ASHRAE	American Society of Heating, Refrigeration, and Air-Conditioning
CAD	Computer Aided Design
CC	Control Cell
CFCs	Chlorofluorocarbons
CFD	Computational fluid dynamics
CFM	Cubic Feet per Minute
CIBSE	Chartered Institution of Building Services Engineers
CNS	Clear Night Sky
CO	Carbon Monoxide
CO_2	Carbon dioxide
DOE	Department of Energy
EAHXs	Earth to Air Heat Exchangers
EER	Energy Efficiency Ratio
EIA	Energy Information Administration
FF	Fabric First
GBP	Great Britain Pounds
GHGs	Green House Gases
HCFCs	Hydrochlorofluorocarbons

HDM	House dust mite
HVAC	Heating, ventilation, and air conditioning
IAQ	Indoor Air Quality
IEA	International Energy Agency
KSA	Kingdom of Saudi Arabia
L.G.A	Local Government Area
NGN	Nigerian Naira
NIA	Nigerian Institute of Architects
OPEC	Organisation of the Petroleum Exporting Countries
PAHS	Passive Annual Heat Storage
PCB	Poly-chlorinated biphenols
PCM	Phase Change Materials
PCS	Passive Cooling System
PM	Particulate matter
PMV	Predicted Mean Vote
PPGPV	Positive Pressure Ground Pipe Ventilation
PUF	Polyurethane Foam
PV	Photovoltaic
PVC	Polyvinyl chloride
RI	Roof Insulation
UK	United Kingdom
UNEP	United Nations Environment Program
USAID	United States Agency for International Development

WHO	World Health Organization

List of Nomenclatures

A	Area [m2]
Btu	British thermal unit
C_p	Static Pressure Coefficient
COP	Coefficient of Performance [kWh]
cT	Tropical Continental
DT_{max}	Peak Temperature Difference
eRH	Equilibrium relative humidity [%]
GOP	Glazed Openings Percentage [%]
H	Height [m]
h	Enthalpy [kJ/kg]
hc	Convective heat transfer coefficient [W/m2·K]
K	Kelvin
k	Thermal conductivity [W/m·K]
Kg	Kilogram
Ktoe	Kilotons of oil equivalent
kW	Kilo watts
l/s	Litres per second
L	Length [m]
m/s	Meters per second
mT	Tropical Maritime

Pa	Atmosphere pressure [101.325 kPa or 14.7 psi]
ppm	Parts per million
R	Thermal resistance [m2K/W]
RH	Relative Humidity [%]
T	Temperature [°C]
TSR	Temperature Swing Ratio
U	Overall heat transfer coefficient [W/m^2K]
V	Velocity [m/s]
v	Volume [m^3]
w	Width [m]
µg/m^3	Micrograms per cubic metre
µm	Micrometre
£	British Pounds
₦	Nigerian Naira
^{o}C	Degree Centigrade
ΔT	Temperature Amplitude [°C]

Subscripts

T_{sky}	Sky Temperature [°C]
T_{air}	Air Temperature [°C]
T_{dp}	Dew Point Temperature [°C]

T_g	Ground temperature [°C]
T_{max}	Maximum temperature [°C]
T_{min}	Minimum temperature [°C]
T_{in}	Indoor temperature [°C]

Greek Symbols

ρ	Density [kg/m^3]
c	Specific heat capacity at constant pressure [J/kgK]
λ	Thermal conductivity
σ	Stefan-Boltzmann constant [5.67×10^{-8} $Wm^{-2}K^{-4}$]
∝	Thermal diffusivity [m^2/s]
ϕ	Radiation from a surface [W]
ε_s	Emissivity of a surface
Θ	Temperature Ratio [°C]

An evaluation of ground pipe ventilation and overnight radiant cooling to displace air conditioning in Warm Humid South Eastern Nigeria

Abstract

Stimulating minimal energy use and a consequential reduction in CO_2 emissions to curb global warming has been a great challenge for mankind particularly when more than half of all prime energy supplied is consumed by the built environment. In Nigeria, 44% of primary energy consumption is used by the built environment with 75% of this used for air conditioning. To compensate for regular power outages in the Nigerian electricity supply system, 80% of households also operate independent electricity generators, primarily to maintain mechanical cooling and food preservation. Energy consumption is expected to rise as most new buildings do not incorporate any significant energy saving techniques that could reduce cooling demands. Providing a solution to this becomes a major challenge for architects and the building industry in Nigeria.

Factors such as pollution, insects, high dust levels and home security, negatively impact on the use of natural ventilation techniques which is a common practice, with most home owners keeping windows permanently closed, increasing their dependence on mechanical means of cooling to maintain indoor comfort. The task is therefore to develop sustainable cooling strategies for buildings in this region without compromising indoor air quality and security. The research assessed and analysed the thermo physical properties and energy performance of existing building types and developed an enhanced "fabric first" solution followed by a synergised application of ground pipe supply ventilation and cool air supply due to clear night sky radiation from roof mounted black body as passive cooling techniques for buildings in South Eastern Nigeria.

Despite the thermal interfaces being less than optimal, the results suggest that the application of such passive cooling strategies in combination with enhanced building fabric using thermal inertia and external insulation, can displace circa 83.5% of energy demand for domestic air conditioning. This could - in the long term - reduce energy consumption in the building sector from 44% to 16.45 %, with a commensurate reduction in the carbon footprint. The energy saving costs in use, were calculated to offset the additional capital costs, in under 8 years. These strategies and techniques are therefore worth further investigation as they represent both an economic and environmental gain.

1. INTRODUCTION TO THE RESEARCH

"Our greatest aim is to work with the Environment and not to run from it".

"*Creating an energy efficient building starts with the right design approach, considering the specific microclimate conditions of the site, orientation and shaping the building form, a conscious selection of building materials and envelope systems aiming to minimise building heat gains. Following this, any active systems should be selected on the basis of high efficiency (e.g. highly efficient lighting systems) or to enable a reduction of cooling loads appropriate to the climate"* (Karsten Ley et al., 2014).

1.1 Background to subject matter

Energy efficiency started to become an important factor after the 1975 OPEC oil crisis, however, as the issues surrounding global warming and impacts on the biosphere have come to the fore, several international summits have called for increasing performance standards for the built environment. This new awareness is attempting to reduce carbon outputs from all sectors. As a byproduct of this effort, individuals and organizations have benefitted from reduced costs amounting to trillions of dollars (Stamatiou, 1991).

Despite these efforts it appears that 'Global Warming' has not been contained, never mind curtailed. The volume of carbon dioxide and methane being emitted into the atmosphere is still increasing. CO_2 is a gas that traps heat warming the planet. This effect is known as greenhouse effect. Although this effect at its origin is the reason the earth has a relatively stable climate suitable for life out with the oceans, the loss of the ice caps will in turn reduce the albedo effect and a mutually reinforcing feedback loop is now becoming a real possibility, especially if the loss of the permafrost in Canada and Russia releases more methane locked in the tundra. Methane has a much greater capacity than CO_2 to drive global warming.

Industrialization and an economy based on coal and oil have raised the concentration of CO_2 from 280ppm to 400ppm over the last 250 years (Figure 1.1). This rise of circa 120ppm has driven global warming and the rate of increase is a key issue on the debate of energy savings and reduced carbon emission (Blunden, 2013). The rise in CO_2 concentrations in 2015 was between 35 to 40 Billion tons (3ppb increase) than the previous year (2014). Other greenhouse gasses like methane are on the increase, rising to 11 ppb (parts per billion) between 2014 and 2015, doubling its rate between 2007 and 2013 (Bob Berwyn, 2016). Other greenhouse gasses on the increase by concentration worth mentioning are Nitrous Oxide (NO) and tropospheric ozone, however

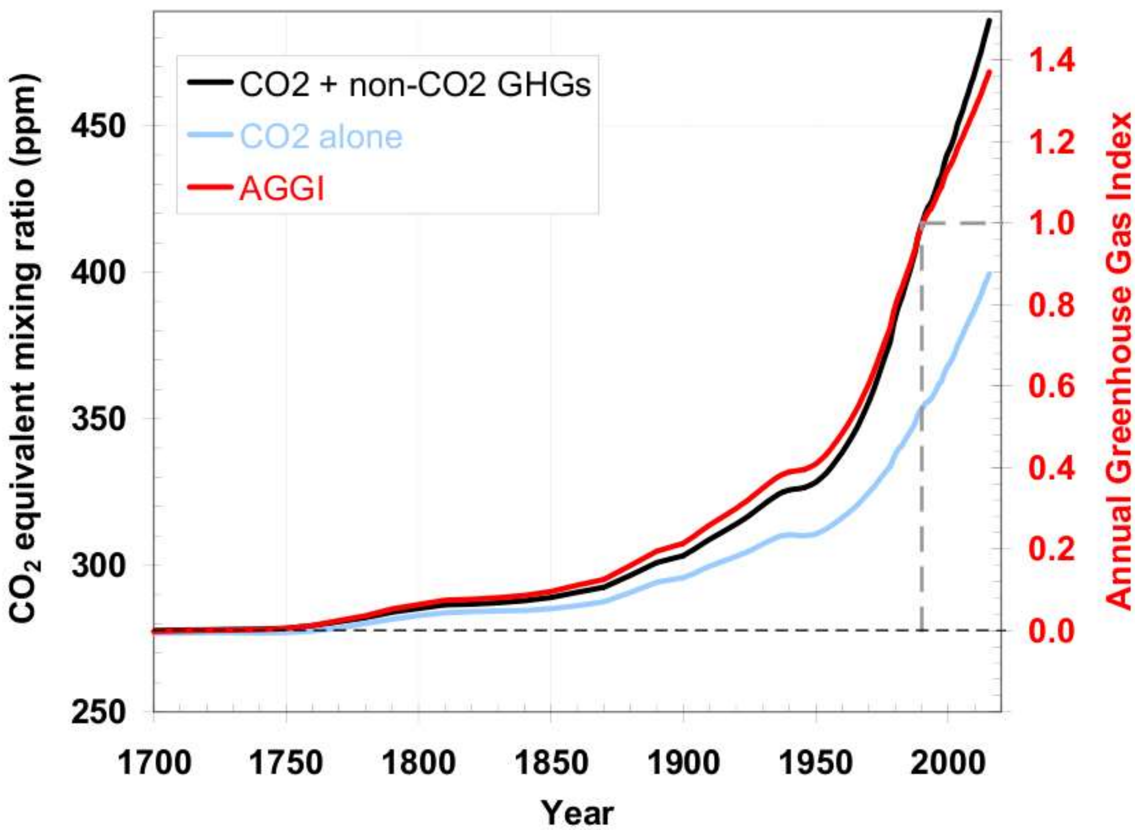


Figure 1. 1 The greenhouse gas inventory showing rise in volume over the years. Credit: NOAA

concentrations of CFCs and HCFCs - that destroy the ozone layer that protects the earth from the sun's ultra violet rays - have been reducing over the last 20 years due to effective international treaties and agreements.

1.2 Emphasis on Global Building Energy Use

The built environment consumes more than half of all prime energy supplied (Aubinet, 1994; Bird & Hulstrom, 1981). This has been identified as a major challenge exposing the building sector as one of the main contributors to the environmental crisis. The rapid growth in the use of air conditioning for cooling has many disadvantages which includes noise pollution, inefficient energy consumption and growth in peak electricity demand, the discharge of harmful pollutants and poisonous gases, global warming, ozone depletion and poor external and indoor air quality.

Therefore, it is a categorical imperative to seek techniques and systems to reduce energy use in buildings while maintaining internal thermal comfort.

1.3 Energy Demand and Supply in Nigeria's Building Sector.

Karsten Ley et al. (2014) claimed that energy savings in the building sector can be achieved through redesigning domestic hot water heating, space cooling and lighting.

This dissertation will spotlight the growing energy use for cooling buildings in sub-tropical Nigeria and formulate and test low carbon design strategies for minimising carbon emissions without compromising occupant comfort or indoor air quality.

Although relatively low when compared with global averages, Nigeria's energy demand for air conditioning is growing. The focus of the government is currently on improving the power generation network, however there remains greater scope for adopting energy efficient programs across various sectors in the Nigerian economy.

Statistics from the international Energy Agency states that Nigeria's primary Energy supply in 2011 was 118,325 Ktoe[1], with 82.2% of this figure representing biofuels (mainly firewood) and waste, 10.6% on oil, 6.8% on natural gas with the lowest being produced by hydro at 0.4%. Figure 1.2 gives the breakdown of energy demand by economic sector.

More than 44% of total Energy supplied is used by the building environment (Karsten Ley et al., 2014), Table 1.1. Figure 1.3 presents a comparison of energy generated in Nigeria with other peer countries. The graphs show a slow rate in growth in Nigeria's energy generation over the past three decades in comparison to Bangladesh and other developing countries. A comparison on energy consumed by various sectors in other developing countries demonstrates that the Nigerian building sector has a considerably higher energy demand.

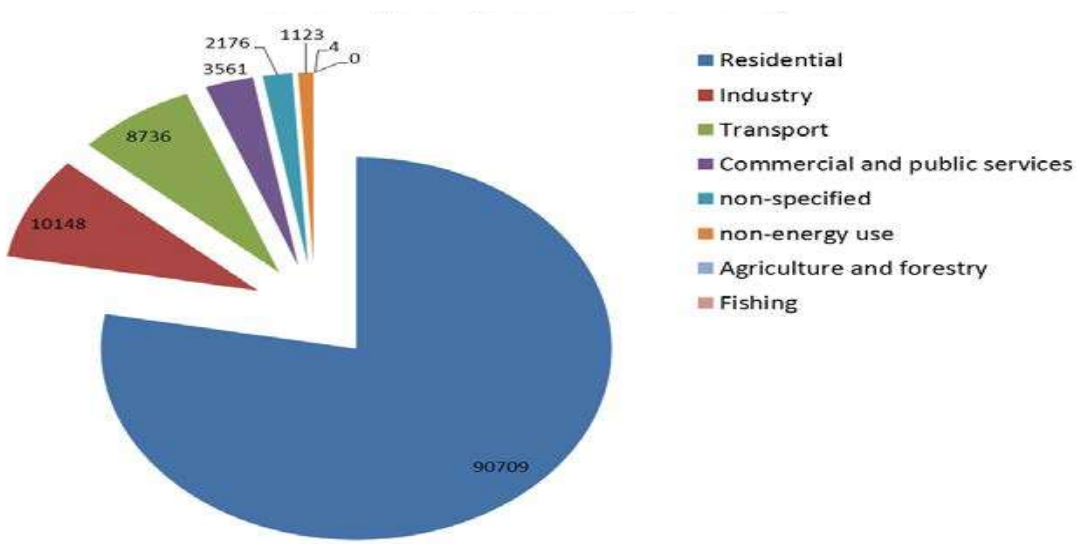


Figure 1. 2 Energy Consumption by Economic Sector in 2012 (Karsten Ley et al., 2014)

[1] Ktoe (kilotons of oil equivalent) is a unit that represents energy generated when 1,000 kg (7.4 Barrels) of oil or 1,270m^3 of natural gas is burnt. It is equivalent to 11.6 MWh (megawatt hours) or 41.87GJ (gigajoules) of energy.

Table 1. 1 Comparison of Energy Consumed by Sectors in Various Countries (Karsten Ley, Gaines, & Ghatikar, 2014).

	Nigeria	Bangladesh	Brazil	Indonesia	South Africa
Total	198,247	37,152	262,412	182,367	94,139
this includes:					
• Industry	11,398	4,293	82,808	4,488	25,566
• Transport	8,189	2,981	74,179	39,177	17,591
• Residential	87,246	12,457	23,246	57,095	15,323

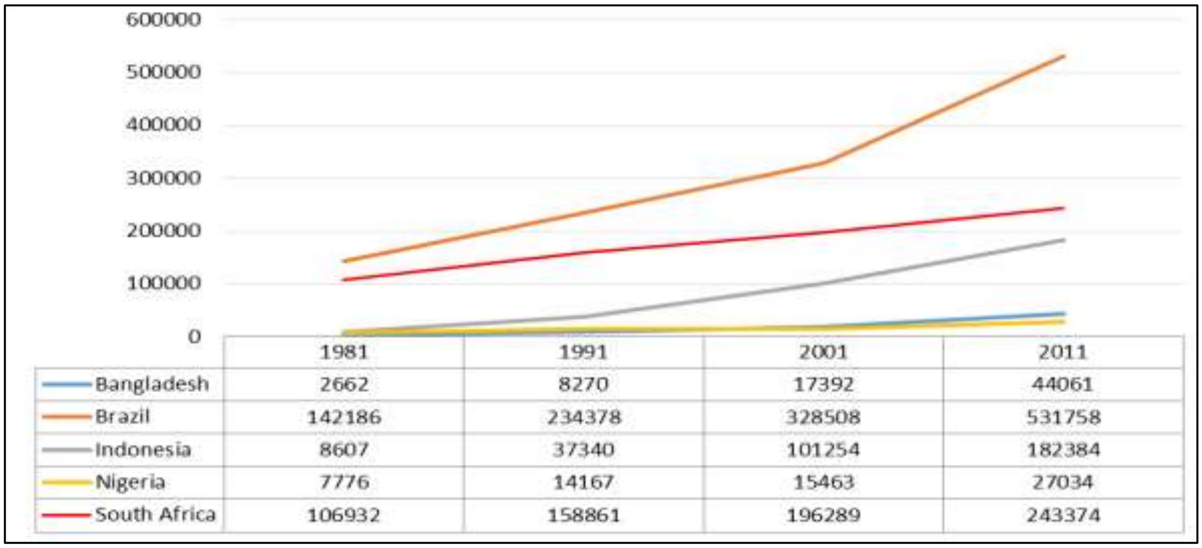


Figure 1. 3 Electricity Production in Nigeria compared to Other Countries (Karsten Ley et al., 2014)

1.4 The Problem Statement

The building sector has been implicated as the major consumer of fossil fuel energy and hence a principal contributor to the emissions of carbon dioxide and other gasses that are harmful to the environment. Improved building standards that lower energy requirements require to be developed to reduce the impact of the building sector on the global energy requirements. This study will focus on the South-Eastern Part of Nigeria known for its humid environment characterised by low wind movements (mostly below 1 ms^{-1}), elevated temperatures (circa 30^{o}C) and relative humidity (levels in the range of 40% - 80%). Given this warm humid climate, passive cooling is challenging and lightweight construction with large openings and elevated locations to aid natural air movement, have historically influenced traditional vernacular methods for the passive cooling of building interiors. These strategies however have proven, in the main, insufficient to cool the buildings effectively to modern performance standards and hence most new buildings depend on mechanical air conditioning.

Karsten Ley et al. (2014) claimed that *"the specific energy consumption of a building is dependent on the quality of the building as such, the building orientation, and the design and material of the building envelope just to name a few criteria. Unlike in former time with the traditional housing, modern architecture and the clients in the urban areas do not account for bioclimatic construction. As a result, the study recommends also top-level policy changes in the building sector such as development of an energy building code, making the compliance with minimum energy requirements and targets to be established compulsory for permits and creation of design catalogue for affordable energy efficient buildings"*.

Open plan designs and the use of large windows openings[2] to ensure free air-flow are dominant. This approach leaves the building interior vulnerable to pollution in locations where external air quality is poor.

According to the World Health Organization (WHO, 2016a), the air in polluted cities contain dangerous particulate matters in high concentrations, which enters the human bloodstream through respiration and has contributed to an estimated 7 million premature deaths globally in every year.

Two cities in South Eastern Nigeria namely Onitsha and Aba have been named amongst the world's most polluted cities (WHO, 2016b) with Onitsha taking the lead. In

[2] The use of thick walls, less fenestration and application of other state of art passive cooling approaches are not a common practice in most Nigerian Contemporary buildings.

Nwangene, air monitor readings were 667μg/m^3 for PM_{10}, which was more than the 594μg/m^3 annual figure that gave Onitsha its name as the world's most polluted city, while the smaller and deadlier particulate $PM_{2.5}$ reading of 290μg/m^3 was higher than the WHO's annual figure of 66μg/m^3. At Ochanja market, the readings were 586μg/m^3 for PM_{10} and 266μg/m^3 for $PM_{2.5}$ (Egbedi, 2017). Yet in these highly polluted areas, buildings are not designed to withstand the hazard, or provide healthy indoor environment. Having to face the effects not only outside, but also inside homes indicates the severity of the situation. Homes are no longer a place of refuge, as black carbon can find its way through open windows. Deposits can also clog the protective nets of doors and windows (Yakubu, 2017).

High concentrations of particulate matter (PM) are attributed to a sizable number of aluminium and copper smelting/recycling activities that are done in the open, thereby discharging huge clouds of smoke into the heart of the city.

The use of windows as the only means of ventilation in such cities where pollution levels are high, becomes problematic as polluted air infiltrates the building interior when the windows are opened. The only option users have in such situation is to shut the windows completely with a resultant rise in indoor temperature attributable to the light nature of building fabric. Poor outdoor air quality encourages occupants to keep windows permanently shut. Fig 1.4 presents a common scene showing pollution activities in a residential area in the city of Onitsha. Port Harcourt in South-Eastern Nigeria also suffers high levels of black soot emissions forcing residents to keep doors and windows permanently shut resulting in elevated indoor temperatures which in turn leads to an increased demand for mechanical air conditioning systems (Yakubu, 2017).

Another source of air pollution and poisoning can be attributed to the use of household electric generators. The use of these machines has been on the increase as a back-up to compensate for regular power outages. This growing practice at homes and offices is not regulated, resulting in an increase in both air and noise pollution.

Figure 1. 4 Cooking fires and burning of garbage contributes to high levels of air particulates in Onitsha, Nigeria, according to WHO measurements made in 2016. Photograph credits: Hadassah Egbedi (Guardian Newspaper).

Environmental regulators have claimed that there is little awareness of the consequences and hazards arising from the spread of these somewhat inefficient and fuel-intensive machines. Household generator sets emit particulate matter containing burnt hydrocarbons and oxides of nitrogen, which are a major additional source of air pollution. Their effects on the environment may even be worse when un-burnt hydrocarbons are emitted due to faulty generator sets (Malik, 2011).

An average of 8 out of every 10 households in Nigeria operate a generator, however, many deaths are recorded yearly due to lack of regulations on the use of these generator sets with majority of reported cases due to CO poisoning. Anyagafu (2014) reports over 10,000 deaths attributed to CO poisoning between 2008 and 2014. According to Farooq Alam, a senior research officer for air quality at the Environment Protection Department in Lahore, Pakistan *"If a generator is installed in every house in a society and you add up all the emissions from these generators, it far exceeds the emissions from a thermal power plant supplying electricity to the entire society."*

Secondly, the use of household generators is a major source of noise pollution. A review of the National Environment Quality Standards (NEQS) in November 2010 set the limit for noise in residential areas at 55db (decibels) during the day and 45db during the night. Household generators that operate on diesel are found to produce as much as 88db, while those running on petrol or gas produce above 95db (Malik, 2011). This also becomes a major concern as most of these generators are run at night.

Apart from air and noise pollution, N1.56 trillion ($13.35m) is spent on fuel annually (Vanguard, 2009). Security issues and insect infestations also limit the functionality of windows in South Eastern Nigeria.

To completely rely on window opening as the only means for cooling buildings in South-Eastern Nigeria becomes problematic when factors such as security, noise, health or pollution come into play. If buildings in the warm humid environment of South-Eastern Nigeria are to be kept within recognised comfort ranges particularly during the peak afternoon temperature swings, new techniques will have to be developed to reduce the reliance on AC systems (Benjamin, Reynolds, & McGuinness, 1992; Diaz, 1994).

The task is thus to investigate 'fabric first' strategies. These will include such techniques as combining high levels of insulation with the use of thermal mass to keep solar heat gains minimal while suppling ventilation through ground pipes to reduce direct ventilation through window openings. In addition, the relatively clear night sky for many months of the year, provides the opportunity for black body radiant 'heat flushing' and coolth supply to the building at night.

There are two basic seasons in Nigeria; the 'rainy season' and the 'dry' season. The dry season is influenced by a dusty wind from the Sahara Desert, known as Harmattan, which is carried by the Tropical Continental (cT) airmass, while the rainy season is heavily influenced by the Tropical Maritime (mT) from the Atlantic Ocean (Eludoyin, Adelekan, Webster, & Eludoyin, 2014). Between the months of November and April is the 'dry' (Harmattan) season. During this season, ambient temperature is usually high during the day, mostly above 38°C, while clear skies drive much lower temperatures at night, usually as low as 12°C (WWCI, 2016). The air is usually dry, and the humidity levels are relatively low during this period with daily averages around RH 45%. Between the months of June and October is the 'rainy' season which is accompanied by thicker cloud cover, heavy rainfall, less dust in the air, high humidity levels and low average ambient temperatures with small diurnal swings. The indoor temperature during this period is relatively low and air movement is minimal.

1.5 Research Hypothesis

Transformations in the design, construction and operational protocols of building envelopes can allow the building to interact intelligently with natural heat sinks for passive cooling, even when the windows are shut, resulting in a significant off-setting of mechanical air conditioning while achieving year-round thermal comfort and 'healthy' indoor air quality, for occupants in low income households in South Eastern Nigeria.

1.6 Aim and Objectives of the research

This research aims to present an investigation into the viability of 'fabric first' clever architectural design methods, in combination with passive and low energy active cooling systems operating in a hybrid formation. Specifically, the research aims at achieving an all in one building formation that will displace mechanical air conditioning, reduce carbon footprint, provide year-round thermal comfort for users, and as well provide the basic functions of a building envelope in a typical residential bungalow in South Eastern Nigeria.

This research will answer the following questions:

- Why do most buildings in the study area depend solely on mechanical air conditioning when the doors and or the windows are closed?
- What are the effects of the thermo-physical properties of the building fabric on indoor temperature and energy demand for cooling due to heat loss, heat gain, heat storage and heat dissipation?
- Can the building fabric be modified to reduce external heat gains and hence reduce the cost of cooling when the windows are not in use?
- Given the fact that warm humid environment in South Eastern Nigeria has less air movement, what other means of passive cooling strategies apart from cross ventilation could be applied in buildings?
- What are the potentials of natural heat sinks for indoor passive air conditioning in a warm humid climate and to what extent can they be applied?
- What are the potentials of a synergy between ground pipe ventilation system and clear night sky radiant cooling on delivering cooler air and expelling warm air via enhanced stack effect when applied to a modified building fabric?
- What are the viable passive cooling strategies that are readily available which can be incorporated in a single or combined system running independently or concurrently?
- Can the identified approaches and techniques perform in a warm humid climate?
- To what extent can these approaches, either individually or in combination, provide a cost-effective solution that will displace air conditioning and its associated carbon emissions?
- Which of the approaches is the most effective in terms of cost and performance?

In order to answer the above research questions, the objectives of the research become the following:

- To investigate why most buildings in the study area depend solely on mechanical air conditioning when the doors and or the windows are closed.
- To investigate the effects of heat moderation as a function of the thermo-physical features of the building fabric on indoor temperature and on energy demand for cooling.
- To identify other passive cooling strategies other than cross ventilation which could be applied effectively in building in South Eastern Nigeria.
- To identify and investigate the potentials of available and viable natural heat sinks and their effects on indoor temperature in a warm humid climate.
- To investigate the potentials and effects of passive cooling techniques on the building fabric enhanced by a combination of insulation and thermal inertia and time lag on indoor temperature to ameliorate temperature peaks.
- To investigate cooling strategies that can be incorporated in a single or combined system running independently or concurrently.
- To investigate the applicability of the identified approaches and techniques in a warm humid climate.
- To establish the efficiency of the applied systems running independently or as a combined system running in synergy.
- To identify the most cost-effective solution.

1.7 Research methodology

Primarily, the present research adopts a quantitative method in data collection. This method will involve various study plans that includes observation, case studies, survey and development of experimental protocols and prototypes. The adopted strategy to conduct this research will make use of data from reviews and measurable data from case study as a running choice to obtain the primary research data combined with field experiment to develop and test a new cooling model(s) that can be analysed, assessed and compared with the primary findings of the case study analysis.

In order to meet the research aims and objectives and answer the research questions, the research plan was divided into three main stages with each stage using a specific practical choice or strategy.

The initial stage was to collect primary data in order to investigate the most significant factors driving high levels of cooling energy demand and consumption in buildings within South Eastern Nigerian. It was important to critically observe and analyse the actual thermo-physical and energy performance of a typical house typology hence, case building was selected to obtain the required data representing context, period and location.

Based on findings from case study it was essential to adopt an experimental strategy in order to design and develop a viable alternative cooling system applicable to the selected case building. An experiment is a procedure that is performed to support, rebut, or validate a hypothesis thereby, providing an expedient understanding into cause-and-effect by demonstrating what result occurs when a specific factor is manipulated. Experimental research methods in engineering and architectural disciplines usually implement a development of conceptual projects, which will challenge conventional and consolidated practices. The main objective of this method being to explore original thought trajectories and develop innovative design tools and methodologies (Creswell & Creswell, 2017; Cross, 1999).

The experimental method in this research is divided into three phases. The first phase involves field experiments to obtain the primary measurement and database such as ambient air temperature, humidity, ground temperatures at different depths and sky temperatures. Based on the data collected from field measurements, the second phase involves the design of low energy cooling systems integrated with 'fabric first' design techniques to reduce the total cooling load with intentions of excluding solar conductive and convective heat gains. The third phase involves the use of physical experimental models or rigs as tools to conduct parametric investigation which will model the various systems applicable and that can be compared with the analysis of the case building to quantify energy savings and running costs.

1.8 Significance of Research

There seems to be a lack of awareness and concern for possible integration of cooling systems with the architectural design formation (building fabric and layout). The research aims to formulate a bridge between the building designers and the building physicists by developing a passive cum hybrid mix mode cooling system, which will ultimately combine with low energy cooling technologies to produce low carbon, energy efficient residential buildings in South Eastern Nigeria. The present research will add to the body of knowledge as follows:

- It will establish new standards by promoting public awareness and creating a more proactive consumer attitude towards energy efficiency and energy conservation.
- It will support and enhance the already developing energy efficiency program in Nigeria by providing a modest energy efficient building types that will not compromise human comfort and security.
- It will define a new standard for energy efficiency in residential dwellings for South Eastern Nigeria, which will provide high profiled performance in terms of heat loss and or heat gain, and therefore a resultant affordable building type that

can operate fully with all windows, and doors completely shut without a drop in comfort expectation levels in such buildings.

- It will develop a hybrid system that can be cost effectively retrofitted into the existing building stock. This can be accomplished while guaranteeing that new buildings meet the energy efficient standard while simultaneously retrofitting the existing housing stock using the developed techniques and systems, which will be both practical and effective.
- The outcome of the research will develop an innovative hybrid low energy cooling system, which explores all integrable techniques with building fabric formation to create a dwelling typology suitable for South Eastern Nigeria. These techniques will be addressed in terms of architectural design and thermo physical performance as a guide for building professionals as it pertains to new buildings. Benefits from such an innovation will not only be exclusive to South Eastern Nigeria as many aspects will be applicable to Nigeria as whole as well as other countries with similar climates.

1.9 Scope of study

This research work has concentrated on the viability of natural heat sinks in combination with low energy fans and PVs applied on an upgraded building envelope to condition indoor environments in residential building in order to moderate indoor temperatures during the hottest months of the year. The investigation was carried out through fieldwork by the development and construction of experimental cells as test beds to investigate and validate the complex interactions between natural heat sinks and the ability of an insulated building envelope to moderate heat transfer. These cells were constructed and monitored in the warm humid climate of Ahaba Imenyi (in Isuikwuato Local Government area of Abia State), a small town in the South-Eastern part of Nigeria.

1.10 Challenges and Limitations

There is relatively limited information on the application of passive and hybrid cooling methods in South Eastern Nigeria. The study however, becomes an opportunity to trigger the development of appropriate systems and techniques to model and test these methods.

Secondly, the distance from the research institution (University of Strathclyde, Glasgow United Kingdom) to where the test rigs were located (Ahaba Imenyi, Isuikwuato in Abia State of Nigeria) was a problem in terms of commuting as modifications were constantly made on the test cells as well as data collection on each of such modification.

Nigeria is a Country with four major climate types namely: Hot dry climate, temperate and dry climate, hot humid climate and warm humid climate. The study concentrated on the South Eastern part with a Warm Humid climate. The challenge is to ensure that the new approach will be applicable to Nigeria as whole.

Human factors also pose some restrains in terms of acceptability and awareness especially where there is an already accepted traditional construction system and a situation where climate specific building codes is non-existent. Awareness on climate change and its impending catastrophic side effects are limited in Nigeria.

1.11 Structure of Thesis

Each chapter opens with an outline of the content and concludes with a summary. Figure 1.5 is an overview of the thesis structure.

Chapter 1 presents an introduction of the topic with a background study, outlining context, scope and the aims of the study. It also presented the hypothesis, research questions and the methods adopted.

Chapter 2 presents the location and climatic characteristics of the study area.

Chapter 3 reviews the relevant literature on heat sinks, mechanisms of heat transfer and heat transfer vehicles, types and characteristics of building envelope including thermal inertia in building fabrics. The primary aim of the review of relevant topics to the study is to have an insight on the basic principles of some techniques, trends, debates and findings and to identify strengths and weaknesses that will serve to refine the strategies and approach.

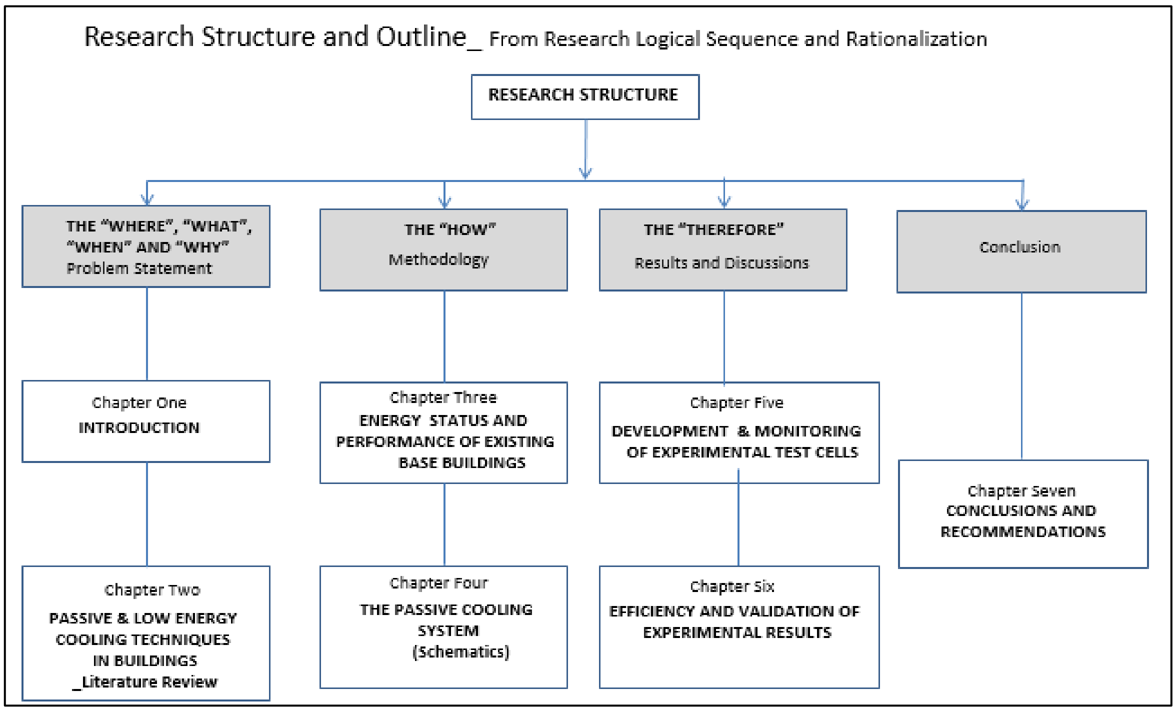


Figure 1. 5 Research Structure and Logical Sequence

Chapter 4 presents field study comprising of investigations and measurements of some existing buildings in South-Eastern part of Nigeria. Configuration of typical building fabric in terms of its characteristics, layout and thermo-physical properties of materials used in the construction of such buildings and how these factors affect heat transfer in buildings and hence the level of thermal comfort attainable in existing case buildings are investigated. Temperature swings and energy demand and use within a typical building were also investigated and monitored. Chapter 4 also evaluates soil temperature and temperature amplitudes at certain depths beneath the earth crust within the study area and the effective sky temperature across the seasons. Data collected from these field studies was then used to drive the design of various systems to be incorporated in whole dwelling thermal models.

Chapter 5 discusses the development, design, construction, testing and monitoring of prototypes. This section also presents an integration of passive cooling approaches using findings from the evaluation of the heat sinks in chapter 4 into an upgraded building fabric with the aim of achieving a synergy and an optimal energy efficient performance while maintaining comfort boundaries within the acceptable comfort zone of the study area. This chapter also focuses on optimising the systems to produce the best possible cooling performance. Data acquisition, results of the tests and presentation of findings are also covered in this chapter.

Chapter 6 presents a critical assessment and analysis of the efficiency and workability of the applied fabric modification measures and the passive cooling strategies applied in the cooling system. These were compared with the primary case building in chapter 4. This chapter considers further improvements to the indoor thermal environment and indoor air quality. The cost implication and benefits of the proposed PCS, which includes the life cycle running cost and the estimated payback period, is analysed and compared with the base case scenario.

Chapter 7 presents the major insights and areas for future research.

2. LOCATION, CLIMATE AND ENVIRONMENTAL ANALYSIS OF SOUTH EASTERN NIGERIA

2.1 Introduction

This chapter introduces the general background of Nigeria, which includes geographic location and an overview of the general climate condition. It also highlights the population density of Nigeria followed by a review of the climate of Okigwe, which hosts the study area.

2.2 A Background Study of Nigeria

2.3 Location

Nigeria is a country wholly located inside the tropical zone of West Africa Fig 2.1. It lies between Latitudes 4^{o}N and 14^{o}N and Longitudes 2^{o}2'E and 14^{o}30'E. It is made up of landmass of an approximate area of 923,770km^{2}, with the North to South boundaries stretching to a span of approximately 1,150km; it is made up of 36 States and a Federal Capital territory Fig 2.2.

Nigeria is grouped under 6 Geo-Political zones namely: North-West, North-Central, North-East, South-West, South-South and South-East Zones. These zones are graphically presented in Fig 2.3. To the West of the country the boundary is shared with Benin republic, and to the North the boundary is shared with Niger Republic, and to the North-East it is bordered by Chad, and to the East by Cameroun, while the southern limits share boundaries with the Atlantic Ocean (Frenken, 2005; Peel, Finlayson, & McMahon, 2007).

Nigeria is one of the nine countries that originally make up the Gulf of Guinea Region. The other 8 countries are: Sierra Leone, Côte d'Ivoire, Guinea-Bissau, Togo, Ghana, Benin Republic, Equatorial Guinea and Liberia. Two new countries have been added to this region recently namely Angola and Congo, making total of 11 Countries.

The Gulf of Guinea Region covers 7% (2.1 Million Km^2) of Africa's Land Mass. Nigeria alone covers 44% of the Area of the Gulf of Guinea Region.

Figure 2. 1 Political Map of Africa showing location of Nigeria and Neighbouring Countries (WorldMap, 2016)

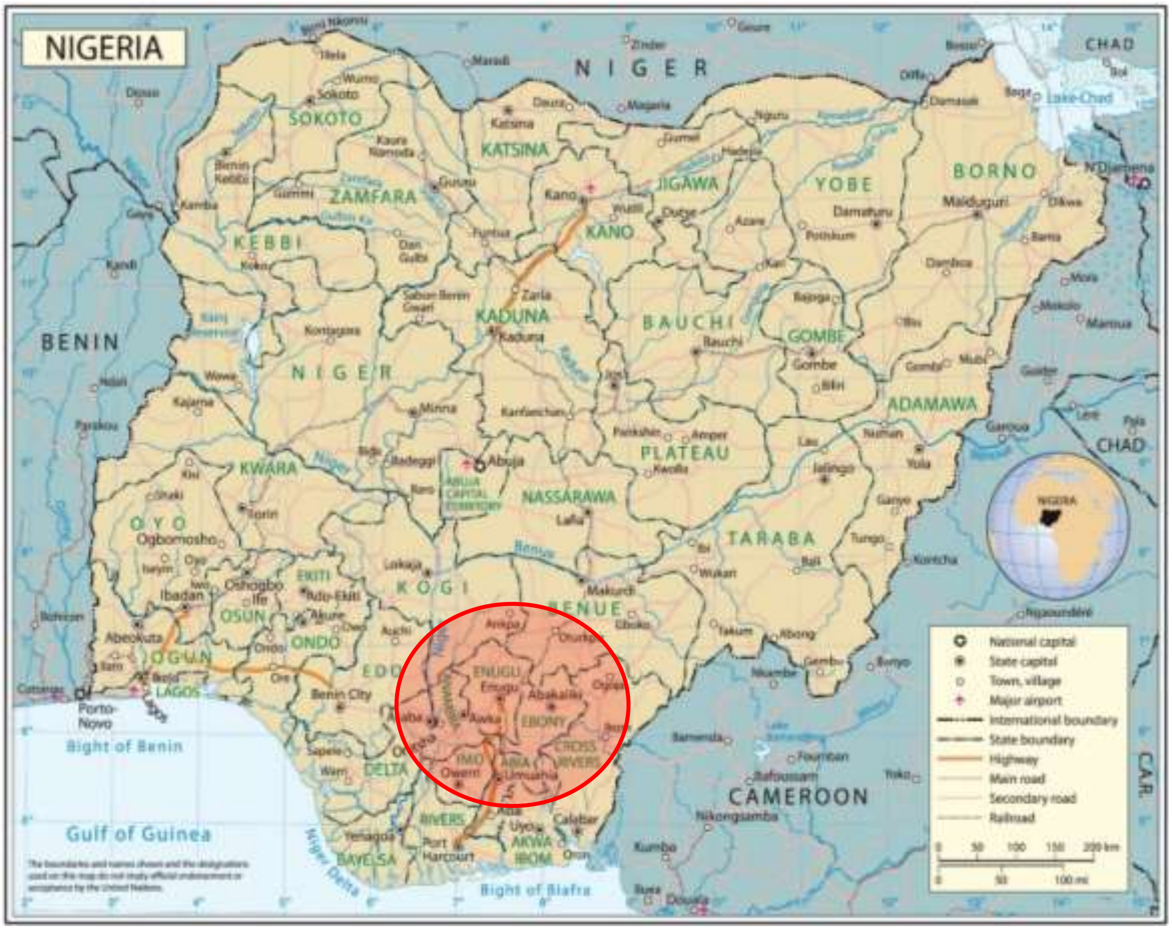
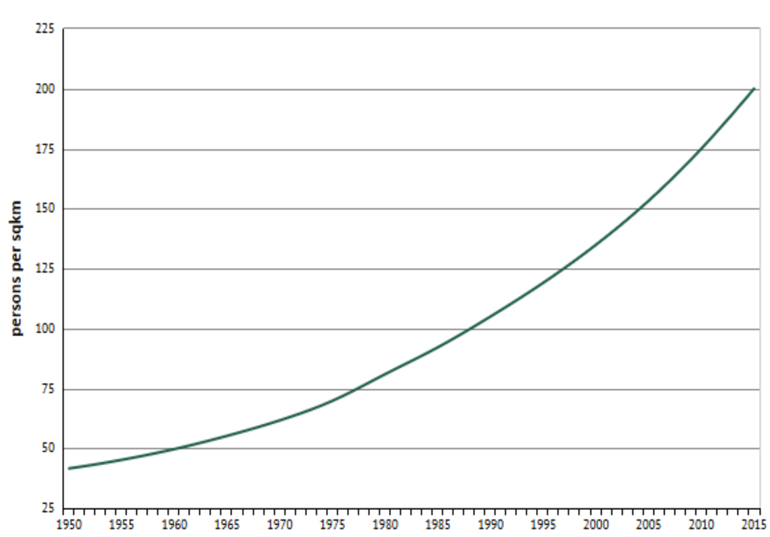


Figure 2. 2 Political map of Nigeria Showing 36 states and Federal Capital Territory (UnitedNations, 2004)

Figure 2. 3 Map of Nigeria Showing the 6 Geo-Political Zones NW(North West), NE (North East), NC (North Central), SW (South West), SE (South East), and SS (South South) (Ajoge et al., 2013)

2.4 Population

As at 2004, Nigeria hosts 65% of the total human population records of 196 million in the Gulf of Guinea Region and 15% of Africa's population (Knoema, 2015). This population has grown annually at a rate of about 3.2% over the last decade rising to approximately 180 million people and a population density of circa 200.05 people per km^2. 61% of the population are classified as rural. This compares with 51% for the rest of the world. Fig 2.4 shows the population density and growth by percentage in Nigeria from 2004 to 2015 (FederalMinistryOfEnvironment-Nigeria., 2014; Knoema, 2015)



Date	Value	Change, %
2015	200.05	2.66 %
2014	194.86	2.70 %
2013	189.75	2.72 %
2012	184.72	2.73 %
2011	179.82	2.73 %
2010	175.04	2.72 %
2009	170.41	2.71 %
2008	165.92	2.69 %
2007	161.57	2.68 %
2006	157.36	2.66 %
2005	153.29	2.63 %
2004	149.36	

Figure 2. 4 Population density (Pers/km^2) from 1950 to 2015 (Knoema, 2015)

2.5 Climate

Mangrove forests, rain forests and near-desert Sahel savannah are the three common land covers encountered while moving from the south towards the northern part of the country. The northern Sudan savannah, the middle belt or the Guinea Savannah zone and the southern rain forests are the three main ecological zones, which are further, grouped under four universal climatic zones namely: Hot dry zone, temperate and dry zone, hot humid zone and warm humid zone as presented in Fig 2.5 and Fig 2.6. Nigeria is situated just North of the Equator and experiences an equatorial type of climate that is characterised by hot and wet environments due to the movements associated with the inter-tropical convergence zone at the south and north of the equator and very heavy seasonal rains. Nigeria experiences 2 major seasons in a year namely the ‘dry’ season and the ‘rainy’ seasons usually from the months of November to April and May to October respectively. The study zone falls within the warm humid zone of Nigeria, Fig 2.6 and is characterised by annual rainfalls of between 1190mm to 2800mm due to its closeness to the equator.

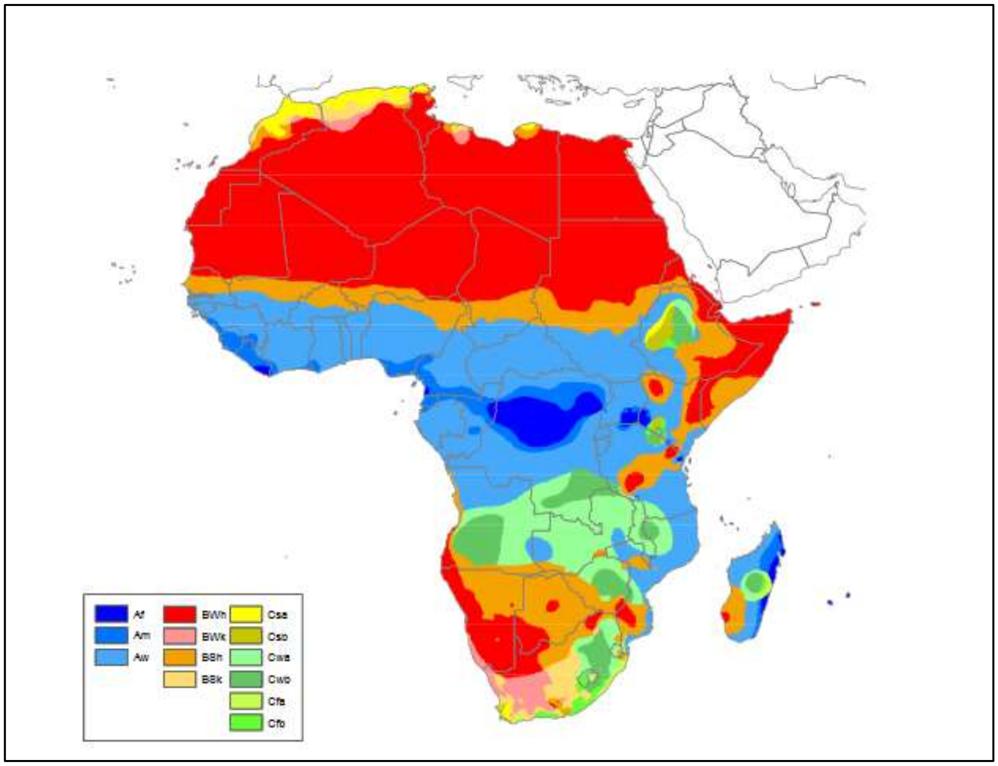


Figure 2. 5 African map of Köppen-Geiger climate classification showing the three predominant climates in Nigeria (Peel et al., 2007)

Two principal wind currents are predominant in Nigeria; the "Harmattan", which comes from the Northeast accompanied by hot, dry and dusty wind from the Sahara Desert, and the "Rainy season" which comes from the Southwest and is characterized by cloudy skies and rainy weather. These two major winds result in the four climate types found as one travels from the South to North of Nigeria. The climate is mostly hot and dry in the North, with higher temperature and humidity swings, and hot and humid in the South, with constant high temperature and humidity levels. The city of Jos is positioned at a high elevation and consequently experiences a cooler climate than any other region found in Nigeria (Ojosu et al., 1988).

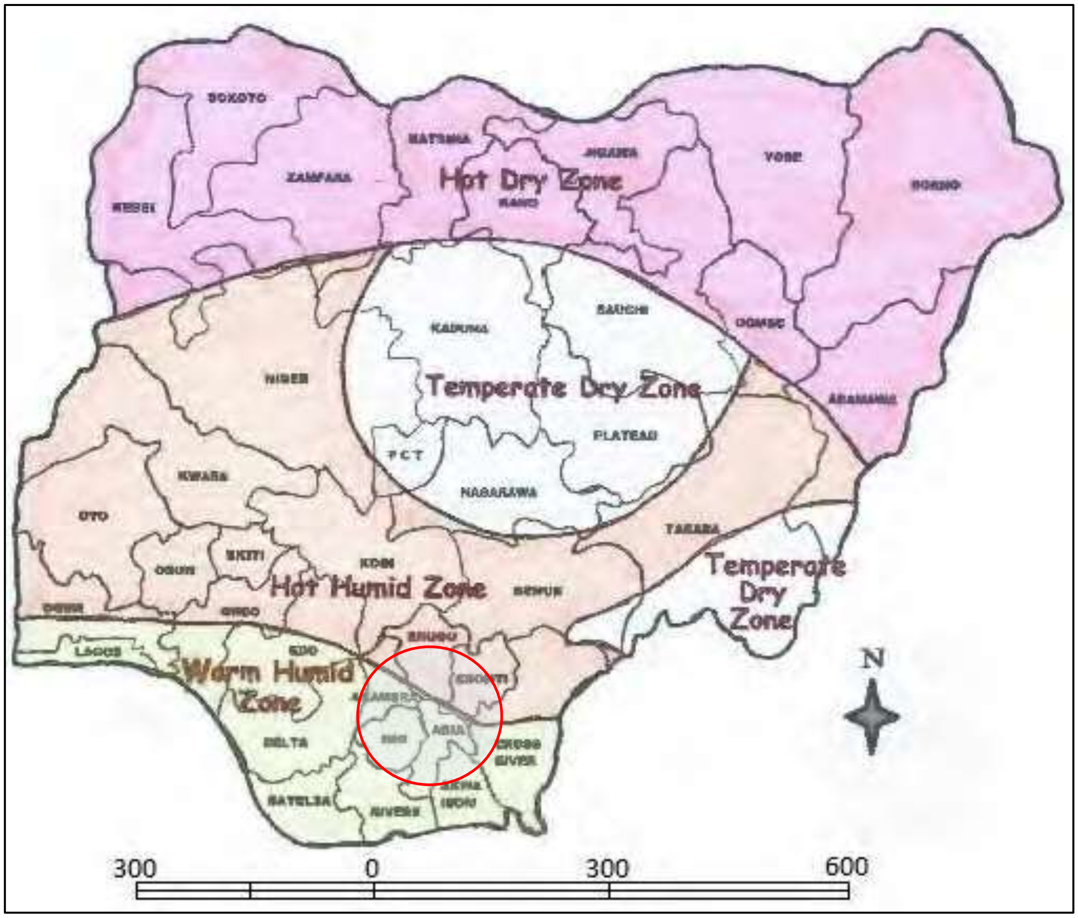


Figure 2. 6 Four Climate Zones in Nigeria (Ojosu et al., 1988)

2.6 Location and Climate Data of Study Area

Three locations in South Eastern Nigeria considered for this study are Enugu (Latitude 6°58’ 57’’ N, Longitude 7° 27’ 25’’ E) a hot humid region, Port Harcourt (Latitude 4°47’ 21’’ N, Longitude 6° 59’ 55’’ E) a warm humid city in the coastal region of Nigeria and Isuikwuato (Latitude 5°32’N, Longitude7° 29’E) surrounded by mountains. Fig 2.7 shows the locations considered in the study, and a map of Abia showing study area. Isuikwuato is a neighboring local government area to Okigwe Fig 2.7 and share the same average weather conditions with Okigwe and Enugu as presented in Fig 2.8 below. Due to the close similarities in climate data collected, Isuikwuato[3] was chosen as a location for further study.

Figure 2. 7 Map of Nigeria showing Abia State by Google Maps. Inset is Map of Abia showing 19 Local Government Areas. Ministry of lands and Urban planning

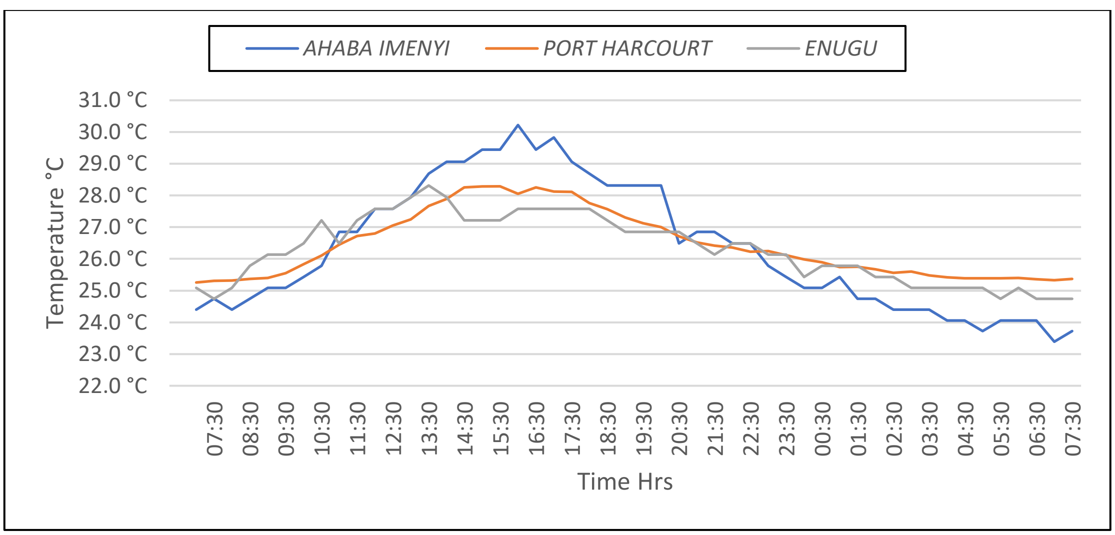


Figure 2. 8 Outdoor Temperatures in 3 Locations in South Eastern Nigeria

[3]. This location is in between Enugu and Port Harcourt therefore making it easier to access given the limited time of this study.

2.6.1 Temperature

The weather of Okigwe is reviewed below as presented by (WeatherSpark, 2016): Okigwe is a usually hot town with average yearly temperature in the threshold of 19^{o}C for minimum temperature and 32^{o}C for maximum. The temperature rarely falls below 15^{o}C and in high season rises to 38^{o}C.

Hot seasons are usually experienced between January and April and lasts an approximate of 2.6 months. During this period, the average maximum ambient temperature rises above 30^{o}C. February 19th is the hottest day in the year with maximum ambient temperatures nearing 40^{o}C that eventually drops to around 21^{o}C at night. The months of June to October presents a period of 4.5 Months of cool season. The average daily ambient temperature during this period is about 28^{o}C. January 1st is the coldest day in every year with an average low at about 19^{o}C and few times it can go below that, and the maximum ambient temperature is around 29^{o}C. Fig 2.9 presents the overall average maximum and average minimum temperature in a typical year as observed in Okigwe. It also highlights the hottest and the coolest months. The micro-climate of the measured site is presented in section 4.6.

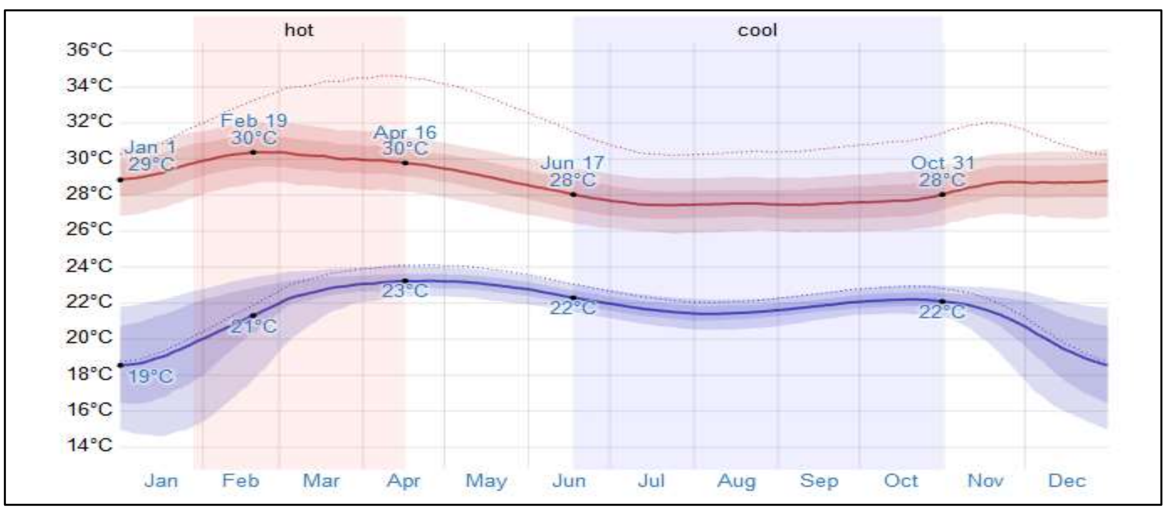


Figure 2. 9 Monthly average high (red) and average low (blue) temperatures in a Typical year in Okigwe (WeatherSpark, 2016)

2.6.2 Humidity

According to data provided by WeatherSpark (2016), dew point was used to determine the humidity comfort level as this predicts whether evaporation will occur through perspiration on the skin or not. Dew point varies slowly in Okigwe unlike the case with temperature drops at night. Figure 2.10 presents the humidity comfort in Okigwe from January to December.

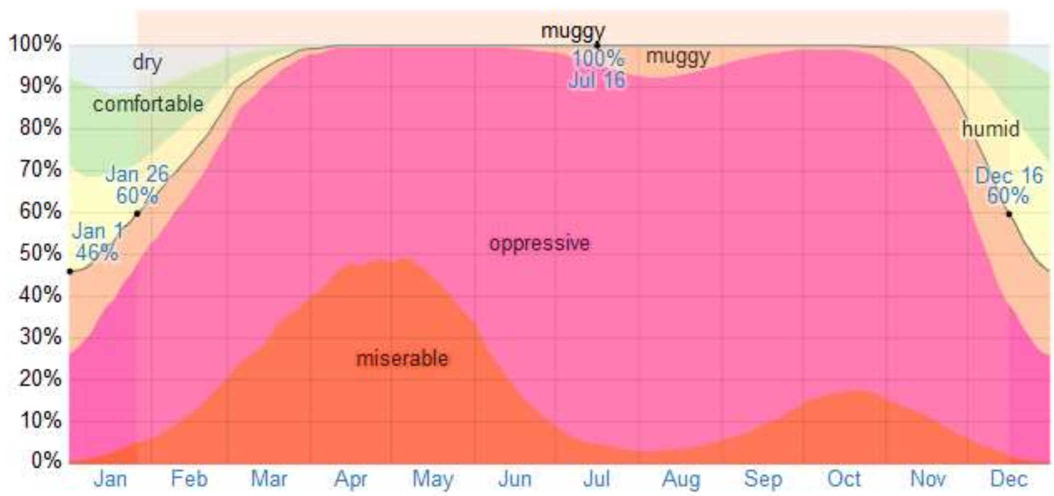


Figure 2. 10 Humidity Comfort levels in Okigwe (WeatherSpark, 2016)

2.6.3 Rainfall and Precipitation

Okigwe experiences seasonal variation in monthly rainfall within the rainy season which lasts for approximately 7.2 months starting in March and ending around November. The 'dry' seasons last for an approximate period of 4.8 months between November and March. Rainfall accumulation varies between 5mm to 263mm wetter months. The chances of daily rainfall in the wet seasons is 48% which increases to 82% in September. The smallest chance of a wet day is observed usually on 1st of January with 3% chances of rainfall. Rainfall in Okigwe is between mild showers to heavy down pours, which is most times accompanied by thunderstorms. Fig 2.11 shows the average monthly accumulation with the maximum in September and minimum in January. Fig 2.12 shows the chances of daily rainfall from January to December.

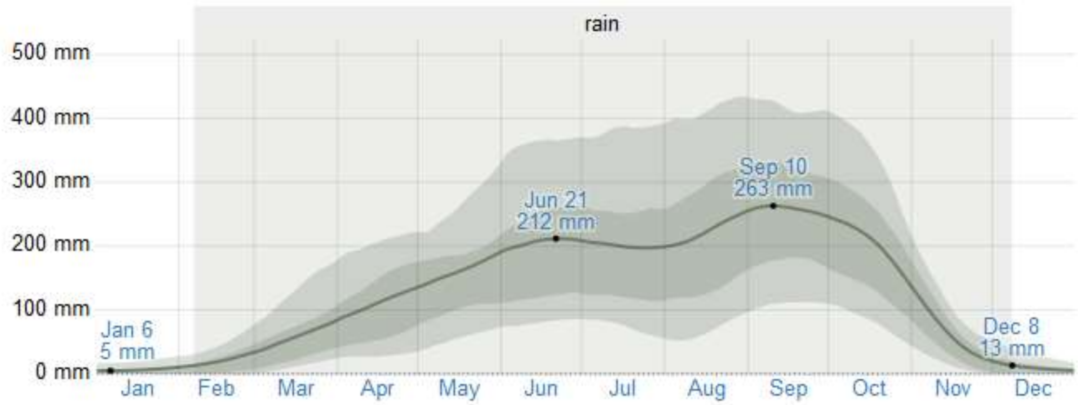


Figure 2. 11 Average monthly Rainfall (WeatherSpark, 2016)

Figure 2. 12 Monthly Chances of Probable rainfall throughout a Year (WeatherSpark, 2016)

2.6.4 Solar Radiation

Early sunrise occurs at about 6.14hrs in the month of May and earliest sunset occurs at about 18.10hrs in the month of November. Late sunrise is experienced in the month of

February at about 6.47hrs and late sunset is in July at about 18.47hrs, Fig 2.13. December to February presents the brightest periods of the year that lasts for approximately 2.5 months. During this period, the average daily incident shortwave energy per square meter is 4.7 kWh. January 2nd presents the brightest day in the year with 5.0 kWh of solar radiation per square metre. September to November are not as bright as the other months, and the average incident shortwave per square meter drops below 3.9kWh during this period. The lowest recorded shortwave is 3.6kWh in the month of October Fig 2.14.

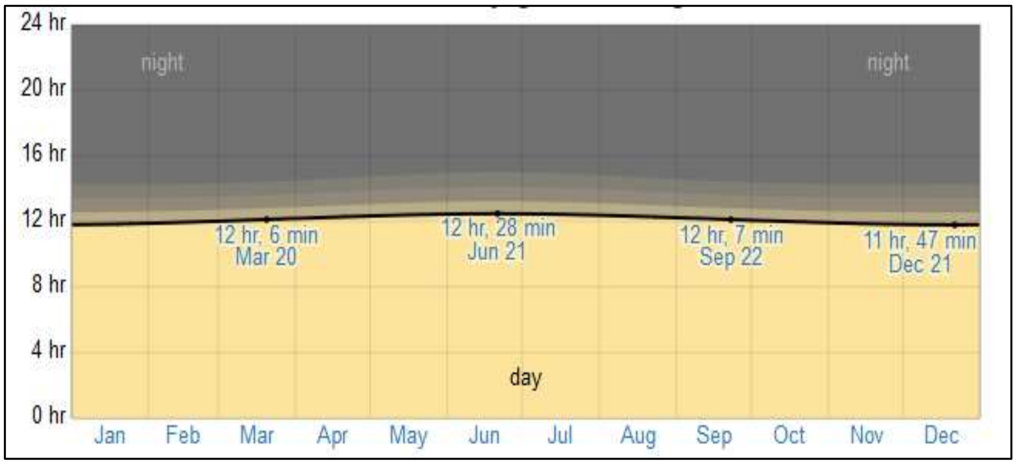


Figure 2. 13 Hours of Daylight and Nightfall (WeatherSpark, 2016)

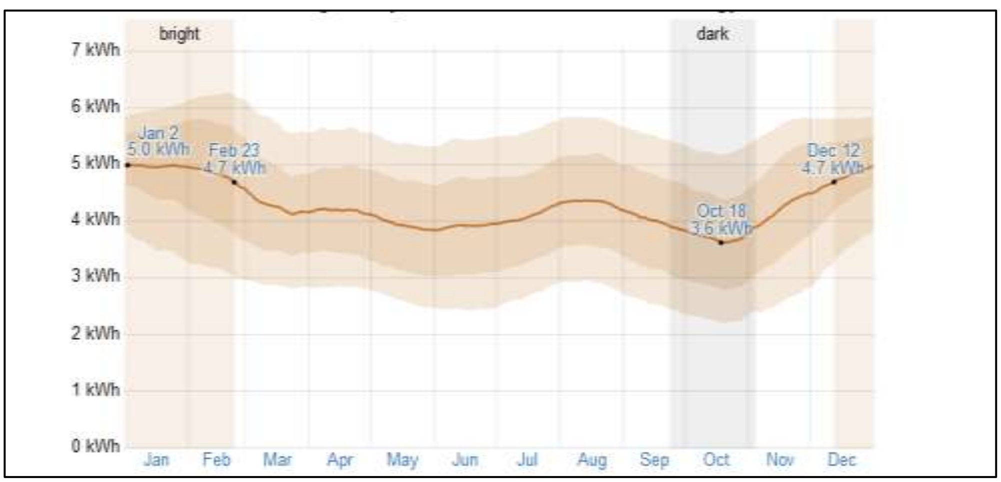


Figure 2. 14 Monthly average incident Shortwave Energy (WeatherSpark, 2016)

2.6.5 Cloud cover

Clear skies are seen between November and March lasting for about 4 months. December presents the clearest days in the year. During this period, the sky varies between clear, mostly clear and partly cloudy 47% of the time and mostly cloudy or overcast for the remaining 53% of the time.

On the other hand, the months of April to October presents cloudier periods that last for about 8 months. During this period, the sky is cloudy 87% of the time and varies between clear, mostly clear or partly cloudy 13% of the time. Fig 2.15 shows the cloud conditions in Okigwe from January to December.

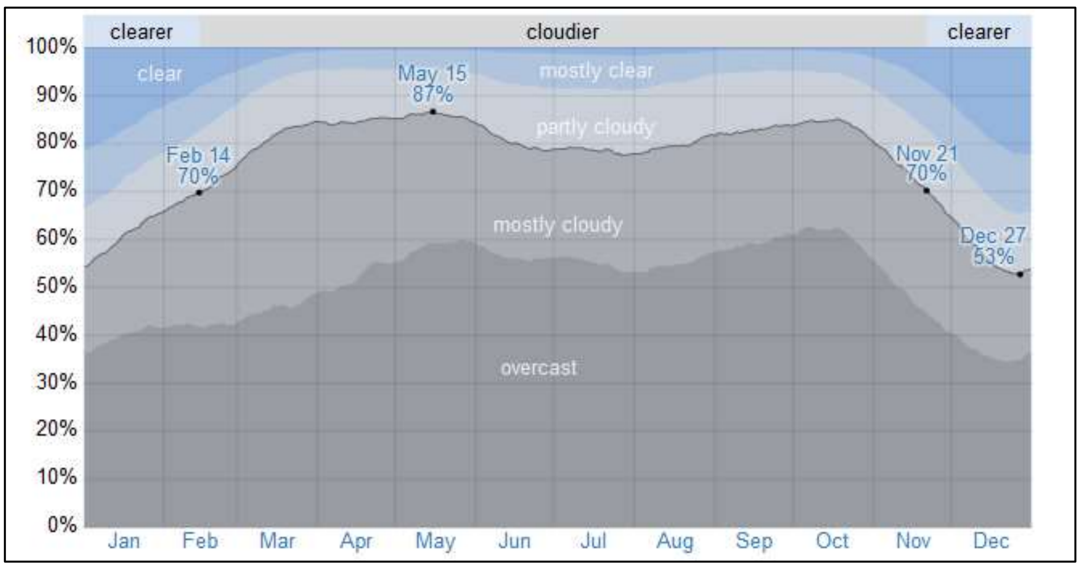


Figure 2. 15 Cloud conditions in Okigwe from January to December (WeatherSpark, 2016)

2.6.6 Wind

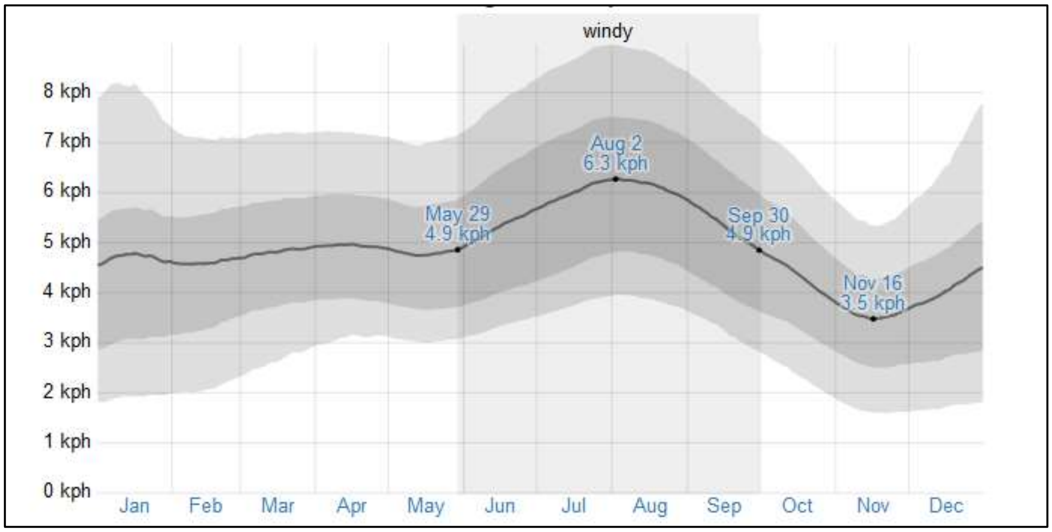


Figure 2. 16 Monthly average Wind Speed (WeatherSpark, 2016)

At 10m above the ground, the wind characteristics are as follows: wind speeds stay around 2.6 kph and above between May and September, being the windier period, which lasts for about 4 months. August presents the windiest period with speeds of up to 6.3 kph. September to May presents calmer periods with average wind speeds around 3.5 kph which lasts for an approximate period of 8 months with November presenting the calmest month with speeds around 3.5 kph.

Wind directions change according to prevailing winds. Winds from the west lasts for about 2.1 months from January to March and 6.1 Months from May to November with the highest percentages in August. Another wind which moves from the south lasts for a period of 1.9 months between March and May with a peak of 55% in mid-April. November to January experiences winds from the North that lasts for approximately 1.9 months with peaks at 54% in early January.

The average monthly wind speeds in the study area are presented in Fig 2.16. Wind speeds rarely exceed 7 kph.

2.6.7 Topography

Okigwe rests on an undulating platform. The vegetation cover is made up of about 31% trees, 28% of cropland, 27% of grassland and 15% of shrubs for every 3 km. The maximum elevation in topography is about 191m and an average of 165m above sea level.

2.7 Chapter Summary

The chapter focused on classifying the macro climate of South Eastern Nigeria. Climatic characteristics of the site (temperature and humidity) were presented. Two major seasonal climate variations were identified. Average minimum ambient temperature of the study is 19^{O}C, while the average maximum temperature is 32^{O}C. Humidity levels can rise above 90% between May and October, with average monthly speeds rarely exceeding 7kph.the skies are clear during hot periods of the year about 47% of the time and 13% clear during the cool seasons. Monthly climatic reports from meteorological observations were also presented.

Any cooling strategies while addressing the seasonal variations identified have therefore to operate optimally within the limits of the immediate environment and must attempt to make prime use of the potentials presented by the immediate environment. In order to achieve these, site measurements will be carried out during ‘field work’ to understand the macro climate within and around the case building and experimental rigs.

3. PASSIVE AND LOW ENERGY COOLING TECHNIQUES IN BUILDINGS

3.1 Introduction

This chapter reviews the previous literature that has focused on the reduction of indoor temperature and the optimisation of thermal comfort using both passive and low energy cooling techniques. While identifying some basic knowledge gaps in the application of low energy cooling techniques in buildings, the study assesses the main principles of some passive cooling approaches that have been established in other climates, which provides a background to demonstrate the importance of the study. It further discusses the application of mechanical cooling systems and the potentials for passive cooling strategies – mainly ground pipe positive pressure ventilation and nocturnal 'black body' radiant cooling strategies in combination with a possible synergistic hybrid arrangement. The review also discusses the likely benefits that can accrue from adopting passive cooling strategies as alternative to mechanical air conditioning and the common practice of use of windows as the only means of natural ventilation in South Eastern Nigeria. Current concepts, relevant data and theories that are important to the subject of study are emphasised in the review.

3.2 Thermal Comfort and Adaption in South Eastern Nigeria

Building shape, building design and choice of material for construction greatly affect the level of comfort achieved within a building. Climate conditions vary over distance and time and have a profound influence on thermal comfort requirements.

ASHRAE defines thermal comfort as "*that condition of the mind in which satisfaction is expressed with the thermal environment*". Hensen (1991) earlier on in a more pragmatic manner defines thermal comfort as, *"a state in which there are no driving impulses to correct the environment by the behavior."*

Givoni (1998a) says that thermal comfort *"is the range of climatic conditions considered comfortable and generally accepted by humans"*. Thermal comfort is affected by climatic conditions, building envelope configuration and user behavior, lifestyle, culture and thermal adaptation. Fig 3.1 presents the range of thermal environments that typify the world's 6 major climate zones/types.

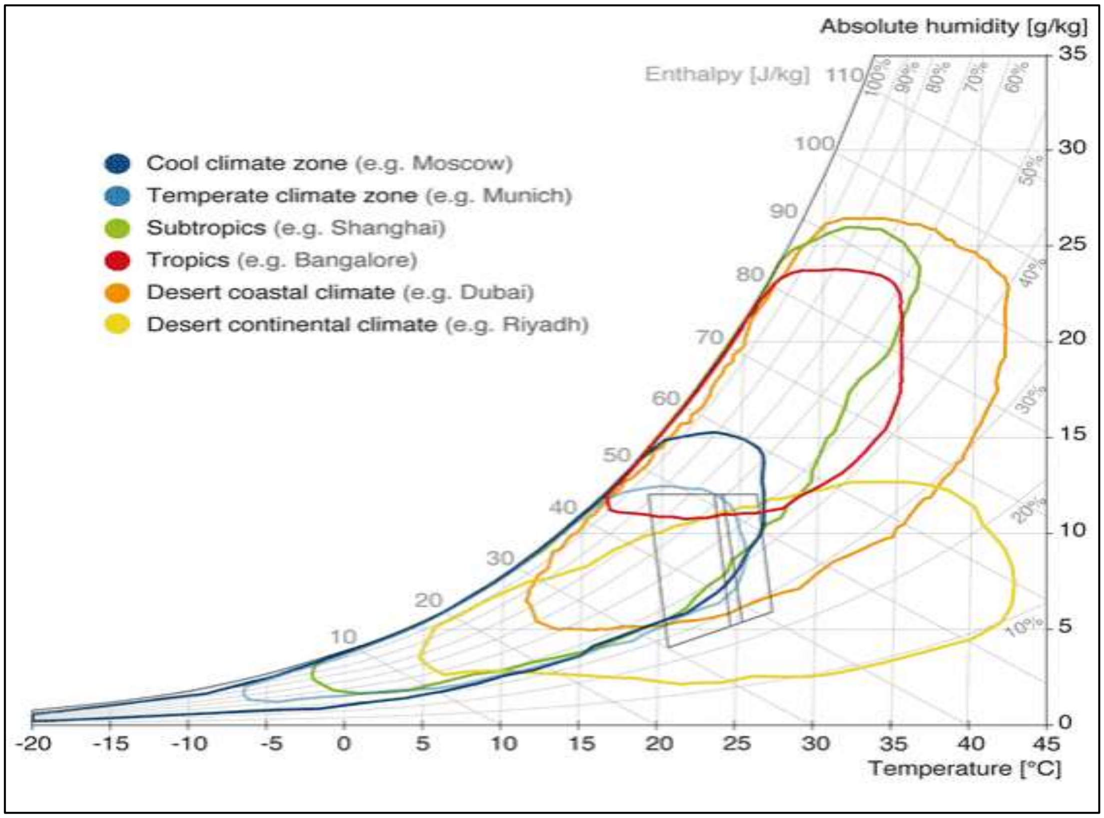


Figure 3. 1 Thermal specifications in buildings according to climate zones (Liedl, 2011).

The main factors that are necessary for thermal conditioning in dwelling spaces are humidity and the temperature. Thorough climate data evaluation of outdoor temperatures and absolute humidity is therefore essential to determine an accurate climate zone classification for building climatology (Liedl, 2011).

3.2.1 The Adaptive Model and Current Standards

It is always a challenging task to determine thermal comfort in any specific location. This is because thermal comfort is generally considered to be down to an individual's subjective perception (influenced by metabolic rate etc.) under any given temperature, humidity and air speed. Individual perceptions are not therefore considered to be reliable (Roaf & Hancock, 1992).

In the early 1920s ASHRAE established the first comfort standard which was applied to HVAC applications (Sreshthaputra, 2003). Standards and indices including charts have also been developed to determine indoor comfort levels across various locations. (ASHRAE., 1974; De Dear, Brager, Reardon, & Nicol, 1998; Dedear & Auliciems, 1985; Evans, 2003; P. Fanger, 1970; Gagge, Fobelets, & Berglund, 1986; Givoni, 1976; Olesen & Parsons, 2002; Olgyay, 2015; Szokolay, 2014)

While most of these studies were based on computer simulations or laboratory based predictions, others determine comfort for human beings using field measurements which claim that occupants adapt to a wide variety of temperature ranges (Ogbonna & Harris, 2008).

3.2.2 Review of Thermal Comfort Studies in Nigeria and West Africa

Few studies have been carried out on thermal comfort in warm humid climate of West Africa. An extension of Auliciems (1981) model was carried out in Ghana by (Koranteng, Mahdavi, Orehounig, & Pröglhöf, 2009) through a study of indoor temperature and relative humidity within 5 different office buildings in Kumasi. The adaptability scale of 90% of (Szokolay, 2014) was used in this work to determine comfort zones. The study concluded that humidity levels of up to 80% and temperatures up to 29^{o}C appeared to be considered acceptable by those acclimatised to such conditions. Such a combination of temperature and humidity may likely feel uncomfortably warm to most northern Europeans.

Adebamowo (2007) conducted a survey on residents from 349 (n = 3490) urban communities in Lagos Nigeria aimed at investigating the concept of adaptability of occupants to varying thermal environments. The outcome of the survey showed disagreements between the ASHRAE and Bedford's scales, as occupants of naturally ventilated houses exhibited greater tolerance to higher indoor temperatures. It appears that occupants accept higher temperatures where they have some degree of control over their environment.

In another survey aimed at understanding user preference and thermal comfort ranges in in Bauchi, (a hot-dry region in northern Nigeria), Akande and Adebamowo (2010) observed the effects of 3 basic comfort parameters (air temperature, relative humidity and air velocity) on 206 subjects in 68 naturally ventilated residential buildings. Data was collected in both the dry and rainy seasons. Indoor air temperatures recorded during dry season was between 21^{o}C and 39^{o}C with relative humidity between 28% and 80%. During the rainy seasons 18^{o}C and 29^{o}C were recorded which exceeds the I. Standard (1994) stipulated 23^{o}C - 26^{o}C and RH 30% - 70% for sedentary (near zero) activities. The study further confirmed the alignment of air speed of 0.13ms^{-1} which is within the standard's threshold of <0.2ms^{-1} for sedentary situations. Comfort levels for this region was way over the range stipulated by (A. Standard, 2004). The thermal neutral temperature for the study area is 28.44^{o}C in dry season and 25.04^{o}C in rainy season while (P. Fanger, 1970) PMV based evaluation stipulated 25.1^{o}C in summer and 22.4^{o}C in winter. They still argued that actual thermal comfort range in Bauchi seemed to be wider than the theoretical value because the theoretical NT is lower than the survey value by 3.34^{o}C for dry season and 2.64^{o}C for rainy season that they attributed to probable effects due to climatic conditions and subject's perception. Results of (A. Standard, 2004) 7 scale was used for the overall comfort analysis/assessment and showed that 86% of respondents voted within the 3 major categories of (-1, 0 and 1) indicating that the thermal conditions were acceptable to the respondents, although individual votes on scales of temperature, humidity and air movement showed some dissatisfaction. 80% voted dry while 85% were satisfied with the humidity levels. Comparisons made with the results of similar studies in hot-dry and warm-humid climates and are shown in Table 3.1.

Table 3. 1 Comparison of Neutral Temperatures across different Hot Climates (Akande & Adebamowo, 2010)

Year	Researcher	Building	Location	Neutral temperature of subjects	
1990	J.F. Busch	Office	Bangkok, Thailand	24.5 °C (ET) for AC buildings	28.5 °C (ET) for NV buildings
1991	R.J. de Dear, K.G. Leow *et al.*	Residential and office	Singapore	24.2 °C (To) for AC buildings	28.5 °C (To) for NV buildings
1994	R.J. de Dear, M.E. Fountain	AC Office	Townsville, Australia	24.2 °C (To) in the dry season	24.6 °C (To) in the wet season
1998	T.H. Karyono	Office	Jakarta, Indonesia	26.7 °C (To) for AC buildings	
1998	W. T. Chan *et al.*	Office	Hong Kong	23.5 °C (To) for AC buildings	
1998	A.G. Kwok	Classrooms	Hawaii, USA	26.8 °C (To) for AC classrooms	27.4 °C (To) for NV classrooms
2003	N.H. Wong *et al.*	Classrooms	Singapore		28.8 °C (To) for NV classrooms

In yet another study set to provide thermal comfort data from a city in tropical savannah region of Africa, Ogbonna and Harris (2008) collected data based on temperature, humidity, CO_2 level and lighting levels not excluding questionnaires for the assessment of occupant's sensation in residential and classroom blocks in Jos-Nigeria. A total of 32 buildings comprising of 29 residential and 3 classroom blocks were surveyed. The total number of respondents was 200 and all the surveyed buildings were occupied. Results from survey confirm disparities in (A. Standard, 2004; I. Standard, 1994) recommended values on operative temperatures. This confirms that thermal comfort assessment is a complicated subjective response to several factors that may affect individuals differently. Procedures corresponding to class II protocols for thermal comfort field experiment were used for the survey. Recorded air temperature ranged between 21.96^{o}C - 29.98^{o}C with minimum readings experienced in the early morning hours around 8:22am, while the highest temperature was recorded around 15:19hrs. The mean radiant temperature varied from 22.86^oC - 32.44^oC and air speeds was minimum at 0.02ms^{-1} and maximum at 1.44ms^{-1}. The recorded average air speed was 0.07ms^{-1} while relative humidity was between 56.5% and 88.43% and an average of 71.9% and median of 71.6%. Acceptable humidity was 68%. Air speed was 0.35ms^{-1} higher than the (A. Standard, 2004; I. Standard, 1994) 0.25ms^{-1} and 0.24ms^{-1} recommendations. However, the survey did not cover the interaction between humidity and airflow, a crucial factor in assessment of thermal comfort. Analysis of data and results indicated a neutral-temperature at 26.27^oC using linear regression weighted TSV comfort range between 24.88^oC and 27.66^oC. These results from this study agree strongly with the theory of the relationship of neutral temperature for specific location to the outdoor temperature for adaptive thermal comfort models. As at the time of this survey, (Humphreys, 1981) adaptive model was the closest to the study's neutral-temperature of 26.27^oC. This study was carried out between the months of July and August 2006.

The predicted thermal comfort range of occupants living in a naturally or mixed ventilated building in the study area should be between 23^oC to 29^oC with the neutral temperature predicted to be 26.5^oC and a relative humidity range of 45% to 75%. While the thermal comfort range for occupants living in air-conditioned buildings is predicted to be between 23^oC to 27^oC with neutral temperature at 25^oC and a relative humidity range of 30% to 60%. Table 3.2 presents a comparison of acceptable comfort limits in warm humid environments. It will determine the base on which comfort limits in this study will be determined, while Figure 3.2 presents a psychometric chart comparing the ASHRAE comfort zone for tropical zones and the acceptable comfort range in the study area as a result of reports from various research studies.

Table 3. 2 Comfort Limits in some Warm Humid Environments

Author	Neutrality operating temperature	location
De Dear (1991)	28.5°C (NV apartment)	Singapore
Busch (1990)	28.5°C	Thailand
Nyuk (2003)	(PMV regression 26.1°C and TSV regression 28.8°C) acceptable range 27.1°C-29.3°C	Singapore
Adebamowo (2007)	29.09°C	Lagos-Nigeria
Ogbonna and Harris (2008)	25.06°C (comfort range between 23.55°C and 26.57°C for rainy season) TSV= 26.27°C (range 24.88°C-27.66°C)	Jos-Nigeria

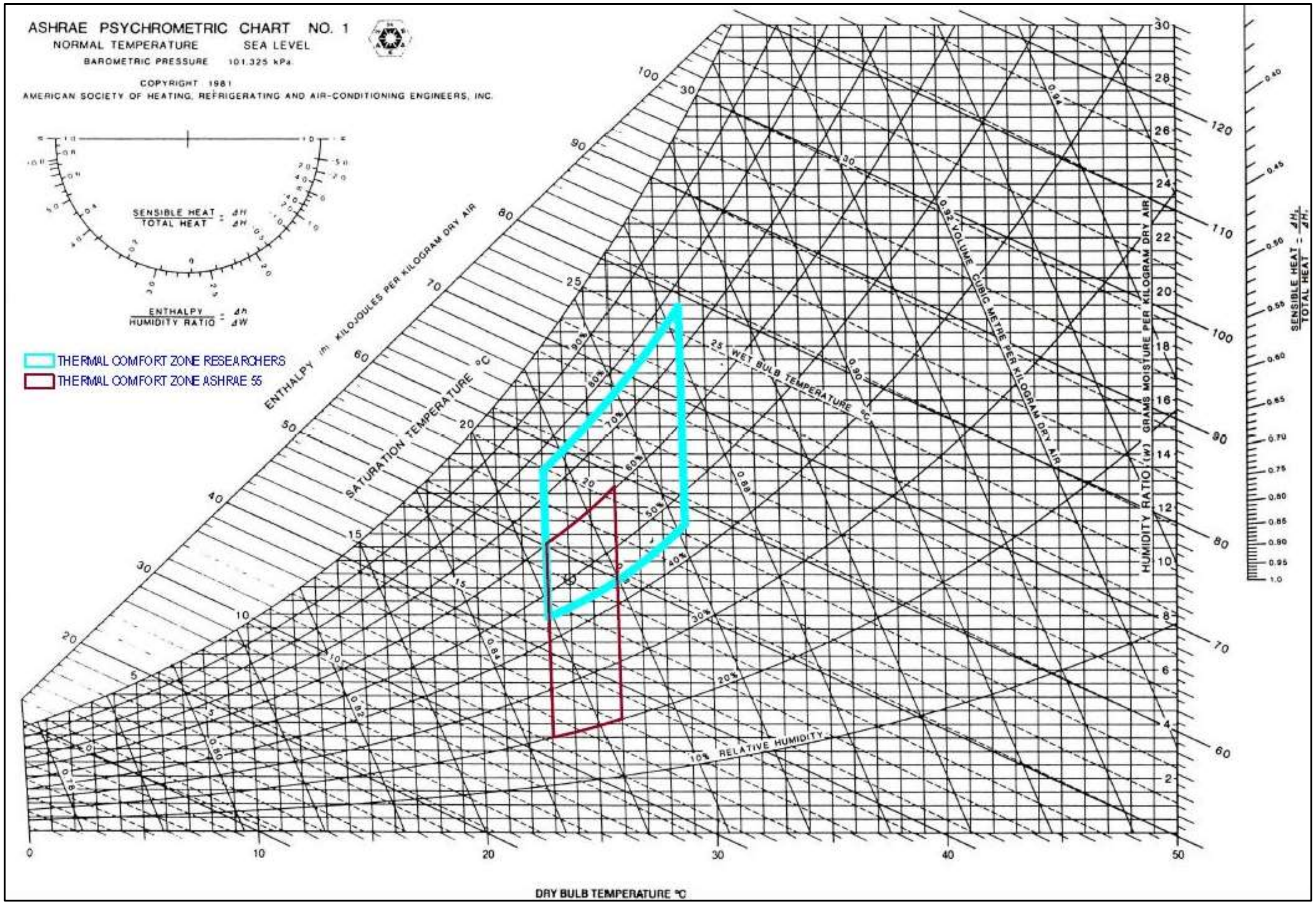


Figure 3. 2 A psychometric chart showing the comfort limit within study area in comparison with ASHRAE 55 thermal comfort limits

3.3 Current Cooling approaches for buildings in South Eastern Nigeria

There is a paucity of research concerning the performance of buildings in the South-Eastern Nigeria. They have adopted a range of vernacular principles to shade buildings such as overhanging eaves, balconies, blinds and dense tree covers where possible, as most users keep windows habitually closed all year round due to factors such as air pollution and dust, insects, security, noise and privacy. Evaporative cooling is mostly provided using ceiling or table fans, and in most cases without a major fresh air inlet. In such situations, the internal air is simply being churned and re-circulated with the likely build-ups of internal pollutants emanating from people and processes or off-gassing from fittings and fixtures. Mechanical air-cooling systems are popular in South Eastern Nigeria as the climate is characterised by high ambient temperatures during the daytime and at Nights. Whole house air conditioning is limited in application due to the capital, running, maintenance and eventual disposal costs. These approaches are grouped into two, namely Active cooling systems and Passive cooling systems.

3.3.1 Active cooling methods

Active cooling systems are those mechanically driven cooling devices, ranging from a simple fan to whole house air conditioning systems. All active systems normally require a source of power to induce cooling.

The data from climate study within the study area shows high temperature during the day and high humidity at nights and as a result, mechanical air cooling systems are mostly required to meet the peak daily cooling demand and consequently a substantial amount of energy supplied to buildings (75%) is consumed to run these machines (Karsten Ley et al., 2014). Some active cooling systems commonly used in Nigeria are discussed below:

1. **Fans**

This group includes ceiling fans, standing fans and table fans. These devices provide localized breeze, which blows through the human skin to induce evaporative cooling. Exhaust fans are another type of fan, which is generally applied in kitchens and bathrooms to remove hot, humid air that may be produced in these areas.

2. **Air Conditioner**

The main aim behind mechanically driven air-cooling systems is to deliver clean, odour-free air at acceptable temperatures, humidity and air velocity within comfort ranges. Designers of these cooling systems are usually faced with the challenge of achieving goals within improved system performance, efficiency and security at a manageable and affordable range. Air conditioning systems are further classified into window units, split unit systems and centralized or whole house air conditioning systems.

In just a space of 8 years (2006-2014), a total of 24 million air conditioning units were imported to Nigeria for domestic use (Karsten Ley et al., 2014). At this rate, the share of air conditioners in household's electricity consumption will continue to grow in the years to come.

There has been a range of experiments and investigations carried out in a bid to reduce energy consumption in air conditioning units and hence, optimised performance of air cooling systems in warm humid area (Huang & Lam, 1997; A. N. Mohammed, 2010; Zhai, Wang, Wu, Dai, & Ma, 2008). Most of these studies concluded that these machines have the capacity to maintain indoor comfort during peak periods. However, their ability to deliver comfort at reduced energy consumption is usually very slim (Fawkes, Howarth, Krarti, & Padmanabhan, 2016). Without a change of approach, HVAC systems will continually influence the energy consumption in buildings found within the warm humid regions especially where the building fabric is perceived as porous to heat waves (Balaras, Droutsa, Argiriou, & Asimakopoulos, 2000; Fawkes et al., 2016).

3.3.2 Passive and Low Energy Cooling Techniques in Warm Humid Climates

The idea of passive and low energy cooling refers generally to the use of building design and choice of materials to deliver cooling in an energy efficient method, therefore minimising or completely removing the application of cooling systems which involves the use of motor-powered mechanical components to move fluids and air (Matheos Santamouris & Asimakopoulos, 1996). Givoni (1994) defines passive cooling as the use of renewable sources of energy to increase heat loss. An instinctive definition to a passive cooling process then becomes any process in which cooling is induced in the absence of any power source(s) or externally powered system, to reduce energy consumption in buildings while improving its thermal environment.

Lechner (1991) has classified sustainable design approach for achieving thermal comfort in hot climates into three ranks. The first-tier concentrates on heat minimisation, by employing some strategies such as an appropriate use of shading (external and internal), landscape and vegetation, orientation, colour, insulation, daylight, roof overhangs, reflective films and coatings, and the control of internally generated heat. The second tier of response is the application of passive cooling and low energy cooling techniques. These techniques include the use of ventilation to align the comfort zone to higher temperatures. There are times in hot climates when the combination of heat prevention and passive cooling and low energy techniques does not yield the desired effect (Givoni, 1998a), in such cases, a third tier which involves the use of mechanical equipment is employed to eliminate remaining cooling load after the application of heat minimisation and passive cooling and low energy techniques. When the first and second ranks are appropriately applied in buildings, the capacity of a mechanical cooling system to consume energy becomes minimal.

Passive and low energy cooling techniques are capable of transferring heat from a building to various natural heat sinks and vice versa (Givoni, 1994). Earlier studies by Cook (1989) and Givoni (1994) have acknowledged four natural heat sinks from which all cooling energy involving passive and low energy cooling is derived namely:

- Ambient air
- Sky or the upper atmosphere
- Water
- Earth / under-surface soil.

Removal of heat by natural means will depend on availability of a heat sink which is at a lower temperature than indoor air and the enhancement of heat transfer toward the sink (Mattheos Santamouris & Kolokotsa, 2013).

There are many approaches to passive and low energy cooling but are generally categorized into five major methods. Effectiveness of these methods will depend on the heat sinks that are employed (Givoni, 1994). These methods are as follows:

- Comfort Ventilation
- Radiative Cooling
- Evaporative cooling
- Ground Cooling
- Nocturnal Ventilative Cooling.

These five major groups are discussed in the sections below.

3.4 Ventilation and Air movements

Air is said to move or circulate when there is difference in temperature and or pressure gradient between two planes due to pressure difference. Air movement serves three basic functions when applied in buildings and they are; supply of fresh air, body cooling and heating or cooling of building fabrics. When air movement is applied for any of these three reasons, it is referred to as ventilation. Air movement in buildings can be through natural means when openings are used to let air into and out of the building space, or through stack effect when there are temperature differences between two planes. Air movement can also be artificially induced using mechanical means. Some ventilation principles relevant to this study are discussed in detail in the sections below.

3.4.1 Elaboration on Some Basic Ventilation Strategies

Ventilation is the dilution or displacement of stale air in a confined space by the supply of fresh air from an external environment. The commonest and easiest method is cross ventilation where windows are placed in an organised pattern to create difference in pressure, thereby inducing airflow from outside across an enclosure. Expression for pressure due to movement of wind to or from a surface is given by Allard, Ghiaus, Santamouris, and Wouters (2006) as:

$$P_w = C_p \rho \nu^2/2 \qquad (1)$$

Where C_p is the static pressure coefficient and ν [m/s] is wind speed at a given level which in most cases is at the window opening or building height. Pressure coefficients, C_p are calculated using computational fluid dynamics (CFD) or physically in wind tunnels.

Ventilation requirements vary across countries as set by the regulatory bodies. Attaining a long lasting comfort zone (range) with natural ventilation using only window openings is a challenging task, as air may be over supplied (Nielsen, 2007). Ventilation is quantified by air change per hour (ACH), which is a fraction between the volume of air introduced or removed in a space and the volume of the space. Minimum rate of ventilation is established according to usage of space. Many techniques have been applied towards the control of ventilation rates in buildings. These techniques range from use of wing walls in one sided openings which create circles of airflow in an interior space (Brown & Solvason, 1962; Khan, Su, & Riffat, 2008), chimneys and cowls (exhaust cowls), wind towers and wind catchers which is a popular passive ventilation technology believed to have originated from Egypt as evident in some paintings dated 1300BC (Gallo, 1998). They are commonly constructed in form of towers which are used to trap air. The principles of stack effect apply to wind catchers when air movement is low to create enough pressure difference between the lower and upper floors. Records have shown that indoor temperature reductions of up to 11°C have been achieved with a wind tower of 4m and cross section of 0.57m x 0.57m, which also produced air flow of up to 0.03m/s (Karakatsanis, Bahadori, & Vickery, 1986).

The derivative form of static pressure (buoyancy) is given by the Equation (Allard et al., 2006):

$dp_s = -\rho(z) \cdot g \cdot dz$ .... (2)

respecting the gas law: $p = \rho RT$ .... (3)

For an increase in Temperature due to height, pressure decreases and is given by:

$p_s = p_r - \rho_0 g T_0 \int_{z0}^{zh} \frac{1}{T(z)} dz$ .... (4)

Where: p_r is the reference pressure at a height z_0, and z_h is the coordinate of the height. Equation (4) can be used to derive static pressure in cases where temperature variation between heights is known.

3.4.1.1 Night ventilation

Night ventilation strives to improve comfort mainly through indirect ventilation. The main approach is in cooling the thermal mass of a building using cool outdoor breeze at night. Performance of night ventilation largely depends on some climatic factors, the technical parameters and techniques applied, and on the thermo-physical properties of the building fabrics.

The effectiveness of night ventilation in the tropics remains a topic of interest and debate as there is a lack of research data, however, there are several hypothesis that suggest increased flow rates in tropical buildings with mechanical means will boost night ventilation (Givoni, 1998b; Liping & Hien, 2007). The effectiveness of night time ventilation depends more on radiant heat exchange between the building fabrics and the indoor environment and as such for maximum performance the conditioned space is normally closed from the warmer external ambient air. In areas where humidity levels are high this becomes a challenge as this is little scope for evaporating perspiration and secondly the amount of water vapor in the air will increase in an enclosed space with high occupancy load factors (M. Kubota, Hamabe, Nakazono, Fukuda, & Doi, 2000; T. Kubota & Ossen, 2009).

Givoni (1994) conducted an experiment to study night ventilation in California, U.S.A. and claimed that night time ventilation was more effective when compared to full day ventilation. This was more pronounced where the buildings have thick walls serving as thermal mass.

The efficacy of ventilation as the sole measure for producing thermal comfort relies upon a complex set of parameters such as, the thermal capacity of the fabric, the position of any insulation layer, air flow rates, diurnal temperature differentials, relative and absolute humidity levels and heat gains due to solar radiation (Pfafferott, 2004; Wang, Liu, Wang, & Liu, 2014).

Night time cooling systems are more efficient in locations where the temperature differences (ΔT) between daytime and night ambient temperatures vary between 10ºC – 16ºC and above, however in areas where daytime ambient temperature are greater than 36ºC, high levels of daytime ventilation is not desirable as thermal walls will be warmed in the afternoons and consequently impact on increased indoor temperatures being elevated at night (Givoni, 1994).

Processes using a bed of desiccant materials incorporated into the roof configuration to dehumidify the passing air, have been reported to reduce the amount of water vapor in the air and in turn reduce humidity levels to levels where natural ventilation for cooling becomes more effective (Givoni, 1998b).

3.4.1.2 Diffuse ventilation distribution systems

Application of diffuse ventilation distribution systems appears to be a growing trend as current research in this field focuses on a more even distribution of conditioned air through a space (Zhang, Heiselberg, Pomianowski, Yu, & Jensen, 2015). Diffuse ceiling inlet ventilation is applied to minimise the effects of localised draughts. Diffuse ceiling inlet ventilation is characterised by the supply of conditioned air into living spaces at low and tolerable velocities using the ceiling area as a ventilation diffuser (Zhang et al., 2015). Other innovations on even distribution of air to avoid draught from source are radiant heating and cooling floors that were used in early types of floors in Korea and later brought by the Romans to Europe in the later part of 1st Century BC. The invention then used exhaust heat from open fires channeled under stone floors which gradually releases the warmth. This innovation became most popular and made easier to apply in the early 1930's after the development of polyethylene pipes by Gibson and Fawcett. Polyethylene pipes are still in use today as cross-linked polyethylene (PEX) pipes which are a more refined version (Anna Jagger, 2008; Olesen, 2002; Robert, Olesen, & Kim, 2010).

3.4.1.3 Radiant cooling systems

Radiant cooling systems deliver by means of sensible cooling where the heat transfer coefficient acts as a regulator and depends on temperature differences between the radiating body and the internal space to be conditioned. In this type of system, air movement is minimal reducing transportation of dust however very low air exchange rates in buildings have negative impacts on air quality.

It is therefore a challenging task to meet all ventilation requirements in buildings by depending only on natural ventilation. Fathy (1986) wrote: *"another science to which architecture is indebted is aerodynamics. The methods of investigating airflow around the wings and bodies of aircraft are now being used to study airflow through, over and around buildings. Scaled and full-sized models can be tested in wind tunnels to determine the effect of size, location and arrangement of opening on the airflow through individual buildings as well as the nature of wind patterns and forces between groups of buildings"*.

Despite the shortcomings associated with artificially induced ventilation using mechanical means, it is still important to note that mechanically induced ventilation is more effective than natural ventilation in terms of efficiency, control and regulation of air flow and indoor temperature. More recent research work has focused on optimizing the performance of ventilation systems by combining natural and artificially induced air movements, popularly known as 'hybrid' systems (Alp, 1991).

3.4.2 Efficiency and Limitations of Wind Driven Ventilation Techniques in Warm Humid Climates

The WHO (1983) defines health as that condition where there is lack of disease and infirmity, but of complete physical, mental and social wellbeing. It is a big task for buildings to provide health while controlling other conditions that might be a threat to health of users, however, there are numerous factors known to affect the efficiency of natural ventilation and the purpose for which airflow is introduced in building enclosures.

The efficiency of natural ventilation is determined by external and internal factors, user behavior, operational awareness and perception. Users open and close windows for many reasons ranging from airflow control against uncomfortable conditions due to overheated interiors or draughts to expelling odours, avoiding poor outdoor air quality and dust, security and avoiding the ingress of pests and noise.

3.4.2.1 Security and Noise

In most of urban Nigeria the fear of attack by burglars is the primary reason why windows are kept securely shut at night despite uncomfortably hot interiors that regularly reach 35ºC during the summer.

A study carried out by Badiora, Oluwadare, and Dada (2014) to determine the experience of “burglary proofing” amongst the residents of a traditional urban center known as Ile-Ife in western Nigeria grouped areas by density: the core, the transition, and the suburb areas. 10% of each group was sampled by interviewing a household representative aged 22 years or over. 62%, 72% and 81% (average of 71.7%) of residents in the three groups respectively had experienced residential burglary at least 6 months before the sampling. 31%, 43% and 49% (average of 41.7%) of these burglaries were carried out through windows. Table 3.3 presents burglary incidences as recorded in Ile-Ife.

Noise is another factor of discomfort that determines the rate of opening or shutting of windows. Residents very close to major traffics and industrial areas are bound to shut windows against noise from the busy road and operations of heavy machines.

Table 3. 3 Operation of burglars in a typical Nigeria City Ile-Ife (Badiora et al., 2014)

Time of burglary occurrence (including attempts) in different residential areas						
Time of the day/Time of the week	Core		Transition		Suburban	
	Weekend	Weekdays	Weekend	Weekdays	Weekend	Weekdays
Daytime	26 (51%)	28 (54%)	53 (52%)	73 (72%)	19 (48%)	30 (78%)
Nighttime	25 (49%)	23 (46%)	49 (48%)	29 (28%)	20 (52%)	09 (22%)
Total	51 (100%)	51 (100%)	102 (100%)	102 (100%)	39 (100%)	39 (100%)
How burglary occurred (including attempts) across different residential areas						
	Core		Transition		Suburban	Total
Door	24 (47%)		50 (49%)		17 (44%)	91 (47%)
Window	20 (39%)		44 (43%)		19 (49%)	83 (43%)
Wall	01 (2%)		00 (0%)		00 (0%)	01 (0.5%)
Ceiling	05 (10%)		08 (8%)		02 (5%)	15 (8%)
Other openings	01 (2%)		00 (0%)		01 (3%)	02 (1%)
Total	51 (100%)		102 (100%)		39 (100%)	192 (100%
Materials loss						
Cash/money	47 (39%)		94 (30%)		35 (33%)	176 (32%)
Properties	32 (26%)		89 (28%)		30 (28%)	151 (28%)
Documents	22 (18%)		54 (17%)		23 (22%)	099 (18%)
Assaults/abuse	21 (17%)		78 (25%)		18 (17%)	117 (22%)
Total	122(100%)		315 (100%)		106 (100%)	543 (100%)

3.4.2.2 Pests, Insects and Bugs

Pests, pollutants and dust can also inhibit the use of windows for natural ventilation. South-Eastern Nigeria suffers mosquito infestation: an insect very common in the tropics, the female anopheles mosquito carries a parasite known as *plasmodium falciparum*. This specie of mosquito spreads this bacterium when it sucks blood from the human skin and the parasite is responsible for all the cases of malaria recorded in this region.

(WHO, 2016a) estimates about 212 million cases of malaria in 2015 and about 429,000 deaths, of which 90% of reported cases and 92% deaths are in sub Saharan Africa alone. Children between the ages of 0 to 5years are most prone to deaths due to malaria with more than 70% of total number of child deaths caused by malaria. As a deadly killer in warm humid climates it becomes the norm to shut all openings in buildings from mosquitos mostly at nights or to use insecticides and sprays to avert its bite, therefore contributing to what many may consider to be an unpleasant and overheated indoor environment.

3.4.2.3 Dust and other Pollutants

Shutting windows to prevent mosquito bites and to enhance security may cause accumulation of toxic gasses within the building. Air pollution can come from within an interior space or from its external environment Figure 3.3.

Indoor pollutants were classified by Bascom, Bromberg, et al. (1996) into three major categories namely; corrosives, irritants and sensitizers according to how the human body reacts to them. Indoor pollutants emanate from various sources within the building enclosure mostly as off gassing from building materials, furniture and interior finishes, while external sources are from contaminated air prevalent in the external environment. S Howieson (2005) listed the most common air pollutants as:

"Ammonia, asbestos, benzenes, biocides, carbon dioxide, carbon monoxide, detergent, dust, ethanol, fiberglass, formaldehyde, hydrocarbons, hydrogen chloride, methanol, micro-organisms, motor vehicle exhaust fumes, nitrogen oxides, ozone, paint, poly-chlorinated biphenols (PCB), pesticides, photochemical smog, radon, solvents, sterilant gasses, sulphur dioxide, tobacco smoke and vinyl chloride"

Prolonged low-level exposure may have a greater insidious impact on health than short term exposure to high concentrations. Ozone for instance if inhaled 0.08 - 0.12ppm and at a rate of 10,000 - 20,000 liters per day is likely to cause lung inflammations (Bascom, Kesavanathan, & Swift, 1996).

In 2015, the World Bank (Group, 2015) reported that 94% of Nigerians were vulnerable to air pollution levels above World Health Organization guidelines, and by 2016 and 2017, the percentage exposed has risen to 100% (Group, 2016, 2017). The use of generators which run on petrol containing benzene (a bio-accumulative carcinogen) generate poor external air quality.

Toxic smoke can also emanate from the burning of waste. This is a widespread practice due to the absence of public waste services and lack of regulations/enforcement of environmental policies. Internal air quality is based on external air quality. It is therefore not good practice to depend on natural ventilation in a polluted environment. One of the commonest air pollutants in south east Nigeria is particulate matter.

Particulate matter (PM –mainly micro black carbon) emanates from the burning of waste and other related activities. PM_{10} are tiny particles (under 10 microns) contained in the air that are 30 times smaller than the width of a human hair and is measured in micro grams per cubic meter. They come mostly from smoke, dust, soot, vehicle exhausts and industries.

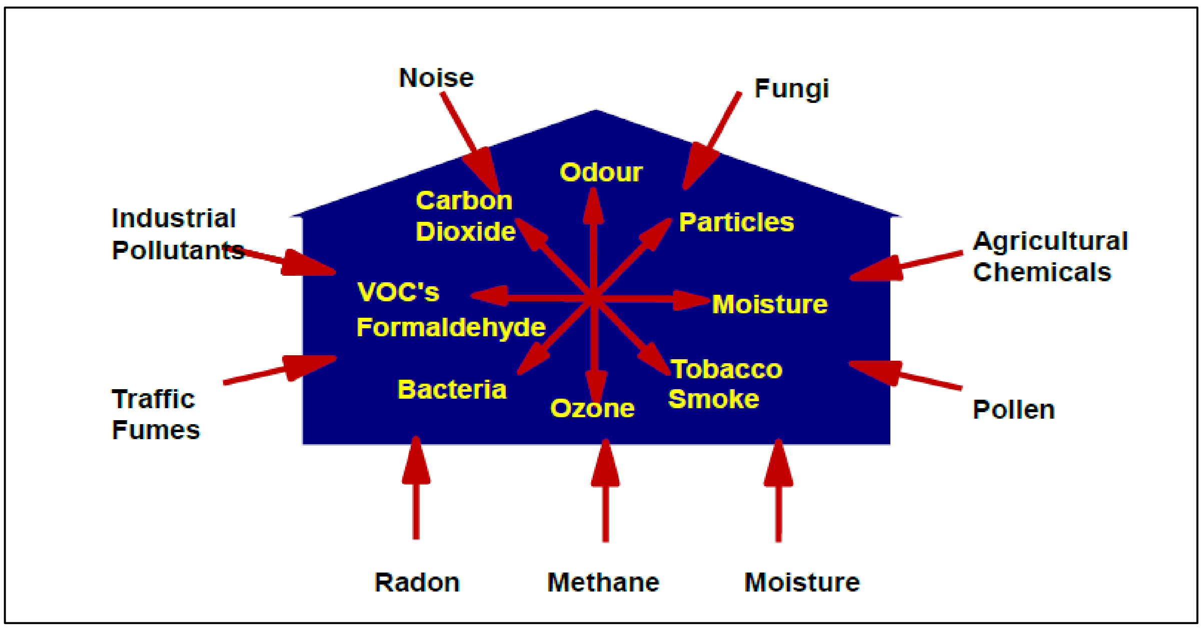


Figure 3. 3 Common types of toxins and pollutants in dwelling spaces (CIBSE, 2006).

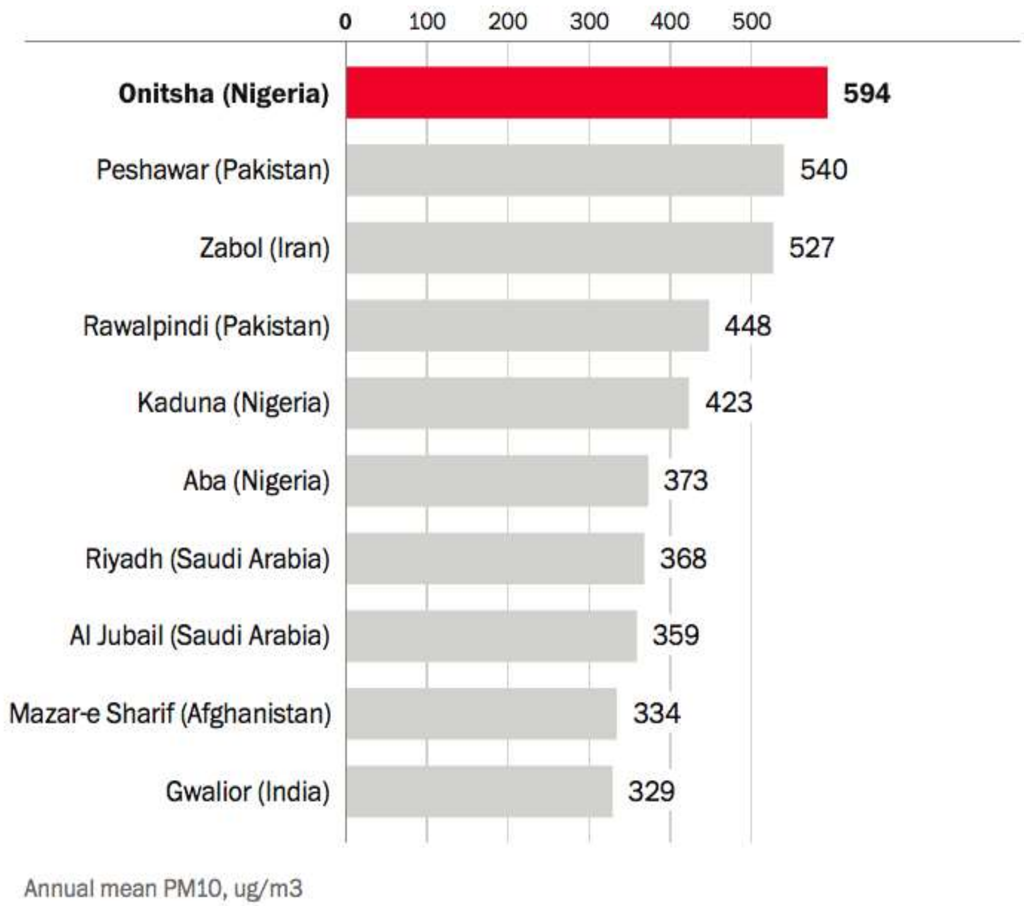


Figure 3. 4 Cities by annual PM_{10} concentrations. Source: (WHO, 2016b)

Onitsha, a commercial city in South-Eastern Nigeria has been identified as the world's most polluted city with exceptionally high levels of PM_{10} particles. According to the WHO, 594µg/m^3 of PM_{10} particles, and 66µg/m^3 of the deadlier $PM_{2.5}$ were recorded. In Nwangene, air monitor readings were 667µg/m^3 for PM_{10}, which was more than the 594µg/m^3 annual figure that gave Onitsha its name as the world's most polluted city, while $PM_{2.5}$ were measured at 290µg/m^3. At Ochanja market, the readings were 586µg/m^3 for PM_{10} and 266µg/m^3 for $PM_{2.5}$ (Egbedi, 2017). These figures are more than double those of highly polluted cities such as Kabul, Beijing and Tehran, and 30 times worse than London.

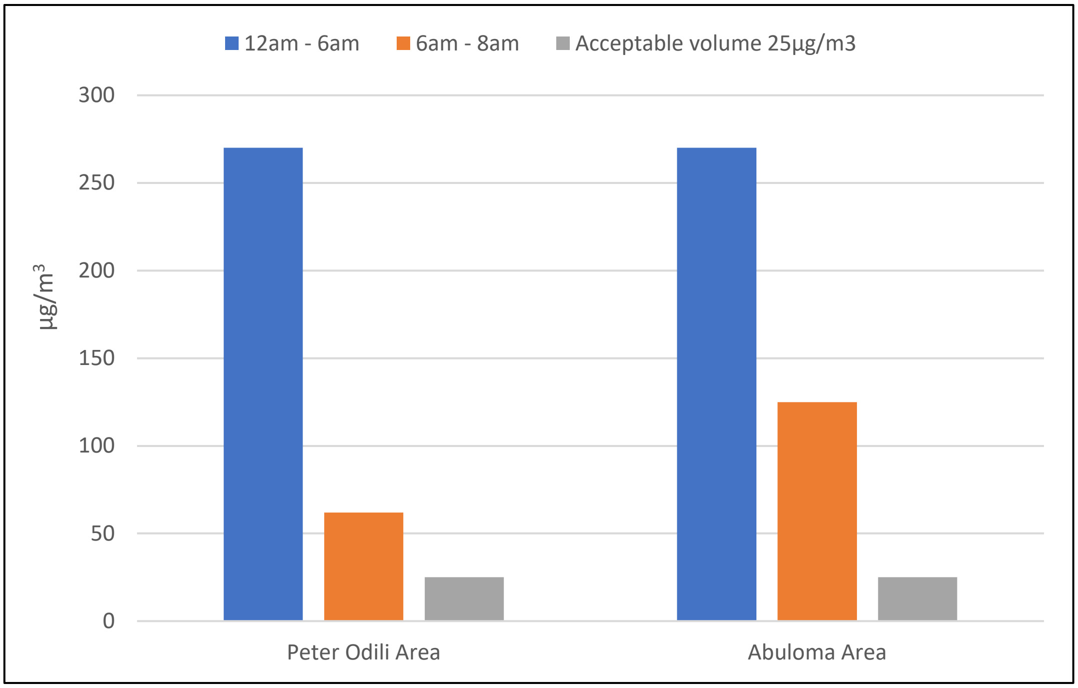


Figure 3. 5 PM_{10} Concentrations in two zones in Port Harcourt Rivers State Nigeria.

The United Nations Environment Program (UNEP) claims that approximately 600,000 people die in Africa every year due to contaminated air. Figure 3.4 shows annual PM_{10} concentrations in 10 cities across the world. Nigeria alone has 3 cities in the list namely Onitsha 594µg/m^3, Kaduna 423µg/m^3, and Aba 373µg/m^3.

Recently there have been reports in Port Harcourt – situated in the oil producing region of Nigeria - of high discharges of black soot. Suspected sources are attributed to activities related to incomplete combustion of petroleum-based substances, carbon materials, illegal refineries, burning of tyres to access copper and gas flaring. This black soot was found to be composed of high levels of nickel and lead, with circa 6 million people exposed in the region (Yakubu, 2017).

In 2016 government of Nigeria set up a task force comprising experts from Ministries of Environment and Health to monitor air pollution. Monitoring in the Abuloma and Peter Odili areas of Port Hardcourt. This report is presented in Fig 3.5.

3.5 Heat Sinks and Air Movement: The Basic Parameters for Optimum Building Response to External Environment

Heat sinks are those bodies or objects (any environment or medium) that can receive, absorb, retain and give back heat when the heat source is removed. They are essentially heat exchangers. Heat sinks exchange heat through conduction, convection and/or radiation with the surrounding cooling medium. These heat vehicles are generally fluids, which can be liquid or gaseous. Air and water are the most commonly used fluids with heat sinks. Research has shown (Nwaigwe, Okoronkwo, Ogueke, & Anyanwu, 2010; Parker, Sherwin, Hermelink, & Center, 2008) that air cooled heat sinks are simpler and more flexible systems to manipulate compared to those powered by liquids and are often a more efficient technique when applied in cooling devices for example, electronic gadgets and computer programming units (CPUs). The air driven system has also been found to be applicable in residential houses for example, night time cooling, which is a strategy that makes use of cool ambient air at night to heat flush the interior and store coolth in the thermal mass embedded in heavyweight building fabric, where it is exposed.

The surface area of a heat sink exposed to any surrounding fluid is a key factor that determines the rate/intensity of heat exchange between the heat sinks and fluids and therefore requires critical analysis at the design stage to calculate and design the optimal cooling or heating strategy. The introduction of fins, studs, pins and micro-channels may for instance increase the heat exchange rate by increasing the surface area of a heat sink. This may also create more turbulence that in turn increases the surface contact between the heat sink and fluid. An innovation by Versarien Technologies (2015) known as VersarienCu® has applied a similar system by taking advantage of the microporous nature of copper foam to increase surface area in CPUs in order to improve performance and decrease the likelihood of component failure.

There are distinct types of heat sinks and are classified under two major categories namely: Natural heat sinks and Man-made heat sinks.

The sky, the Earth crust, the Sun, Water bodies and the Atmosphere are some natural heat sinks. This research work will consider their potentials as primary heat source to buildings. Other types and applications of heat sinks in the building fabrics are explored and discussed in sections below.

3.5.1 Heat Source

Heat energy describes a certain behavior of molecules in an object. An object is said to be ‘hot’ when the molecules are vibrant. Cold objects have less ‘noisy’ molecules. Heat moves in one direction, always moving from hot to cold. When this happens, the former is then said to be a heat source to the latter. Heat energy is transferred through conduction, convection or radiation or a combination of two or the three transfer types simultaneously in a process.

The sun is the only source of heat in our solar system. It produces solar radiation that keeps the earth warm. The earth in return gives out heat to the sky through black body radiation at night. Solar radiation will warm building surfaces during the day. These surfaces will then re-radiate most of this energy at night especially if the night sky is clear of clouds.

Fig 3.6 shows some basic external factors that influence indoor thermal behavior of a typical building form. These external factors relate to the building envelope through a complex combination of conduction, radiation and convection. Energy flows are therefore highly dynamic and can quickly reverse. The principles of heat transfer have guided the behavior of buildings in any given environment. These have generated some basic rules of thumb influencing the design of vernacular buildings. The sections below discuss the types of heat sinks and their influence on thermal behavior and energy consumption in residential buildings.

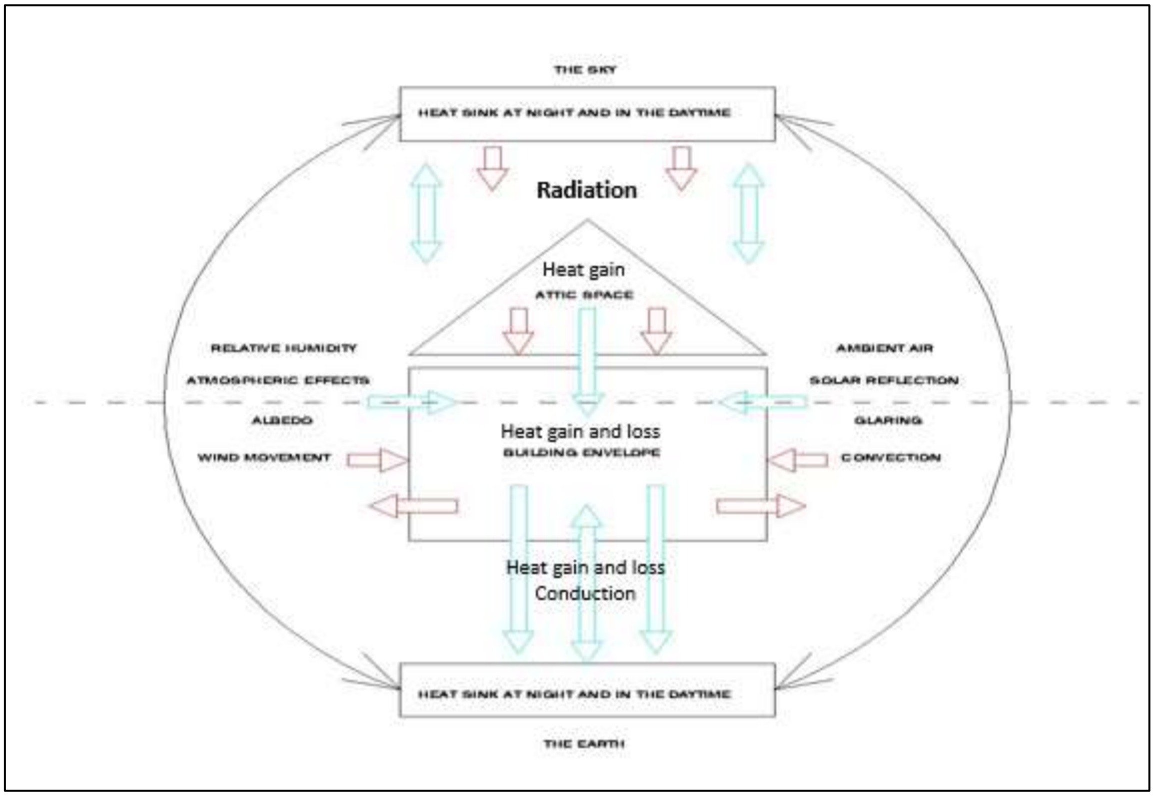


Figure 3. 6 Relationship of Building Envelope with the Immediate Environment.

3.5.2 The Sky

The sky is a natural heat sink that exists above the close earth atmosphere. It transfers heat by long-wave radiation and at night temperatures are normally below ambient air temperature. Higher temperature differences "ΔT" between the sky and ambient temperature increases the effective temperature or the cooling potential of the sky through radiation emitting from exposed surfaces that have a view to the dark cosmos. Heights and transparency of the atmosphere at those levels to certain bands is attributed to the coldness of the sky (Ezekwe, 1986; Hottel & Egbert, 1942; Mills, 1995). The perceived temperature of the sky is known as the ‘effective’ temperature of the sky. The sky temperature under clear atmospheric condition can drop to between 5ºC - 30ºC below ambient (Cooper, Christie, & Dunkle, 1981; Rosenlund, 2000).

Some factors are known to affect the effective temperature of the sky and hence its cooling ability. Water vapour (clouds) and carbon dioxide concentrations will significantly reduce night time radiant heat losses as they act as a thermal blanket (Paul Berdahl & Fromberg, 1982). Dew point and site conditions are among other micro conditions that may affect the effective temperature of the sky. When dew points are between -20ºC and 30ºC, the effective sky temperature can be derived from the equation below under a cloudless sky condition (J. H. Lienhard, 2013):

$$T_{sky} = T_{air}\ [0.711+0.0056\ T_{dp}+ 7.3x10^{-5}\ T^{2}_{dp} + 0.0013\ \cos(2\pi t/24)]^{1/4} \quad (5)$$

Where T_{sky} and T_{air} are in kelvin and T_{dp} is in °C

Measuring devices and models for calculations have been developed to measure the sky temperature (Paul Berdahl & Martin, 1984; Centeno, 1982; Fuentes, 1987; Garg, 1982; W CQJR Swinbank, 1963; Whillier, 1967). The simplest model was developed by Dreyfus’ (1960) who assumed that the sky temperature approximates to ambient temperature when the sky is completely overcast ($T_{sky} = T_{amb}$).

Errors may occur with the use of instruments due to the difficulty associated with conflicting radiation of the immediate environment and that of the measurement instrument itself which in most cases are at a comparable wavelength to the radiation being measured (Ezekwe, 1986). Cloud cover increases sky emissivity that in turn increases sky temperature as perceived on the earth’s surface. Radiant heat transfer is determined by the sky temperature and the emissivity of the exposed surface material.

Improvements have been made to increase the emissivity of black bodies. Selective surfaces for example are those that have high absorptance/emittance for incident solar flux or visible light - short wavelength –, and lower absorptance/emittance for thermal or infrared radiation - long wavelength. They are used to increase incident solar absorption while suppressing heat losses due to thermal radiation from the surface. The selectivity is defined as a ratio of solar radiation absorption (α_{sol}) to thermal infrared radiation emission (ε_{therm}) and can be achieved by means of surface coating or material configuration of the radiating surface (Masterson, 1977; Nunes, Costa, Sade, Araújo, & Silva, 2018). Selective surfaces radiate at almost all wavelengths as against the atmospheric window of 8-13µm common to simple blackbodies. Using a selective surface on roof surface with high emissivity therefore offers opportunities for night cooling.

While most studies have concentrated on development of models for determining the sky temperature, others have concentrated on determining the radiation intensity of skies and black bodies. Radiation intensity has been measured in previous studies as evident in the works of (Ångström, 1915; Armenta-Déu, Donaire, & Hernando, 2003; Cavelius, Isaksson, Perednis, & Read, 2005; Dobson, 2005; Eicker & Dalibard, 2011; Maurer, 1887; Saitoh & Ono, 1984).

Eicker and Dalibard (2011) developed photovoltaic-thermal collectors in an attempt to provide both electrical and cooling energy simultaneously. Their system provided cooling power between 60 and 65W m^{-2} when used for cooling a water tank and 40–45 W m^{-2} when the system was used to cool ceilings. Their system also generated 205 $kWhm^{-2}$ of electricity when tested in Madrid and 142 $kWhm^{-2}$ in Shanghai.

Al-Nimr, Kodah, and Nassar (1998) conducted a study in Irbid - a city in Northern Jordan, where a 0.6 m^2 radiative cooling panel was tested under a climate condition of 28–55% relative humidity and 16–27^{o}C ambient temperature. Good agreement was achieved between the theoretical and experimental data, with the system emitting up to 13 MJ/m^2 of radiation to the sky producing an average temperature reduction of circa 15^{o}C for a 120litre capacity storage tank.

Parker (2005) developed an innovative cooling system using heat exchange between the roof covering and clear night sky, where the medium for heat exchange was air. Complexities associated with configuration and operations of basic radiant cooling systems at night as noted by Hay (1978) and Swami, Fairey, and Kerestecioglu (1990) were resolved using heavy insulation on the ceiling to avoid heat gain into the building in the day time when the sun radiation is highest on the roof covering.

These studies confirm that there is therefore potential to use a lightweight roofing material with a high emissivity selective surface to cool an air steam in direct contact with it, if the configuration includes an insulated boundary layer directly below the air corridor when night skies are clear.

3.5.3 Geothermal heat sinks

The correlation between temperature and depth of the earth is known as the geothermal gradient. Studies have shown that potentials for geothermal energy resource within the earth crust are considerable. This study reviews the temperature variations and patterns within depths of up to 5m under the earth surface. Recent studies have shown that the time lag of the first few meters into the ground are large enough to maintain an almost constant temperature equivalent of the mean ambient at such depths throughout the year (Givoni & Katz, 1985).

A model for daily and annual variation of ground temperature was developed by Kusuda and Achenbach (1965), who having found out that the temperature of the soil is affected by the depth and the time of the year, expressed his findings in the following mathematical relationship:

$$T_g = T_m - A_s\, e\, [-z(\pi/365\alpha)^{0.5}] \cos \{2\pi/365\, [t - t_0 - \frac{z}{2}\sqrt{365/\pi\alpha}]\} \quad (6)$$

Where: T_g is the ground temperature (^oC), T_m is the annual outdoor air temperature (^oC), z is the depth from the surface (m), α is the thermal diffusivity of the ground, t is current day of the year, t_0 is the day of the year of the minimum surface temperature. $A_s = (T_{mo,max} – T_{mo,min}) / 2$, were $T_{mo,max}$ is the maximum monthly temperature and $T_{mo,min}$ is the minimum monthly temperature.

The thermal capacity of the earth renders it a good heat sink especially where the conductivity of the soil is relatively high (high moisture content). It has been proven that the first few meters into the earth crust lags behind ambient air temperature. The earth maintains this quality to depths of about 12m (Mihalakakou, Santamouris, Asimakopoulos, & Tselepidaki, 1995; Pfafferott, 2004; Sanusi, 2012). Figs 3.7 and 3.8 are results from calculations showing typical patterns in temperature variations as affected by depths and time. Passive cooling innovations have ventured into identifying the best approach to this method and strategies for optimal use of these characteristics of the soil as a source of warmth during winter and coolth during summer.

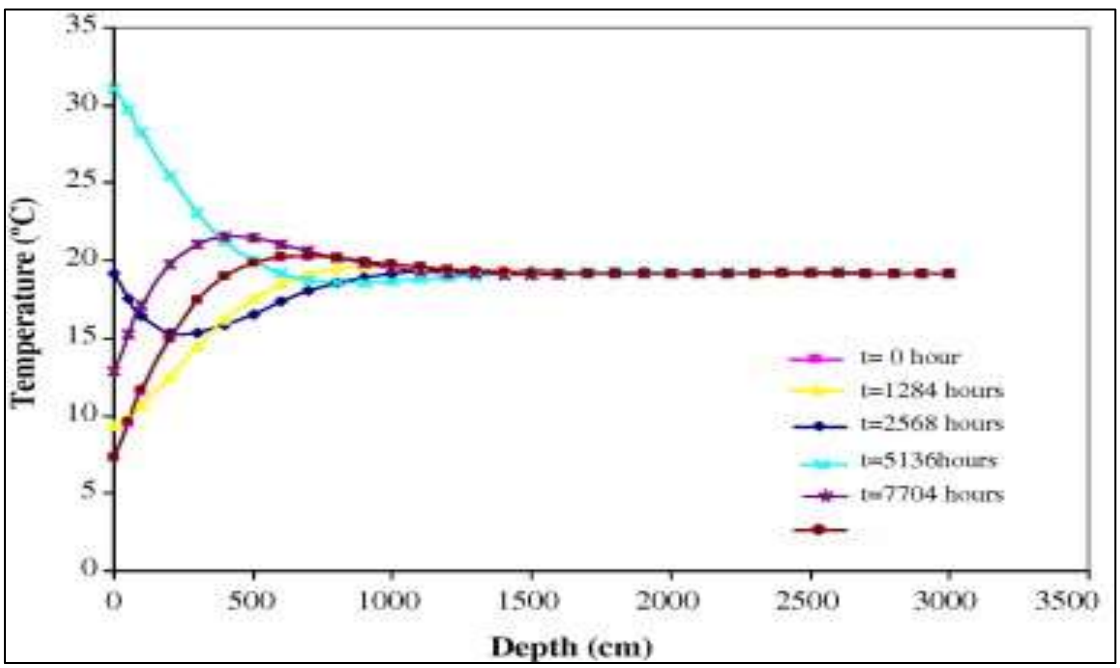


Figure 3. 7 The Effect of Solar Heat on soil Temperature due to differences in Depth (Ozgener, Ozgener, & Tester, 2013)

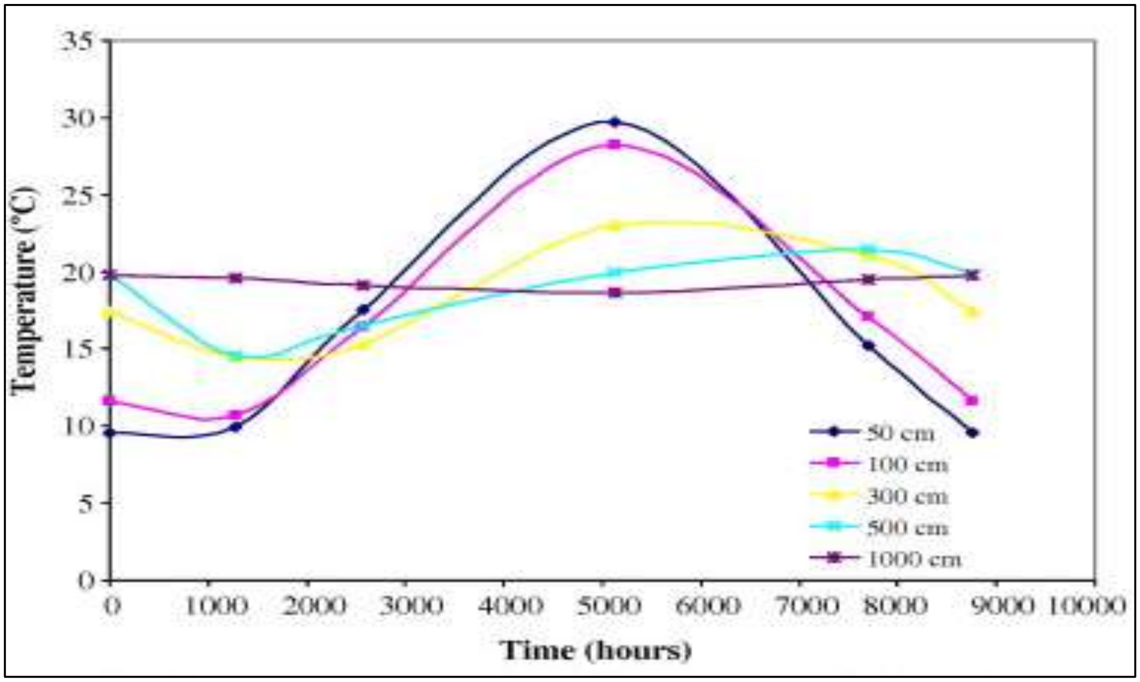


Figure 3. 8 The Effect of Solar Heat on soil Temperature due to time (Ozgener et al., 2013)

In Poland, Popiel, Wojtkowiak, and Biernacka (2001) compared the effects of covered and uncovered soils on temperature distributions at a depth of 1m. Results retrieved after analysis was in agreement with results of (Givoni, 2007; Jacovides, Mihalakakou, Santamouris, & Lewis, 1996; Mihalakakou, Santamouris, Asimakopoulos, & Papanikolaou, 1994) and showed that the covered soil was 4^{o}C cooler than bare soil.

3.5.4 The Atmosphere

The atmosphere is generally known to be a mixture of gases mainly Nitrogen 78% and Oxygen 21% by concentration, which covers the earth and is held in place by the gravitational force of the earth. The remaining 1% of gaseous mixture is shared between particles, water vapor and other gases that includes carbon dioxide. Acting as a blanket over the earth, the atmosphere protects the life on Earth against the harmful radiation from the sun while also functioning as a major heat sink that by retaining of the heat from the sun to keep the earth and life within it warm. The sun illuminates the earth at about 1.74 x 10^{14} kW, with 33% reflected immediately leaving 1.16x10^{14} kW for our immediate use and to sustain other natural processes around us before it is re-radiated back to space (I. Lienhard, Lienhard, & John, 2006).

Human activity from fossil fuel burning, over the last two centuries, is altering the configuration of the atmosphere. While Chlorofluorocarbons (CFCs - a man-made gas) has deleterious effects on the ozone layer, other naturally occurring greenhouse gases like methane and carbon dioxide increase the heat retaining ability of the atmosphere, which in turn results in global warming.

An intelligent building is that which can optimise and harmonize the prospects presented by the atmosphere's regulatory function towards heat gain and loss on the earth's surface. Figure 3.9 illustrates the distribution of sun's energy to and from the earth's surface by the atmosphere as presented by (J. H. Lienhard, 2013).

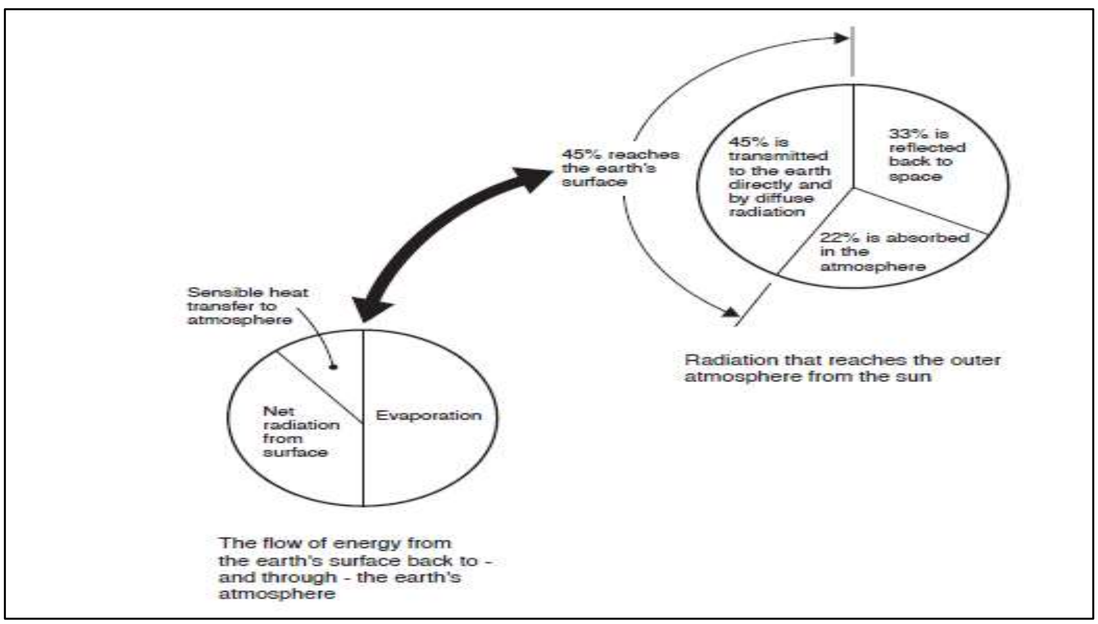


Figure 3. 9 An approximate distribution and flow of sun's energy in and out of the earth's surface (J. H. Lienhard, 2013).

3.6 Ground Based Cooling Strategy: Earth to Air Heat Exchangers

Earth to Air Heat Exchangers (EAHXs) make use of pipes (mainly PVC) buried in the ground with the primary aim of extracting the heat reserve stored in the Earth to warm indoor spaces. They basically operate by taking advantage of the earth's capacity to sustain a fairly consistent temperature throughout the year to cool or heat spaces. The soil temperature of any location at certain depths (usually between 0.5m to 5m) fluctuates well below the average ambient air temperature. The justification behind this idea lies in the daily and annual temperature amplitudes in the soil that softens with increasing depths. Soil depths between 5m and 8m are rarely affected by annual ambient temperature swings and soil depths between 3m and 4m have been found to remain constantly around the average annual ambient temperature (Givoni, 1994; Kreider & Rabl, 1994; Pfafferott, 2004; Sanusi, 2012).

Earth to air heat exchangers are basically applied in two modes namely: Open Loop systems and Closed Loop systems. Closed loop systems mimic the operations of a basic mechanical air conditioner by recirculating used air through pipes buried in earth in loop forms with the building, but this approach has a major setback which is poor indoor air quality, elevated humidity levels and other disadvantages related to high humid environments like legionnaires disease (Bisoniya, Kumar, & Baredar, 2013).

Despite the advantages, earth to air exchangers generally have high capital costs due to the extensive ground works required to install the serpentine ground pipe loops. It also becomes a problem to apply this strategy when there is limited land space. EAHXs can provide breeding grounds for micro-organisms due to condensation that can occur in the pipes as the air temperature can regularly drop below dew point towards the end of the pipe runs. Fig 3.10 shows a simple application of an earth to air heat exchanger. The basic purpose of an earth to air heat exchangers is the ability of the high thermal mass of the soil to dampen the amplitude of the air flow temperature. This principle can be used to cool dwellings during summer when the ground temperature is significantly below the air temperature, and in winter to warm the spaces where the reverse may be the case.

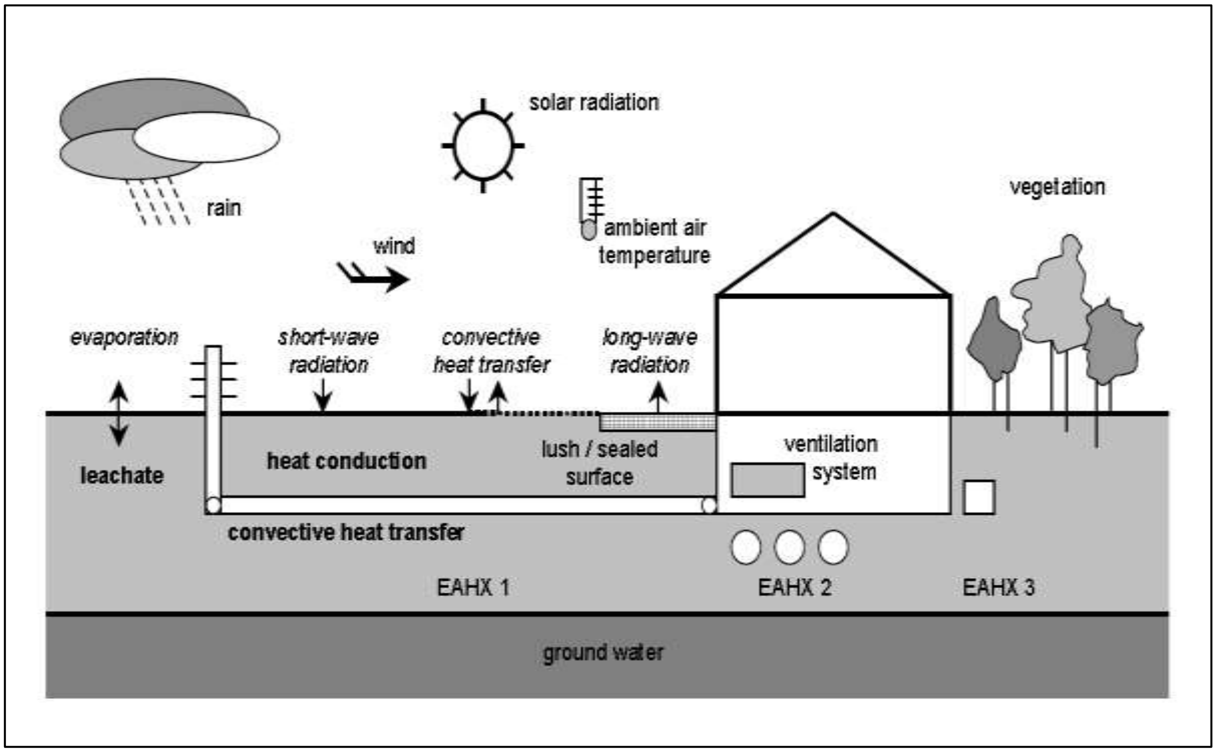


Figure 3. 10 Basic thermodynamic and factors for the design and Operation of EAHXs (Pfafferott, 2004).

Heat exchange between the earth and the pipes are conveyed when fluids are applied (usually air). Air is gently blown through pipes buried at depths between 1m to 5m, where the soil temperature is near the yearly average ambient temperature. The principle strongly depends on the heat exchange at the interface between the earth and the pipe and consequently between the pipe and the air. This passive cooling technique is believed to eliminate the need for mechanical cooling in buildings. Fig 3.11 shows the temperature behaviour of the soil with varying depths measured in Cyprus between January and August 2005 (Florides & Kalogirou, 2007). The temperature fluctuation reduces as the temperature remains fairly constant at depths beyond 3m.

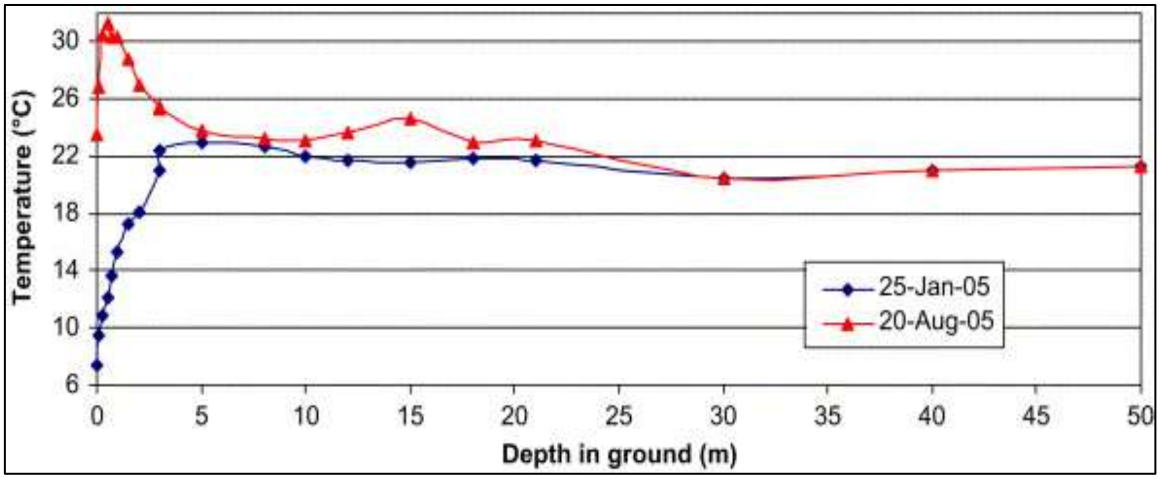


Figure 3. 11 Temperature behaviour in the soil due to depth (Florides & Kalogirou, 2007)

The first stages of EAHX studies presented one dimensional study in the 1980s, then later moved to two dimensional in the 1990s and more recently 3 dimensional studies are going on in the field. Studies on the characteristics and subsequent development of models have been recorded through simulations that have been validated by field experiments (Bojić, Papadakis, & Kyritsis, 1999; Hollmuller & Lachal, 2001; Mihalakakou, 2003; Mihalakakou, Lewis, & Santamouris, 1996; Mihalakakou, Santamouris, & Asimakopoulos, 1994; Mihalakakou et al., 1995; Sehli, Hasni, & Tamali, 2012). Studies looking at the effects of pipe length, air flow rate and pipe radius under various climatic conditions have been carried out to determine the typical performance of a EAHX (Lee & Strand, 2008; Mihalakakou et al., 1995).

Assertions have been made that almost all the methods of calculation to determine the output of EAHX produce reliable results. The introduction of sensitivity test however stipulates that after a certain limit, the length of pipe, the diameter of the pipe and the air velocity through the pipe have little effect on the output temperature (Tzaferis, Liparakis, Santamouris, & Argiriou, 1992). Accuracy in ground temperature prediction is usually influenced by the surrounding environment and material composition of the soil, which as a result makes the physics of thermodynamics within the soil enclave rather cumbersome. Calculation methods for heat loss and or heat gain and energy efficiency of an earth to air heat exchanger have also been proposed (Bojic, Trifunovic, Papadakis, & Kyritsis, 1997; M Santamouris, Mihalakakou, & Asimakopoulos, 1997).

Another dimension was taken by De Paepe and Janssens (2003) who derived some methods for calculating energy efficiency by deviating from the traditional electricity in use demand method. He optimised energy efficiency of a system by using distribution energy due to pressure loss to derive the COP of the system.

EAHXs offer potentials for reduced energy needs for heating and cooling, hence reduced energy consumption that also extends to reduced rates of emissions of CFCs and HCFCs by displacing the use of large HVAC systems.

In a study aimed at demonstrating the performance of an EAHX, Pfafferott (2004) used a 3-step approach to quantify the operations of the system namely temperature behaviour, energy gain as a function of outdoor temperature and a model to confirm performance.

In the desert climate of Kuwait, Al-Ajmi, Loveday, and Hanby (2006) recorded reductions of up to 17 kW during peak cooling loads with the indoor temperature being reduced by circa 2.8^{o}C. The associated reduction in energy demand for cooling was also recorded at 30%.

Woodson (2012) carried out a study in Africa by using a 25m length pipe buried at 1.5m depth in a location in Burkina Faso. When air is passed through at a rate of 95m^3/h the output temperature was reduced by up to 7.6^{o}C.

Chua, Chou, and Yang (2010) estimate that an average sized EAHXs produces about 29038 kg of CO_2 per year. This is around 50% of the output associated with a standard HVAC system for the same cooling performance.

3.6.1 Design Parameters for Earth to Air Heat Exchangers in Warm Humid Climates

There are four characteristics of earth to air passive cooling applications as identified by Pfafferott (2004).

Temperature Ratio: R_T describes the extent of the drop between inlet and outlet air temperature. It is mathematically expressed as:

$R_T = T_{out, max} – T_{out, min}/T_{in,max} - T_{in, min}$ .... (7)

This value estimates how the EAHX influences the thermal conditions in an enclosed space. Depending on weather conditions at some cases EAHX can deliver over-heated air or over-cooled air. These may occur when the system is run at ambient temperatures that are almost the same as the temperature in the soil. The smaller the R_T value is, the more cooling energy is supplied to the building. To avoid the malfunction of the EAHX in terms of overheating/overcooling, the ambient temperature can be set as a control to trigger the operation of the system when the ΔT can deliver air close to the target optimal temperature. This approach is believed have advantages over the use simple time clock controls.

Energy Performance Q_{air} of a system is derived from the air flow V_{air} and the volumetric heat capacity of air ρC_{air} and the difference between the inlet and outlet temperatures. It is mathematically expressed as:

$Q_{air} = V_{air}. \rho C_{air} (T_{out} – T_{in})$.. (8)

When a mean Temperature value T_{mean}, the temperature amplitude Δ_T, a phase shift t_Ψ, and variation curves for inlet and outlet air temperatures of the ground are analysed, the efficiency of the system becomes easier to resolve and can be defined mathematically as:

$T(t) = T_{mean} – \Delta_T.sin.(2\pi.(t-t_\Psi)/8760)$ .... (9)

T can be replaced by any of the 3 variables T_{in}, T_{out} and T_{ground} to suite the intended outcome of calculation. A dimensionless number known as number of transfer units

(NTU) and the operation time of the system t_{op} can be applied when the ground temperature T_{ground} is known to derive the outlet temperature T_{out} represented as:

$T_{out}(t) = T_{ground}(t) + [T_{in}(t) – T_{ground}(t)]exp[- NTU(t_{op})]$... (10)

Another characteristic is **Temperature Ratio** Θ which expresses the temperature behaviour of the EAHX system output and is given by:

$\Theta = T_{in} – T_{out}/T_{in} - T_{ground}$ .... (11)

The ratio between the energy gain and electricity demand in an EAHX due to operation of fans for moving air in the system is known as the **Coefficient of Performance** of the system COP (kWh) and defined as:

$COP = \frac{\sum_{toperation}(Qheat+Qcool)}{\sum_{toperation}(\Delta\rho.v)}$... (12)

When the length of an underground pipe is increased, the thermal performance and the pressure drop of the system are consequentially increased. While the thermal performance increases with smaller tube diameters the pressure drop increases. When more tubes are arranged in a parallel form, the pressure drop is lowered but the system efficiency increases. A more profound design method can be achieved by applying the specific pressure drop factor (De Paepe & Janssens, 2003):

$J = \frac{\Delta\rho}{NTU}$.. (13)

Where J is equivalent to the pressure for 1 unit of NTU, which increases with flow rate V and decreases with pipe diameter. When air flow velocity is increased the mass flow rate in the pipe increases therefore resulting in a decreased heat exchange rate.

3.7 Night Cooling Strategy

Night cooling is considered as one of the low energy passive cooling technique which operates to lessen cooling loads in thereby improving the thermal comfort of the occupants by using outdoor air obtained by increasing night time ventilation rates. It is an effective cooling approach which uses the outdoor ambient air as a source of natural cooling to reduce indoor temperature.

Many researchers have studied the effectiveness of night ventilation strategies. In an experiment carried out in California, Givoni (1994) conducted an experiment which studied night ventilation. The results showed that application of night ventilation in buildings with relatively high thermal mass was more effective when compared to a full-day ventilation approach.

Pfafferott (2003) identified ventilation rates, the thermal storage capacity of the building fabric, the difference between the exterior and interior temperatures, and solar and incidental heat gains as some significant factors that influences the efficiency of night ventilation.

Sreshthaputra (2003) used a computer based computational fluid dynamics (CFD) simulations to explore some findings on night ventilation cooling in the hot-humid tropics, in a case study that observed some temples in Bangkok, Thailand. Results showed that when night ventilation with ACH of 20 air changes per hour is applied, maximum air temperature the next afternoon can be reduced by 2°C as against a daytime ventilation alone. In the tropical region of northern Australia.

In general, night-time cooling tactics can be more efficient in areas where the daytime temperature range is between 30°C to 36°C, and the ambient 20°C or below at night. In most situation as this, daytime ventilation is not necessary, as heat can be stored in the thermal mass of the building resulting to elevated indoor temperatures at night (Givoni, 1994).

3.7.1 Clear Night Sky Radiation / Radiant Cooling

The roof of any building protects the building from the direct impact of the Sun's radiation that peaks at mid-day during the summer months. This radiation increases the temperature in roof attics. The temperature rise sometimes may be up to three times the value of the ambient temperature. During the night, when the environment becomes cooler, the roof loses most of its heat to the open sky through radiation. The fundamentals of atmospheric radiation are like that of radiation from non-luminous gases in furnace design. A knowledge of the sky temperature is essential in the design of radiating systems for cooling. The sky temperature is very close to absolute zero, when there are no obstacles like radiating gases, water vapor and dust. It is a good design strategy to keep in mind that under clear sky conditions, the effective sky temperature can be lower than the ambient by up to 25^{o}C (Bliss, 1961). Night sky cooling is a concept that is based on the exchange of heat due to the cool sky temperature to surfaces directly below it. Objects with a solar reflectance above 95% and high thermal emissivity will also cool during the day (P Berdahl, Martin, & Sakkal, 1983). Under clear-sky conditions, the temperature of the sky (effective sky temperature) can be as low as 30^{o}K (-243.15^{o}C).

The property of the roof as a shield and as a radiating surface to the sky can therefore be harnessed as a means of cooling the building envelope and interiors at night. It can also serve as a means for heat flushing from the roof attic

3.7.2 Principles and Application of Clear Night Sky Radiant Cooling

Ezekwe (1986) identified the cooling potential of the skies in Nsukka, a town in the South-Eastern part of Nigeria however no follow up studies have been carried out on his findings or the potentials of application as a cooling strategy for contemporary buildings. A well-designed night cooling system would aim to optimise the heat exchange between a black body exposed radiating surface and the clear night sky. This coolth could be collected by a fluid (air or water), which will absorb heat if subsequently circulated within the interior space. A black body is a surface that radiates heat to the sky, the human skin radiates heat at an emissivity of 0.95.

Radiation from any surface is given by:

$\phi = A\varepsilon\sigma T^4$ .... (14)

where ϕ (watts) is the radiation from a body of area A (m^2) at a temperature T (K). ε is emissivity, a dimensionless value usually between 0 and 1 which determines a surfaces' ability to radiate and absorb heat and σ is the Stefan-Boltzmann constant, $5.67x10^{-8}$ ($Wm^{-2}T^{-4}$).

Most radiating surfaces exchange heat with the sky at wavelengths between 8µm – 13µm (nanometer). This range is usually referred to as the atmospheric window. At this wavelength/range, surfaces with high emissivity will radiate energy to a clear night sky at 95% or above. In single or double storey building with large roof area ratios to floor space there is therefore considerable potential to use this technique for overnight heat flushing and 'coolth' storage within the buildings thermal mass.

3.7.3 Trends in the use of Clear Night Sky Radiant Cooling Strategies

Results from several studies designed to calculate the cooling potential of the night sky have been carried out in various locations and climates. The studies have identified the key factors that affect the way in which exposed surfaces radiate to the clear night sky. They have confirmed that various surfaces have the potential to radiate between 40 Wm^{-2} to 90 Wm^{-2}.

An increase in surface contact between the radiating surface and the transfer fluid will clearly influence the overall co-effieicnt of performance of any specific system. Golaka and Exell (2007) focused on airflow and obstacles that affect the free flow of air, which might minimise the heat exchange between surfaces and fluids. Their results show that convective heat transfer can be increased by the introduction of wind shields of 25mm while those between 50mm and 100mm reduced convective heat transfer, however radiative cooling is optimised when the surface texture is relatively plain.

Bliss (1961) proposed a model for net radiant cooling energy calculation where he outlined a sequence for the calculation of atmospheric radiation on horizontal surfaces close to the ground. His proposal is considered suitable for most engineering calculations on sky radiant energy. Hottel and Egbert (1942) developed a model for calculating water vapour which has been adopted in this procedure.

Another study was carried out by Armenta-Déu et al. (2003) in the Namib desert of Gobabeb in Namibia. The study aimed at establishing a precise method to calculate radiative heat exchange between two bodies that was used to determine factors such as, plate emissivity, clear-sky index and the sky temperature. Their results showed that reduced conduction and convection is paramount for accurate results in any radiative heat transfer calculations.

Dobson (2005) used a mathematical expression computed through excel spread sheet to define the thermal behaviour of different components of a system. Using this technique, he calculated that there is a potential to remove 84MJ of heat from a water storage tank with a volume of 4.15m^3 over a period of 8hrs using a radiating panel of 48m^2 surface area.

Eriksson and Granqvist (1982) asserts that the spectral sky radiance greatly influences the radiative cooling power of the sky which is based on the principles of atmospheric radiance. This was demonstrated in a study they carried out using LOWTRAN 5 code which was aimed at the evaluation of spectral radiance data, reported from models comprising of 6 climatic types. It was found that free radiating surfaces cool between 58 Wm^{-2} and 113 Wm^{-2} depending on ambient temperature and surface characteristics for a variety of model atmospheres, while the maximum temperature difference for a device with a non-radiative heat transfer coefficient of 1 $Wm^{-2} K^{-1}$ is between 11°C and 21°C, a near perfect blackbody has the potential closer to 18°C to 33°C.

The radiative cooling power of a surface was also evaluated by Hamberg et al. (1987) as a function of emittance (ε_s) of an exposed surface, air temperature and humidity using LOWTRAN 5 code. Data from meteorological station was further used to identify the effects of these characteristics on the reduction of frost formation on radiating surfaces. SnO_2 used on surfaces with ε_s=0.02 reduced frost formation reasonably in a Swedish environment.

The advantage of a selective radiating surface over a basic black body is its ability to cool at low altitudes and even in a 'dirty sky' atmospheric situation. It can even cool during daylight hours depending on climatic conditions.

Catalanotti et al. (1975) carried out a theoretical and experimental presentation on the effective radiative cooling in the relatively 'dirty' atmospheric environment of Naples by using a selective surface with optical properties matching the atmospheric window of 8-13µm. Comparisons with a basic black body radiative type showed effectiveness in the cooling abilities of the selective surface when exposed to clear sky. Cooling effects were also achieved during the day.

Brunt (1932) presented a note on a sequence for estimation of net loss of heat due to radiation from ground at night where various absorption spectrum of water vapour was used for the estimation. He derived a formula to express the downward radiation from the atmosphere and the total black body radiation at a known temperature and water vapour:

$$\phi_s = \sigma T^4 (a + b\sqrt{e}) \quad (15)$$

Where ϕ_s is radiation from atmosphere, σT^4 is total blackbody radiation at temperature T and e is vapour pressure and a & b are constants 0.550 and 0.056 respectively. Temperature drops below dew point were found to cause condensation.

Ezekwe (1986) carried out a nocturnal radiation measurement in a Warm and Humid South-Eastern Nigerian environment where he studied the net thermal radiation to the night sky from a flat plate at ambient temperature. The experimental radiator was constructed from a flat mild steel plate of dimensions 1.22 × 2.44 x 0.0033m which was painted with a black enamel paint of emissivity of 0.9. Steel tubes of 0.017 m diameter were run in contact under the radiating plate and finally the plate and tube assembly was placed on an insulated plywood base. Data was obtained from February to May which are periods with clear skies. The effective sky temperatures obtained is circa 12.2°C lower than the ambient air temperatures and the radiating power was between 60 - 70 Wm^{-2}. The experiment was carried out in a location at an altitude of 488m above sea level.

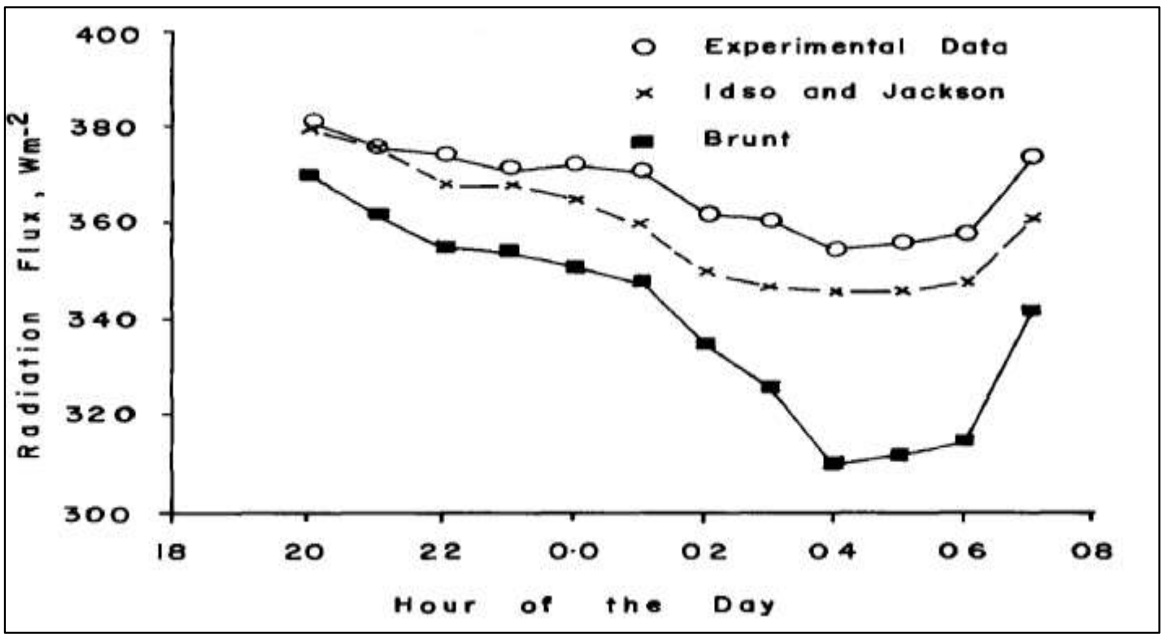


Figure 3. 12 Comparison of the Downward flux of the atmosphere in South-Eastern Nigeria (Ezekwe, 1986)

Fig 3.12 presents a comparison between calculated sky radiating power using 2 mathematical formulae and a measured sky radiating power on a site in South-Eastern Nigeria. The plots show that the analytical values derived from Idso and Jackson's empirical model gave the best agreement within 5 per cent with the experimental data. The Idso Jackson formula is expressed as:

$\phi_s = \sigma T^4[1 - 0.261 \text{ x } \exp\{-7.77 \text{ x } 10\text{-}4(273 - T)^2\}]$ .... (16)

where T is the absolute screen level air temperature in degrees Kelvin.

Predicting sky temperatures depend on many factors such as humidity, amount of cloud cover, type of cloud cover and elevation above sea level, which cannot be used in a simple thermal model that depends only on ambient temperature inputs. W. C. Swinbank (1963) proposed an equation for clear sky conditions which depends on ambient temperature and is given as:

$\phi_s = 0.0552.T_a^{1.5}$ .... (17)

but because Swinbank's approach ignored the effects of humidity and cloud cover due to elevation, may have on sky temperature. The regular amount of cloudiness can be estimated using a clearness index. There has therefore been series of modifications to Swinbank's formula.

Fuentes (1987) modified Swinbank's approach by calculating the average 'clearness index' for 68 cities of the USA. This was reported as 0.61 (61% of the time skies were clear) and that cloudy and hazy skies drop the sky temperature closer to the ambient by about 32%. This modification can be expressed as:

$\phi_s = 0.68 . (0.0552.T_a^{1.5}) + 0.32T_a$.. (18)

Goforth, Gilchrist, and Sirianni (2002) also modified Swinbank's formula by introducing a new model to calculate thermal 'down welling' sky irradiance as a function of temperature, relative humidity, cloud height, and percentage cloud cover with an operational error of 9.7%, this was achieved after the thermal 'down-welling' sky irradiance was increased by 34% due to an introduction of low overcast clouds assumed to be at altitude less than 2km and 100% cloud cover. The new model is given as:

$\phi_s = (1+kc^2)\ \vartheta T_a^{5.852}\ RH^{0.07195}$ .... (19)

where *k* and c are variables see Table 3.4 for Values, ϑ is a constant equivalent to 8.78×10^{-13}, T_a = Ambient temperature in Kelvin and RH is the relative Humidity.

Table 3. 4 Values of k and c from modified Swinbank Formula (Goforth et al., 2002)

no cloud (clear sky)		overcast sky		
		hight<2km	*2km<hight<5km*	*5km<hight*
c	0	0.34	0.18	0.06
k	0	variable from 0 to 1 depending on the cloud coverage		

Ezekwe (1990) carried out a further investigation on (Ezekwe, 1986) by demonstrating the ability of night radiant energy impacted on a radiant surface to cool and transfer cooling energy through tubes to a cooling chamber of a locally constructed refrigerator. The results of this study showed that under clear sky conditions, a cooling power of 68 Wm^{-2} was achieved on a radiant surface exposed to the sky. The ambient temperature was reduced by up to 7.2^{o}C. The temperatures in the cold storage chamber varied between 12^{o}C and 15^{o}C when ambient air was between 19^{o}C and 22^{o}C. The lowest temperature recorded on the radiator plate was 10^{o}C showing that the sky temperature of 7^{o}C could cool a surface. The cooling capacity of the refrigerator is 628 kJm^{-2} per night, and the system COP was calculated to be 0.26. The minimum recorded temperature in the chamber is 12.8^{o}C.

Eicker and Dalibard (2011) recorded 60– 68 W/m^2 with an innovative cooling and power supply radiating surface made from PVC. 90% of sky radiation originates within 1km above the ground while about 40% originates from 10m above the ground level. Radiation intensity is a factor of location (Eicker & Dalibard, 2011).

Under cloudy sky conditions sky temperatures become close to ambient (ISO, 1996), however improved approximations of the sky temperature under a cloudy situation were postulated by (Aubinet, 1994; P Berdahl et al., 1983; Bird & Hulstrom, 1981; Kasten &

Czeplak, 1980). Other works on night sky cooling can be found in (Ångström, 1915; Sima, Sikula, Kosutova, & Plasek, 2014).

3.7.4 Radiative heat transfer techniques with fluids

Due to Nigeria's rainy season the normal roof configuration for domestic properties is to adopt a medium pitched roof (angle between 10° and 35°) (Mijinyawa, Adesogan, & Ogunkoya, 2007). The use of water as heat transfer fluid will result in significant design changes to the exposed layer and additional loading on the structure. Although this can be accommodated in new build with an additional cost penalty, retro-fitting to existing roofs appears to be highly problematic (Hijazi, 2018).

Air cooling systems on the other hand, are relatively simple and economic to construct. They can be easily applied in small residential buildings such as bungalows and duplexes. Careful consideration is required to ensure that the attic space does not overheat while maximising the night radiant cooling capacity of the metal roof material (Parker, 2005).

Khedari, Waewsak, Thepa, and Hirunlabh (2000) applied 4 systems of roof radiators with different configurations in a study on night radiation cooling, in a tropical setting that was tested under different sky conditions (rainy, cloudy and clear skies). The results obtained showed that surface temperatures were reduced by 1°C - 6°C below ambient air in a clear sky.

Simonetti, Fracastoro, and Perino (2008) used a school building under construction in Italy as a case study and results were in close agreement with the CFD transient analysis that had predicted a 50% saving in cooling loads.

An experimental evaluation of a system developed by Parker (2005) is carried out by Parker et al. (2008) to verify the potential of the proposed night cooling concept in a 2-unit test structure arrangement with dimensions 3.7m x 4.9m and 17.8m^3 in volume located in the Florida Energy Centre (FESC) in Cocoa Florida. The experimental unit is roofed with a highly conductive metal of a desirable emissivity known as 5-vee roof which sits on metal battens and is insulated with sealed ceiling panels of 250mm thick RSI $5.3m^2Kw^{-1}$ and linked to a dwelling space underneath by means of a circulation fan in a duct. With this approach, Parker et al. (2008) was able to successfully avoid overheating. When the interior temperature was maintained at 25.6^oC in both cells, the air conditioning load was reduced from 4.6 kWh/day to 3.6 kWh/day. The system cooling power was between the ranges of 5 – 10 Wm^{-2} with a 6-hour overnight run dissipating 2.4 kWh for a roof area of $186m^2$. Under clear sky conditions, an average roof area can produce up to 7 kWh of cooling overnight. A 15% saving in energy demand was recorded over a period of 8 months. This result is in agreement, although slightly lower than the result produced by Parker (2005). Parker et al. (2008) concluded by suggesting that heat gain reduction in building envelopes will maximise the performance of the system. Key results from the study are presented in Fig 3.13 and Fig 3.14.

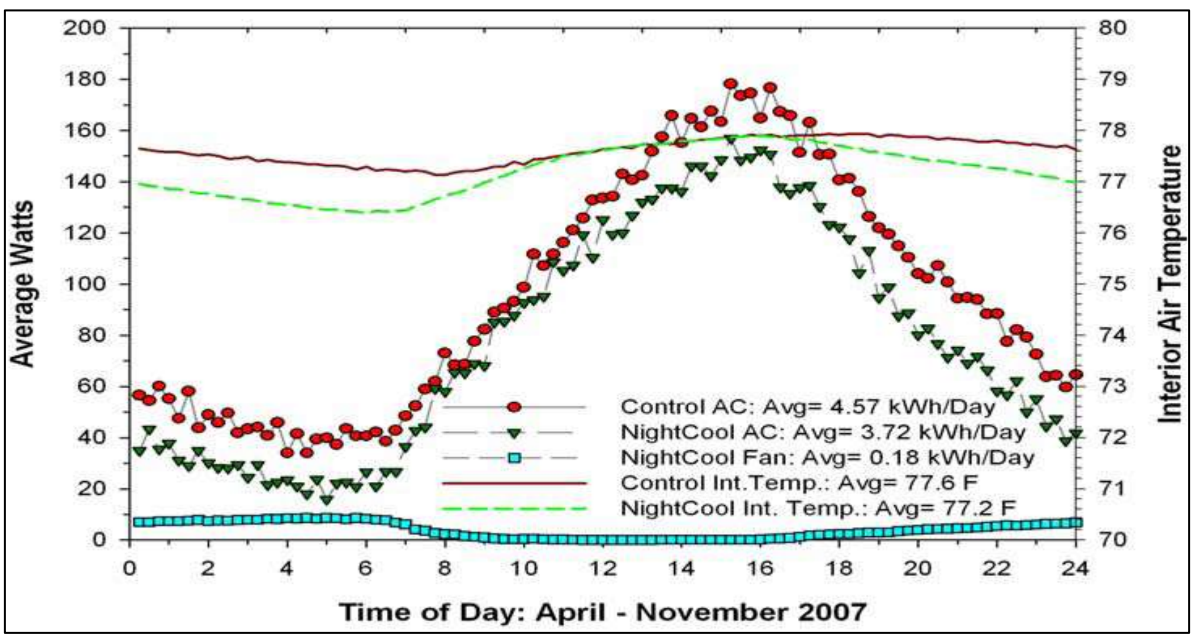


Figure 3. 13 Comparison of cooling Performance of the Control and night cool and air conditioning energy demand (Parker et al., 2008)

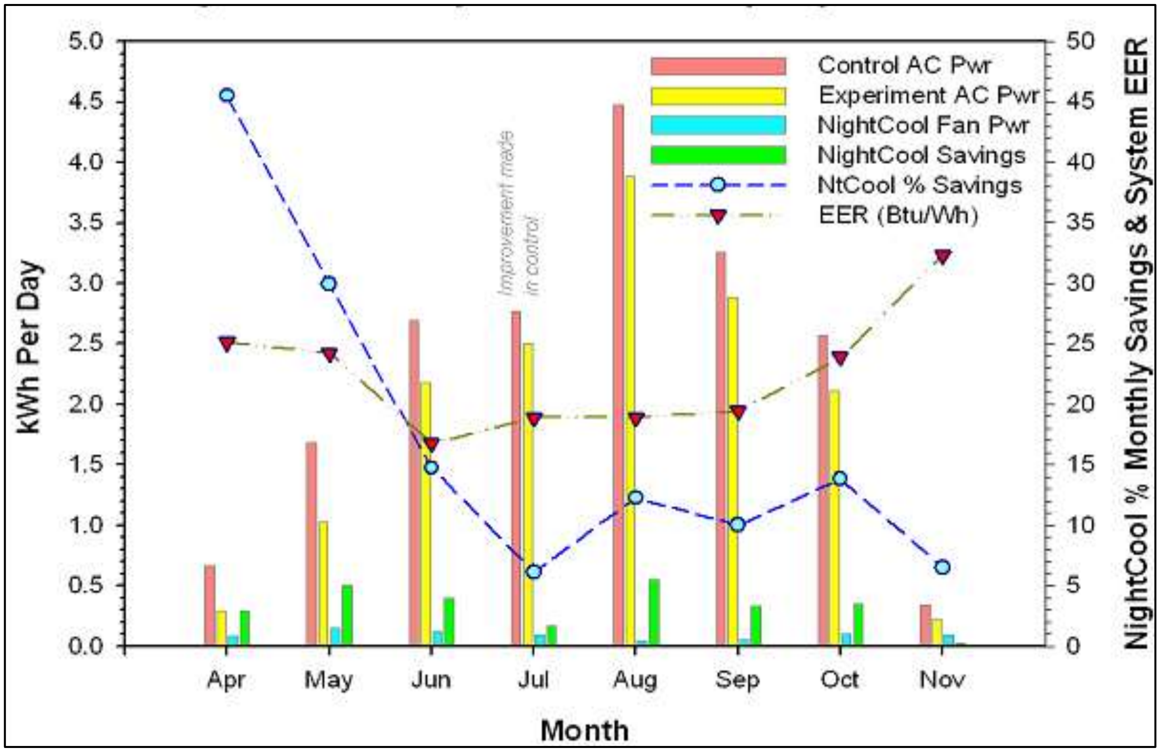


Figure 3. 14 Monthly Average Performance of the Night Cool System April - November (Parker et al., 2008)

Fig 3.14 presents a comparison of overall cooling performance. On average, air conditioning requirements are at the peak between 14.00hrs and 16.00hrs daily, with peak energy demand in the control unit at an average of 40W above the energy required to run the proposed unit during overheating periods under the same climatic conditions. Fig 3.14 presents a general overview of AC and fan power consumption requirements in both the control and the experimental units. It also highlights the general energy saving pattern in percentage terms from April to November 2007. The energy efficiency ratio (EER) was highest and lowest in November and June respectively. Applying these results to other climatic regions can give a better understanding on how to resolve night cooling strategies in warm humid regions. Table 3.5 shows details of a numerical summary of the cooling performance of the cool system within the test period.

It also shows details of summarized energy performance, system efficiency and thermal comfort related performance.

Table 3. 5 The total performance of the night cool system, showing energy requirements, efficiency and thermal performance of the test facility between April and November 2007 (Parker et al., 2008)

Power and Efficiency								
	April	May	June	July	August	September	October	November
Experiment AC (kW·h/day)	0.292	1.027	2.176	2.507	3.886	2.881	2.109	0.224
Experiments fans (kW·h/day)	0.080	0.151	0.121	0.094	0.046	0.049	0.104	0.095
Control AC (kW·h/day)	0.683	0.682	2.694	2.767	4.481	3.257	2.567	0.341
Experiment lights (kW·h/day)	2.723	0.682	2.660	2.575	2.641	2.689	2.693	2.694
EER (Btu W·h)	24.6	23.9	16.5	18.6	18.6	19.3	23.6	31.8
RTF (run-time-fraction)	0.185	0.358	0.291	0.216	0.120	0.118	0.250	0.227
T (°F) ($T_{return} - T_{supply}$)	2.73	0.65	1.83	2.07	2.07	2.14	2.62	3.53
Percent *NightCool* Saving (%)	45.5	0.0	14.7	6.0	12.3	10.0	13.8	6.5
Building Conditions								
	Avg	Avg	Avg	Avg	Avg	Avg	Avg	Avg
Experiment Attie Temp. (°F)	73	79.9	83.8	85.2	86.2	83.5	80.8	68.5
Control Attie Temp. (°F)	81.0	85.7	90.0	91.8	94.9	89.2	85.6	74.7
Experiment Room Temp. (°F)	77.3	78.9	80.1	79.9	74.6	79.2	79.1	76.5
Control Attie Temp. (°F)	77.9	79.1	79.2	79.0	78.7	78.6	78.6	77.0
Experiment Room RH (%)	47.5	45.4	44.0	43.9	39.5	41.8	46.7	53.0
Control Room RH (%)	45.1	40.5	40.3	41.9	39.2	42.7	44.4	54.8
Weather Conditions								
Ambient Temp. (°F)	69.6	74.5	78.5	79.9	82.9	80.2	78.3	67.5
Ambient RH (%)	63.7	68.5	77.7	82.9	6.3	79.7	79.4	76.3
Solar (w/m^2)	250.0	253.5	235.0	210.9	235.5	181.6	150.5	151.6
Dewpoint (°F)	57.9	64.0	71.6	74.9	75.0	73.6	71.7	59.8
Sky Temp. (°F)	50.1	58.6	66.8	70.5	70.8	69.6	67.7	49.0

3.7.5 Efficiency and Limitations of Clear Night Sky Radiant Cooling Strategies

Studies reviewed above show that if night sky radiant cooling is efficiently utilised using appropriate parameters and design tools by means of radiating surfaces and optimised heat exchange between heat conveying fluids and the plates, cooling potentials of up to 14kW can be delivered by a highly emissive metal roof surface of $225m^2$. Clear night sky radiant cooling in desert regions has the potential of close to 75 Wm^{-2}, while in the humid regions it may be lower at around 65 Wm^{-2} when the sky is clear.

The sky is mostly clear between November and April in South Eastern Nigeria. During this time, the daytime ambient temperature is high. Studies have recorded similar net radiations in South-Eastern Nigeria where the ambient temperature dropped below 10^oC in a cooling system (Ezekwe, 1986, 1990).

Effectiveness of night sky radiant cooling was also demonstrated in the works of Parker (2005) and Parker et al. (2008), where it yielded up to 2.4 kWh of cooling from a standard roof area of $225m^2$.

Cloudy skies have been shown to have about 45% of the cooling potential of a clear sky, however clear skies are associated with the warmer seasons in Nigeria when cooling demand peaks. Heat convection and exchange process may be a huge set back in the application and integration of a night cooling system in roofs in areas with high humidity levels and in areas with little or no diurnal swing. The impact of cloud cover on radiation can be found in (C. Clark & Blanpied, 2013; G. Clark, 1981; G. Clark & Blanpied, 1979; Fuentes, 1987; Goforth et al., 2002). Other constraints identified are wind speed, physical factors, radiator temperature, air flow rates and fan efficiency.

Night time ventilation requires ambient temperature swings of a minimum of 6˚C. This temperature difference is however only naturally available for a few months in the South-Eastern part of Nigeria. These ranges (temperature and time) could possibly be increased if cool air is passed through a radiating surface open to the clear sky and into the building at night.

Passive or natural means of cooling are those methods used in the conditioning of indoor spaces by making use of outside air or climate conditions. They can be said to be those techniques that will naturally transfer the indoor heat to the closest natural heat sink.

Passive cooling techniques are influenced by 5 factors namely: ventilative cooling, evaporative cooling, heat control, earth coupling and radiative cooling. The major aim of passive cooling is to achieve a comfortable indoor environment by controlling heat gain or heat loss (Givoni, 1994).

The South-Eastern part of Nigeria is known for its relatively elevated temperature, with small diurnal swings, high humidity levels, heavy rainfall and low air velocity hence, the primary reason why buildings in this region are designed with light fabric (Arup & Genre, 2016). Buildings in this region are generally characterised by open design features with building envelopes consisting of low thermal walls. Large windows openings are widely used for optimized free flow of air, and sometimes courtyards are introduced to enhance ventilation by increasing the area of the envelope in contact with the outdoor environment. The design objective in this region is to minimize heat gain and optimize heat loss in buildings.

3.8 Limitations of Passive Designs and Energy Efficient Buildings in South Eastern Nigeria

At present the codes and regulations relating to building in Nigeria make little or no reference to energy efficiency in buildings. Energy efficiency of new buildings in South Eastern Nigeria will determine the building sector’s energy consumption, and developing ways to conserve energy in this case cannot be over stressed (Kawuwa, Sani, Mustapha, & Ishaku, 2015). The National Energy Policy which was developed in April 2003 by Energy Commission of Nigeria is primarily focused on energy consumption in Industries, Agriculture and Transportation. The National Building Code which was developed with the aim of setting minimum standards on building pre-design, design, construction and post-construction stages (National Building Code, 2006) with the view to ensuring quality, safety and proficiency in the building industry made no reference to energy efficiency in buildings, same also is the case in the establishment of National Centre for Energy

Efficiency and Conservation at University of Lagos where no reference was made to energy efficient buildings. With all these developments, it becomes overbearing to propose a strategy for energy code development and ways to implement and enforce these codes in the Nigeria building sector.

In a research that attempted to highlight and illustrate the role of government in setting and enforcing energy codes and standards, and of several public policy efforts made locally and internationally on the ways to handle energy efficient issues, Kawuwa et al. (2015) suggests a five-step approach to effective energy code development, execution and compliance in Nigeria. The study also recommended that the Professional body of Architects- the Nigerian Institute of Architects (NIA) and the regulating body; Architects Registration Council of Nigeria (ARCON) should include energy efficiency as a module in their Mandatory Continuing Professional Development Programme.

In a recent development, the Nigerian Institute of Architects (NIA) has formed a committee to partner with the ministry of environment and energy and also consider the application of passive cooling techniques in Nigeria (Odogwu, 2016). The strategies developed by the NIA committee to boost green Architecture are as follows:

- To partnership with GIZ (Gesellschaft für Internationale Zusammenarbeit), a German co-operative agency in Nigeria to train Nigerian Architects in energy efficiency in building design.
- To set up curricula known as ‘train-the-trainer’ in 2016 with the aim to roll out a professional development in few years which would target 3,000 Architects to be talented in energy efficiency in building designs.
- To build the right capacity which in turn will be able to achieve circa 30% reduction in energy consumption in Nigerian buildings in just few years.
- To establish an open conversation with the ministry of environment on the impact of design decisions on the management of the environment, hoping that the dialogues will produce resolutions which will eventually transform into codes.

- The committee is also to develop a conceptual framework for ‘waste to wealth’ projects which proposes to use waste materials to generate electricity and organic manure for Agriculture, with the aim of reducing CO^2 emissions while providing by-products of important economic value.

According to the European Union, the German government and United States Agency for International Development (USAID), have undertaken research that has claimed that Nigeria could reduce energy demand in buildings by circa 57% if there is better awareness of the impending consequences associated with poor energy efficiency and a willingness to embrace innovation (Okafor C, 2016). According to the Nigeria Institute of Architects (NIA) this could only be achievable when energy efficiency and sustainability is addressed through the context of Architectural intervention which must not only contribute to the beauty of the city but at the same time contain the consequences of the acts of construction.

The Nigerian Energy Support Program started in 2013 as a supportive move to the Nigerian Government in the development of the Nigerian Building Energy Efficiency Code. The Nigerian Building Energy Efficiency Code (BEEC) was officially approved and launched by the Federal Minister of Power, Works and Housing on 29 August 2017. Despite the fact that the BEEC was developed to be accepted by the society, which is key to becoming a widely accepted construction standard, most of its requirements are limited to very few feasible and accepted energy efficiency minimum requirements applicable throughout Nigeria. Geissler, Österreicher, and Macharm (2018) presented some foundational activities in a study which was carried out in Abuja in order to come up with proposals for a legal framework that will suit the Nigerian energy-efficient mass housing situation. One of the activities involved a building analysis carried out in relationship with a Nigerian developer working with stakeholders in accordance with a developed Nigerian Building Energy Efficiency Guideline. The results of the preparatory activities specified that in Nigeria where there is an estimated deficit of 17 million housing units, any activity for Architectural intervention/code must put weight on climate adaptive design and must outline requirements and procedures in a clear and simple way to allow for effective enforcement. Only then can energy-efficient mass housing be feasible in Nigeria (Geissler et al., 2018). A study of the building components and some passive design measures to enhance 'fabric first' designs as practiced in different parts of the world are discussed in the sections below.

3.9 Building Fabric: Form, Materials and Design Concepts

The structure, fabric and envelope are the primary components of any building. It is the medium that moderates between the outdoor and the indoor environment. Its primary functions are to protect and provide a comfortable environment for the occupants. The building fabric modulates the indoor environment by functioning as a control for heat flow between the external and internal environments. The building structure is primarily made up of building materials of different thermal composition, behaviour and characteristics. A 'fabric first' approach can therefore be taken as the primary starting point (Givoni, 1983; Gupta, 1993).

The incorporation of both thermal mass and insulation can reduce and moderate both heat gains and losses. The thermo-physical properties of building materials therefore play a key role in the control of heat transfer in buildings and as such, they have a profound influence on the performance of a building in terms of user comfort and running costs (Jakob & Madlener, 2004). High density in building materials indicates high thermal conductivity (Hyde, 2008). Studies over the decades have focused on the improvement of energy efficiency in buildings by the management of the thermal behavior of the building envelope through intelligent design and or application of appropriate building materials (T. Taylor, Counsell, & Gill, 2013). The use of phase change materials (PCM) for instance and some other passive cooling innovations are becoming popular. Though most of these innovations are geared towards the "fabric first" approach as seen in most UK homes (T. Taylor et al., 2013), these innovations while reducing energy expended in running buildings should focus also on improving the quality of indoor environment desired within such buildings (Walsh, Kenny, & Brophy, 2006).

On the other hand, insulation materials are used to stop heat gain or heat loss within a medium. Various materials react differently when exposed to a heat source, the higher the density and conductivity, the higher the heat storage ability.

3.9.1 Building Character

The purpose of climate responsive design is to create optimal comfort and protection by applying some apposite principles through a selection of appropriate building materials, form and fabric, with the aim of reducing the need for mechanical equipment especially for space heating or cooling. If this can be achieved, the building could be defined as 'intelligent'. Intelligent building is defined by the Intelligent Buildings Institute as

"one which provides a productive and cost-effective environment through optimization of four basic elements: structure, systems, services and management, and the interrelationship between them."

Some and not all its qualities include regulation of air flow, heat moderation, lighting of interior spaces, security and the provision of a 'healthy' indoor environment. These features are best incorporated at an early stage in the design.

Before the advent of HVACs, building forms were invariably required to incorporate passive cooling strategies such as cross ventilation. Compartmentalisation of spaces may affect the indoor air quality especially in warm humid climates, where it is regarded as a bad practice to depend solely on a single sided ventilation system.

Passive buildings are those designed to make use of natural approaches to eliminate heat or prevent heat loss to maximise indoor thermal comfort (Givoni, 1983).

3.9.2 Foundations and Floors

Foundations are the lower part or that component of a building on which the entire building structure depends on for stability and support. Foundations provide stability to a structure by evenly distributing the gravity loads of the building to the surrounding earth. Studies have shown that the function of foundation goes beyond the provision of support for buildings, as they have been found to deliver other functions such as provision of heat transfer medium between the earth and building structure as demonstrated in the works of (Day & Roaf, 2007; Givoni, 1969; Hyde, 2008). Policies have also targeted good foundations geared to enhance overall energy performance in buildings (Designing Buildings Wiki, 2018).

Passive heating/cooling strategies involving the use of foundation to store and transfer heat energy can be found in (Givoni, 1969; Hyde, 2008; Hyde & Pedrini, 2002) which have looked at recent innovative engineering techniques known as ‘thermo-active foundations’. Thermo-active foundations attempt to increase the coefficient of performance for ground source heat pumps and installation costs by embedding heat exchanger pipework within building foundation structures known as geothermal piles (Kwag & Krarti, 2017).

Geothermal Piles are a new renewable energy technique; whereby geothermal energy is used in the foundation piles of a building to supply energy and power. They function both as structural components as well as a source of energy. Geothermal energy is transported through a closed pipe work system within the pile foundations from the surrounding ground. Geothermal piles may prove to be a cost-effective source as they reduce initial ground loop installation costs and impressive results have been achieved in Keble College (Oxford) and Westminster Academy UK (Vasili Gordeyev et al., 2012). These studies confirm that there is considerable potential in using the ‘deep earth’ as either at heat source or heat sink.

3.9.3 Roofs

Designing roofs to conform to energy efficient policies while maintaining its primary functions is an aspect of passive design for buildings that have been widely explored in developed countries as is evident in the works of (Hollick, 2013; Parker, 2005; Parker et al., 2008). Using the roof surface as a diurnal heat loss technique has not to date been explored in Nigeria. This could be attributed to some factors that are linked to the warm humid nature of this location. The contemporary roofing styles (mainly gable and hipped) which are greatly influenced by culture and climate is the trend in this region and little or no efforts have been made by researchers or architects to consciously shift this practice towards other passive and energy efficient roof designs to enhance the level of comfort achieved during the hottest and coldest months in the year respectively, without compromising its primary function. Where heating demand predominates roofs have been known to provide a good harvesting environment during the daytime.

Fig 3.15 and Fig 3.16 show the effects of sunshine on the attic temperature of a roof in Edinburgh Scotland, a city with insolation levels below 1500 W/m^2 per annum.

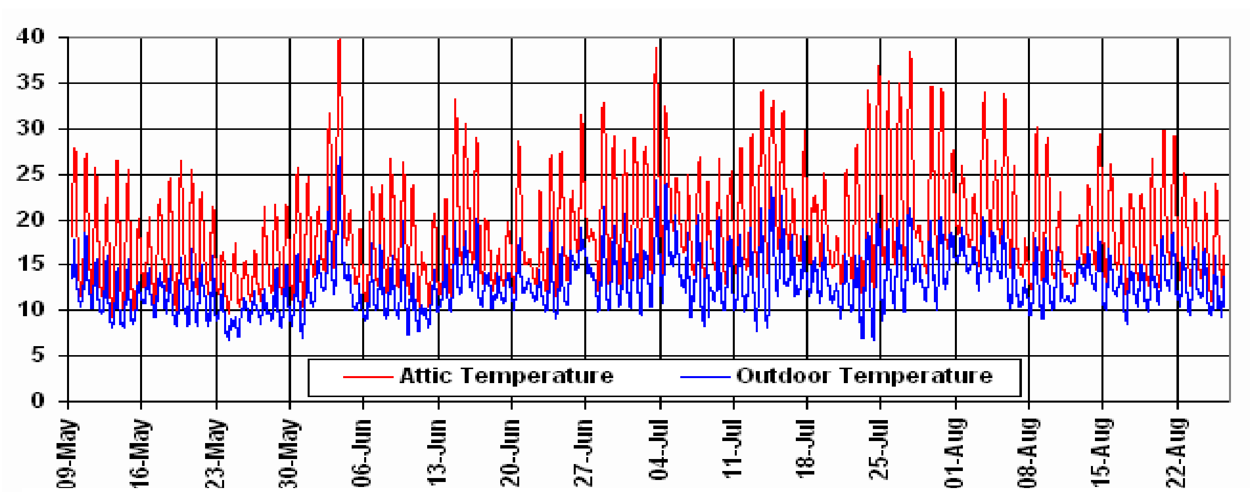


Figure 3. 15 May to 26 August 2012 Balerno, Edinburgh, Scotland attic and outdoor temperatures (Attic Heat Harvester, n.d)

Roof attic spaces can gain temperatures 2-4 times higher than that of ambient air during sunny days, however, where the insulation is fitted at ceiling level, relatively little of this heat will be transferred into dwelling spaces unless some form of transfer strategy is incorporated (fan and ductwork etc.). Incorporating insulation in walls, floors and roofs can reduce the energy demand for heating and/or cooling. It is by far the most cost-effective strategy to be incorporated when adopting a 'fabric first' approach.

The cooling demand can be calculated from the formula below:

$kW/h.m^2 = (T_{roof} - T_{indoor}) \times Ufactor$

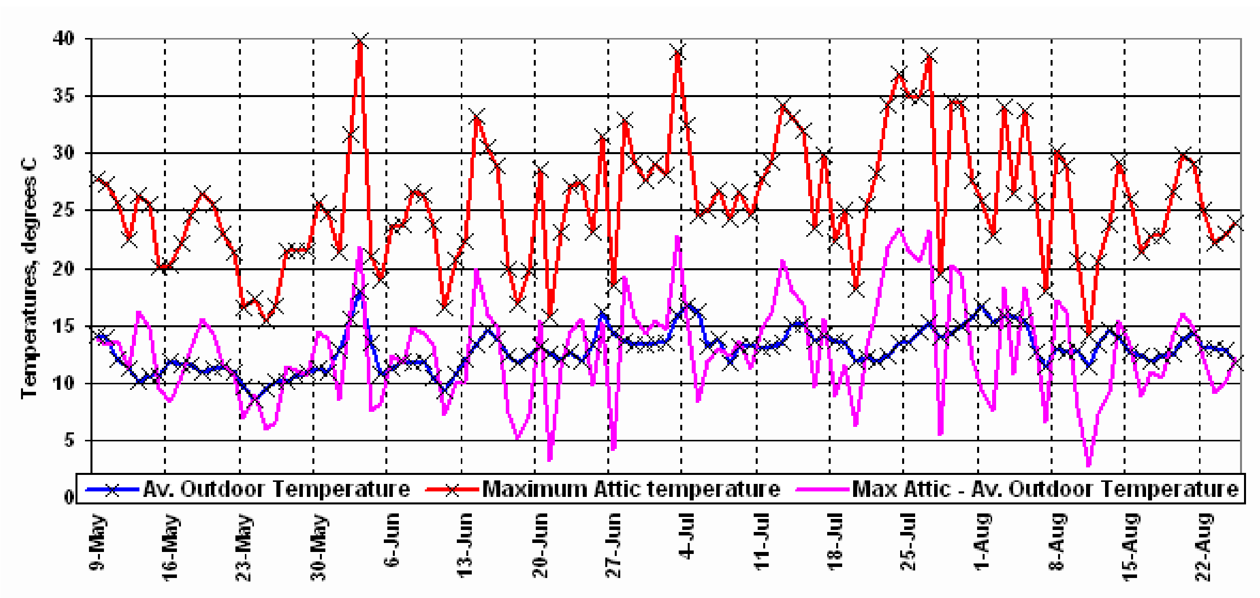


Figure 3. 16 Daily maximum attic, average outdoor and difference temperatures 9 May - 26 August 2011 (Attic Heat Harvester, n.d)

Sometimes air may be passed beneath the roofing sheet. When this is done it is known as Sheathing Ventilation. This approach does not only remove unwanted heat, but it is also known to facilitate the drying of moisture due to condensation in the attic space.

According to Oak Ridge National Laboratory in Hollick (2013), *"we serendipitously discovered the second major advance in roofs for our century: we found that elevating the roof cover from the roof deck to induce above sheathing ventilation is as important as* *increasing solar reflectance and may be the stronger player in reducing heat gain into attic. The two combined can reduce heat gain through the roof by 50% compared to nailed asphalt shingle roofs".*

At night, the roof temperature due to radiation to the sky is reduced to as much as 10^{o}C below the surrounding environment, however, by applying the principle of convective heat transfer to these roofs, 'coolth' can be delivered. In a study conducted by Hollick (2013), heat transfer was achieved using micro perforated shingles.

3.9.1 Glazing

Selecting a window type and material for glazing in ratio to space area are important in achieving a comfortable indoor environment. Glazing in windows, doors and walls give them the attribute for a direct visual interaction between the indoor and the outdoor space without direct contact.

Window types, glazed area and glazed ratio and thermo-physical properties of glazing materials and its effects on the indoor conditions have been discussed by Ghisi and Tinker (2005). These reports have covered topics such as heat accumulation and retention, dehumidification and overheating risks and health related issues associated with the misapplication of materials and principles of glazing.

The opacity and transmittance of glass can play a significant role in controlling solar gain (Givoni, 1976; Givoni, 1994). Heat gain in the building through glazed areas is mainly in form of solar radiation which is either absorbed or reflected to be released later, resulting in increased indoor temperature which can drive up space cooling demands. Window design, orientation and choice of glazing determines internal day lighting levels and can lead to energy savings where artificial light is displaced.

Window sizes and position in a building envelope can affect the energy demand for heating, cooling and electric lighting as demonstrated by Bokel (2007), who assessed the possibility of yearly calculations for energy demand for heating, cooling and electric lighting through computer simulations using a dynamic thermal program (Capsol) that could simulate total yearly demand for lighting, heating and cooling in buildings. He claimed that smaller windows and ventilators can reduce cooling demands.

Table 3. 6 Various glazing configurations showing U-values and Shading Coefficients (Hijazi, 2018).

Glazing Type	U – Value (W/m^2K)	R-Value (m^2K/W)	Shading Coefficient (SC)
Single clear	5.4	0.19	0.82
Single reflective (bronze)	4.0	0.22	0.20
Single tinted (bronze)	5.2	0.20	0.57
Single tinted (green)	5.0	0.21	0.56
Single low - E (bronze)	4.6	0.22	0.42
Single low - E (clear)	4.8	0.22	0.66
Single low - E (green)	4.4	0.23	0.41
Double clear	3.2	0.31	0.65
Double tinted (bronze)	3.1	0.32	0.48
Double tinted (green)	2.9	0.34	0.46
Double tinted (grey)	2.8	0.35	0.45
Double reflective	2.5	0.38	0.16
Double low - E (clear)	1.98	0.50	0.45
Double low - E (bronze)	1.89	0.52	0.35
Double low - E (green)	1.88	0.53	0.37
Double low - E (grey)	1.91	0.52	0.34
Triple pan clear	1.87	0.53	0.28
Triple tinted (bronze)	1.69	0.58	0.28
Triple tinted (green)	1.66	0.60	0.28
Triple tinted (grey)	1.74	0.56	0.28
Triple low - E (clear)	1.16	0.86	0.28

Kontoleon and Bikas (2002) used a dynamic thermal-circuit zone model comprising of four major structural heat-flow paths, to study the influence of the glazed opening percentage (GOP) and type of glazing on the indoor temperature extremes during and after solar hours of a winter and summer season. He concluded that buildings with double glazing and insulated slabs on the inner surface are prone to overheating when the glazed opening percentage (GOP) exceeds 70% in winter and in summer when GOP is less than 60%.

The measurable thermal performance of glazed partitions and windows will depend on the U-values of such glazing material. Design and application of glazing materials with low U-Values will increase heat gain resistance (Day & Roaf, 2007; Gan, 1998; Kontoleon & Bikas, 2002; McLeod, Hopfe, & Kwan, 2013; Ouedraogo, Levermore, & Parkinson, 2012) and reduce condensation on windows (Lowe & Johnston, 1997), as evident in the application of double and triple glazing in windows. Table 3.6 presents different gazing configurations showing their U-values and shading coefficients.

The implementation of new technologies in glazing can result in an increased energy efficiency output delivered at affordable costs. In Switzerland, Jakob and Madlener (2004) examined the technological progress and cost margins involved in the developments and the implementation of energy efficiency measures related to the building envelope using data from 1975 to 2001. The analysis reveals technical progress factors of circa 3% per annum for wall insulation and 3.3% per annum for double glazed windows. Despite these technological improvements, the costs of glazing and windows have dropped by 25% over the past 30 years, while that of wall insulation has remained almost constant with a 0.6% reduction in price.

3.10 Light and Heavy Fabrics.

Building fabrics come in different compositions depending on climate and location. In the temperate regions, thick walls, floors, roofs and ceilings also known as heavy fabrics are predominantly used in construction of external and internal components of the building envelope due to the need for warmth in such building interiors during winter by keeping cold out, while in Arid regions the reverse is the case as they are used to protect the building interior from hot air especially in the daytime. Warm humid climates are known for limited air movements, high RH and prevailing high ambient temperatures. This region hosts lighter external wall configurations, roofs, ceilings and floors also known as light fabric, this type of building envelope configuration is believed to offer attributes of dynamic response of the indoor environment due to micro climatic changes in the immediate outdoor environment (Agas, Matsaggos, Santamouris, & Argyriou, 1991; Cammarata & Marletta, 1990; Givoni, 1992). Humidity, temperature and air movements are the major physical factors that determine the composition of the building fabric.

3.10.1 Heat gain and Heat Loss in Light and Heavyweight building fabric

Thermal mass is contained in the building fabric: walls and partitions, ceilings, roofs, floors and windows. Thermal inertia describes a material's capacity to store and release heat. The rate at which thermal mass responds to heat storage/release depends on the thermo-physical properties of materials, their location within the building configurations enclosure and its exposed surface area (Blondeau, Spérandio, & Allard, 1997; Hyde, 2008).

The building mass may also determine the effectiveness of daytime or night ventilation. Liping and Hien (2007) with the aid of building simulation software ESP-r and CFD (FLUENT), investigated the impact of a building envelope with thermal conductances ranging from 0.17 to 2.9 W/m^{2}K over a timespan of up to 0 - 60 hours on the indoor thermal environment in naturally ventilated dwellings, in Singapore. Their findings concluded that dwellings with low thermal mass are not as effective for night ventilation as they are during the day. This they attributed to the limited ability of light fabrics to absorb, retain and effectively distribute/reradiate heat energy and concluded that maximum cooling may be achieved if the thermal capacitance of the building fabric is increased. Doing this may also require the application of an indoor humidity control strategy during daytime (T. Kubota, Chyee, & Ahmad, 2009). Hall, Casey, Loveday, and Gillott (2013) in a study using the E.ON Retrofit Research House (Nottingham, UK) suggested that a decrease in the static U-Value of external walls which may also include glazed areas, in combination with increased air-tightness (reduced ACH) and upgrades in heating/cooling system efficiency, may be a positive approach towards solving some operational inefficiencies. Operational deficiencies of a building may be attributed to those characteristics of the building structure that may lead to elevated levels of heat admittance through its layers resulting in the requirement to use some mechanical means to heat, cool and control humidity. Increasing thermal capacitance and inertia in building envelopes will require more time and energy to stabilise the effects of the massing on the target environment. When used in extreme climates, seasonal swings are targeted instead of diurnal swings. This principle is evident in Earth coupling where the intended heat or coolth is stored in the Earth mass. One of the most significant concepts for energy conservation in buildings is the use of seasonal heat transfers between the building and the surrounding earth which is known as Passive Annual Heat Storage (PAHS), (Hait, 1983). The concept of PAHS was first introduced by John Hait (1983). It is designed to absorb and transfer solar heat by the building envelope during overheated periods. Heat is absorbed by different components of the building fabrics that is then gradually transferred by conduction to the surrounding soil. This absorbed heat is then retrieved when the next seasonal swing commences (Anselm, 2012). PAHS strategy was also applied in Mile End Park, East London, a design that was inspired by the principle that says that heat moves through a 1m of dry Earth in approximately one month (Meir & Roaf, 2005; Sassi, 2006).

Meir and Roaf (2005) however noted that extreme thermal inertia may be counter-productive stating that most cases of overheating within a building environment is attributed to a poorly designed building envelope that causes delayed heat transfers from one surface to the opposite side of the component. In other words, the overall behavior of a building space will depend on the position of insulating materials in relation to the thermal mass. Diaz (1994) believes that *"thermal mass and its thermal effect is a major component of the building and although it requires careful study, it should not be treated in isolation but as part of a global design strategy".* Thermal mass when correctly positioned can therefore help to achieve, heat attenuation, temperature control and reduce energy requirements for both heating and cooling. (Sodha, Bansal, Bansal, Kumar, & Malik, 1986)

Athienitis and Santamouris (2013) presented some calculation methods to model sun spaces, bearing in mind the effects of thermal inertia on the sun space. Effects of thermal mass and wall thickness on the indoor environment are shown in Figs 3.17 and Fig 3.18 respectively.

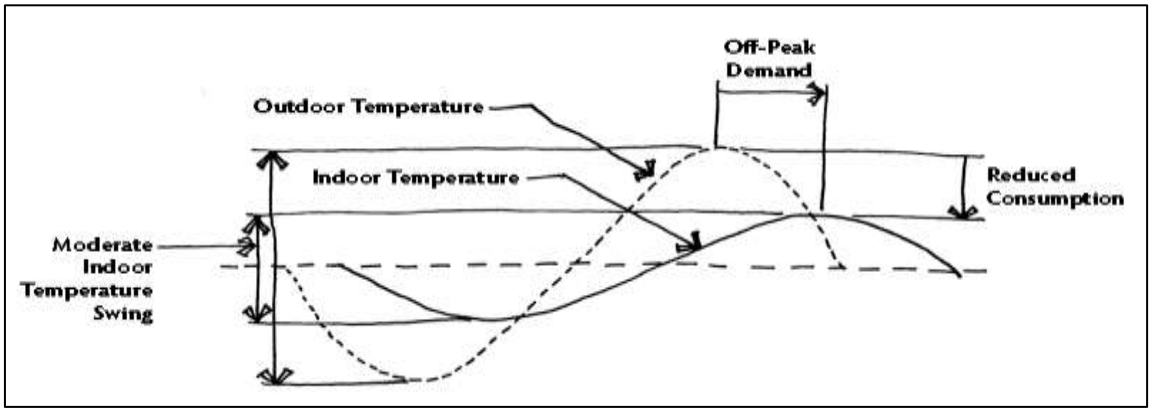


Figure 3. 17 Effects of thermal mass on a building Envelope and its Energy Consumption

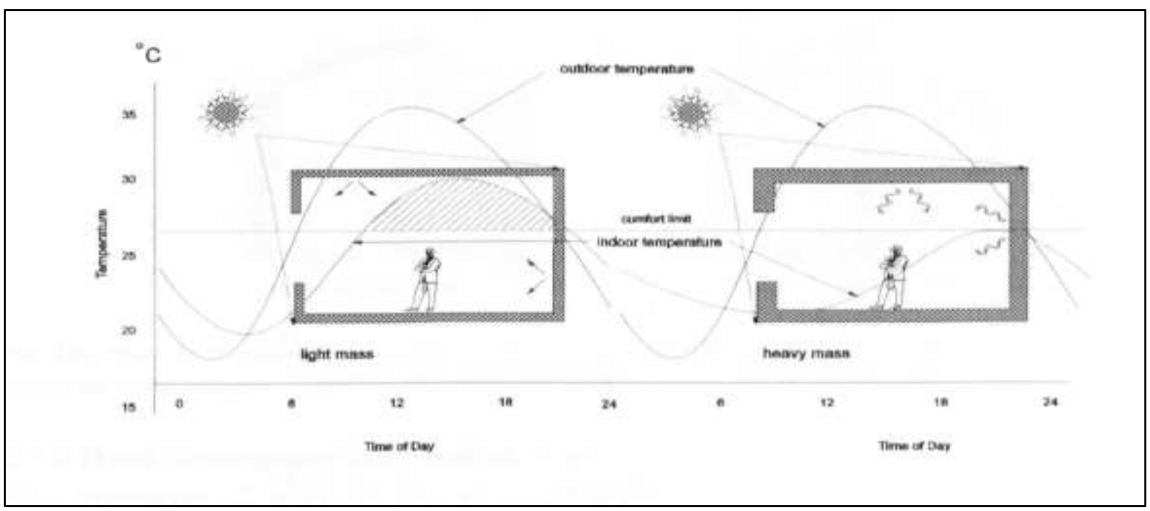


Figure 3. 18 Effects of wall thickness on indoor temperature swing (Diaz, 1994).

3.10.2 Heat transfer.

The means of heat transfer between two objects or planes are governed by three basic thermal principles namely: conduction, convection and radiation. Heat transfer coefficient at any surface is expressed in units as $Wm^{-2}K^{-1}$.

Heat transfer by contact between two particles is known as **Conduction**, the ability of any material to transfer heat by conduction is quantified by its U-Value. This form of heat transfer is more effective with low ventilation rates over thermal mass where conductive heat transfer is controlled.

Radiation is a type of heat exchange between two or more surfaces without any form of physical contact. This usually happens when two surfaces of different heat excitement levels are close by within a communicable wavelength. Radiative heat exchange/ transfer usually occurs in form of short wave or infrared radiation. In this type of heat transfer mode, the warmer surface loses its heat to the cooler surface thereby becoming cooler, this is because heat moves only in one direction towards a cooler plane. Radiant heat transfer can only take place where there is radiant energy between two surfaces. Two surfaces of the same surface temperatures cannot radiate heat between each other. Heat transfer by Radiation between two planes is given by (Anderson, 2006):

$$h_r = 4\sigma T_s^3 \qquad (20)$$

where h_r is the radiative heat transfer coefficient ($W \cdot m^{-2} \cdot K^{-1}$), σ is the Stefan-Boltzmann constant (5.67×10^{-8} $W \cdot m^{-2} \cdot K^{-4}$) and T_s is the surface temperature (K). For night time clear skies, this may vary due to large temperature differences between the sky and the radiating surface. Night time clear-sky radiation is discussed in detail in section 2.4.4.

Convection is a mode of heat transfer within a fluid (liquid or gaseous) by the inclination of hotter/less dense material to rise above cooler/denser material which sinks due to gravity. Convection in a space is usually induced by temperature differences between surfaces causing heated air to rise. This is the major principle of air cooling in spaces which depends upon temperature differences between surfaces and air movement through them. Convection is affected by the roughness of the excited surface and the direction in which the heat flows (Anderson, 2006). See Table 3.7. Convective heat transfer mechanism can cool or heat surfaces that are not directly near the heat source. Room temperature heating or cooling due to convection is given by the Equation:

$$h_c = 4 + 4v \qquad (21)$$

where h_c is the convective heat transfer coefficient
($Wm^{-2}K^{-1}$) and v is the air velocity at the surface (ms^{-1}).
Details of heat transfer in complex situations can be found in (Engineers, 2001).

Table 3. 7 Convective heat transfer coefficient, h_c (Anderson, 2006).

Direction of heat flow	Convective heat transfer coefficient†, h_c / $W \cdot m^{-2} \cdot K^{-1}$
Horizontal	2.5
Upward	5.0
Downward	0.7

† Assumes still air conditions, i.e. air speed at the surface is not greater than $0.1\ m \cdot s^{-1}$

3.10.3 Heat Storage.

A material is said to store heat when it can retain part of the energy transferred to it from an external heat source for a reasonable period. Building fabrics may gain heat primarily through external sources such as solar radiation and cool night breeze, it can also gain heat internally from internal heat sources such as cooking, electronics, heaters and other heat generating appliances and human activities. The stored heat is then released gradually to surrounding bodies (which are cooler) in form of sensible heat. Heat storage in thermal massive structures can serve two major purposes: as a "heat battery" when the heat stored is desired for a later use within the building space. This situation usually arises when the outdoor temperature rises above (cooling Purpose) or drops below (heating Purpose) the indoor temperature. The second purpose for heat storage is when the heat stored is not desired "heat purge". In this case, internally generated heat is stored in the building fabric and is then gradually removed from the thermal mass when the outdoor is slightly cooler than the indoor. This method is applicable mostly in climates with very little diurnal outdoor heat swings. Design of thermal mass to keep heat away from outside of the building envelope in overheated period leaves the only source of heat accumulation as internal heat gains from human activities and heat radiated from electric gadgets and therefore calls attention to means for proper removal of internally generated heat from within. The purpose for which heat storage in building fabrics is required, either as a "heat battery" or a "heat purge" is best determined during the design process.

Heat can also be stored in materials whose physical state can change. An example is an innovation developed in the 1940s by Telkes and Raymond (Agyenim, Hewitt, Eames, & Smyth, 2010). This type of storage has the ability/advantage to make use of a lesser volume and weight of a material for heat storage within small temperature intervals (Diaz, 1994). This system of heat storage is popularly known as **latent heat storage**. The mechanism of this system of heat storage works by the change in phase of the heat storage material usually from liquid (hotter) to a solid (cooler) state. This explains the principle of heat storage behind phase change materials (PCM). The application of phase change materials became popular after the energy crises of late 1970s. Assessment and investigations of the design fundamentals, system and process optimization, transient behaviour and field performance has been the areas widely researched on this topic and as a result, characteristics of new materials have been identified and developed. These developments are evident in the application of latent heat storage on different building materials either by incorporating liquid PCM into the pore space of the material or by addition during the manufacturing process of the material.

Early innovations on improvement of thermal performance of concrete using phase materials was carried out in Canada by Hawes, Banu, and Feldman (1990) in a study aimed at examining concrete alkalinity and ways to improve concrete compatibility with PCMs.

Issues like means of incorporation, effects of PCMs temperature, concrete temperature, immersion time and frequency, PCM dilution and absorption during impregnation were carefully examined in this work. Also observed was a reduction in moisture absorption which may help reduce humidity levels in warm humid environments. The economic impact of PCM concrete were also amongst issues examined and considered in the work. Tests on the thermal characteristics of PCM concrete were carried out using differential scanning calorimetry (DSC) on various concrete types including ordinary Portland cement. The techniques recorded impressive results as thermal storage abilities of test concrete were increased by up to 30%.

Pozzolans are a type of highly hygroscopic materials that are used to regulate the absorptivity/alkalinity of concrete impregnated with PCMs. Increased permeability and absorption of PCMs was checked by the introduction of a lower hygroscopic entraining compound that was also found to reduce the alkalinity of the concrete, increasing its compatibility with alkaline sensitive PCMs. This was claimed to be a cost-effective strategy that may also help dehumidification of building interiors (Hawes et al., 1990).

Another method of PCM impregnation is the immersion of concrete before it is used on site. This method can also be applied to batch concrete blocks and may give it an advantage over the other systems. This research work showed that the thermal performance of ordinary Portland cement amongst other concrete types could be maintained while increasing the energy saving potentials to up to 30% (when natural energy sources are used for heating or cooling the concrete mass) when mixed with compatible PCMs like dodecanol (Hawes et al., 1990).

A combination of heat exchangers and vapour remover with PCMs can condition an enclosed space within thermal comfort ranges and in a cost-effective way using low energy fans (Isaacson, 2014).

Many researchers have however, claimed that the low thermal conductivities possessed by many PCMs represent major disadvantages (Agyenim et al., 2010).

For any material with the ability to store heat, thermal conductivity (λ), density (ρ) and specific heat capacity (c), are the determining factors of heat storage. Heat storage is represented as the product of these three factors and the values of this is directly proportional to the amount of heat stored by a material.

3.10.4 Heat Distribution.

All heat distribution between particles in a material or surface to surface is aimed at achieving heat equilibrium or thermal balance. When a part of a building fabric is excited with heat/ temperature changes, the other parts of the fabric that are not in direct contact with the heat source will tend to absorb some of the heat to create an equilibrium or a uniform heat condition throughout the surface. This also happens when a fabric is made of layers from varied materials with different thermo-physical properties. The differences in their temperatures will increase the level of heat transfer either through convection or radiation towards attaining equilibrium within its surface and or the surrounding environment. Heat balance then can be used to transfer heat from one point in a building fabric to another as is applicable in the principle of heat pipes (Ezekwe, 1990). Temperature differences of different components of an internal space will also influence heat distribution/balance.

The term temperature stratification is used for this process. Different components within a space have different temperatures always, the floors, the walls, the ceilings, the furniture within the space and even the users in the space have different body temperatures and they will always gain or lose heat in order to attain equilibrium (Balcomb, 1983). The temperature distribution of all surfaces is disturbed by this process and is always changing. The temperature of a thermal mass may be higher or lower than that of the internal space and depending on the situation, either of them will gain heat from the other to attain equilibrium. Other factors that affect temperature distribution in a material are: the area, the geometry, the thickness, the location, and the colour of the finishing (Diaz, 1994). Studies focusing on increasing thermal capacitance appear to be a promising approach towards the optimisation of heat distribution. Innovations like hypocausts have also been used to achieve greater surface area in such designs.

Ventilation rates may also affect the sensible heat distribution in an enclosed space. This technique has been used to charge thermal mass and distribute heat from exposed surfaces through convection. The rate of airflow from a night ventilation system or any other cooling means introduced in an internal space determines the rate of heat storage in the fabrics, indoor air changes and in most cases evaporation. The rate of cooling derived from the same source varies between the fabric and the indoor air temperatures (Givoni, 1998b; Pfafferott, 2004). The thermal mass will take a longer time to absorb and distribute heat within itself and with the heat source.

3.10.5 The Physics of Heat Flow and Heat Storage in Materials.

According to Houghten et al (1932) in (Diaz, 1994) *".. by blowing cool air through a church during the night and keeping the building closed after sunrise, the temperature of the inner contents will be lowered considerably, and they will absorb heat given off by the audiences during services until about noon. This will maintain a comfortable condition approximating that obtained by* ***refrigeration****…".* (Houghten, Blackshaw, Pugh, & McDermott, 1932).

Over the last 80 years more research has been undertaken of such strategies as time lag, decrement factor, lag angle, sol-air temperature, finite differences, admittance method, diurnal heat capacity, seasonal heat capacity. The way in which a building or any material responds to heat or temperature changes because of summation of other elementary responses of smaller elements making up the mass is known as the **Response Factor**. Response factor is the summation of the responses of different elements in a system due to heat excitement and is chiefly used to calculate the general excitement of a material due to temperature changes (Muncey, 1979). It is an old method of calculation which was popularly applied in the USA between 1960 and 1970; a revolutionary breakthrough introduced by (Stephenson & Mitalas, 1967). The response factor is commonly used for the calculation of conductive heat flow at the surface of materials. Kusuda (1969) modelled conduction heat transfer through roof decks, gables and vertical eaves using the response factor and the thermo-physical properties of the material, a system which successfully and significantly improved the calculations of transient heat transfer through building fabrics including other surfaces within the building and the surrounding air.

An alternative model of calculation "ESP-r" was introduced by J. A. Clark (1978) in which he used a digitalized approach to calculate and simulate transient heat transfers in A/C plant components and other systems that use cooling coils. The system also covers the concept of the heat balance technique in building components.

Heat attenuation and control of temperature swings are two major characteristics of thermal mass in providing thermal comfort and reducing energy used for air conditioning (Diaz, 1994). These are achieved by the mechanism of heat transfer which is expressed in any given building fabrics through the energy movement in the fabric, energy release within the building, energy stored in in the structure and the effect of ventilation on coefficient of heat transfer.

Another method known as the **Admittance Method,** highlights temperature swings and establishes a 24-hr temperature variation cycle of heat flows to and from any given surface. Thermal admittance simply means a materials ability to absorb and or release heat (Heat exchange) due to temperature differences between the materials surface and the surrounding ambient temperature. For any small room or area (A) the elementary admittance values (Y), and the total admittance can be expressed in (W/K) through the equation:

$Y_t = \Sigma (AY)$ .... (22)

It should be noted that the admittance method does not account for the thickness of any material as it only considers density and the surface area of the material.

Admittance however, is the ratio of heat flux variation to temperature variation in a 24hr cycle and is expressed by (Balcomb, 1983) as :

$Y = \sqrt{\frac{2\pi\lambda\rho c}{P}}$ .... (23)

The higher the conductivity of a material, the better the heat storage ability of the material. Gado and Mohamed however identified the inability of admittance method to account for solar radiation in a space as its major limitation.

Thermal admittance which is the ratio of heat flux variation to temperature variation ($2\Delta\Phi/\Delta T_i$) during a 24-hr cycle is expressed by the equation (Diaz, 1994):

$\Phi_t = AU (T_{sol} - T_i) + AU\, dcr (T_{sol} (t) - t_{lg} - T_{sol}) = \Phi + \Delta\Phi(t)$ .... (24)

To attain equilibrium due to internal heat gains through ventilation and conduction, heat loss is affected, and the heat balance equation becomes:

$\Phi_s + \Phi i = (qv + qc) (\Delta T)$.. (25)

Where Φ is the total heat flow during a diurnal circle, t is specific time, (AU) is heat gain through glass due to conduction and (AUdcr) is heat gains through opaque materials due to conduction. Ventilation gains is given by (0.33NV).

Givoni (1976), expressed thermal resistivity as the reciprocal of thermal conductivity ($1/\lambda$). Further to this, the greater the thickness of a material (density d), the slower and lower the rate of heat flow through it hence resistance becomes d/λ and thermal conductivity becomes λ/d. The thermal resistance of air on surfaces is added to the thermal resistance of walls when the rate of heat flow from indoor to outdoor or vice versa is calculated. The total resistance can then be expressed as:

$R = 1/h_i + d/\lambda + 1/h_o$ .... (26)

Where h_i and h_o are coefficients of indoor and outdoor air respectively.

The reciprocal of the total resistance of any material or group is known as the **U Value** (thermal transmittance) and is given in units as W/m^2K and expressed mathematically as $U = 1/R$. The total thermal transmittance (U_T) of a wall made from different layers of materials with different thermal resistances R_1 to R_n then becomes:

$U_T = 1/R_1 + 1/R_2 \ldots + 1/R_n$ .... (27)

Heat capacity is *"... the amount of heat required to elevate the temperature of a unit volume of a material or a unit area of the surface by 1 ºC"* (Givoni, 1976). It is expressed as volumetric heat capacity when it is increased by volume per temperature rise and heat capacity when it is determined by surface area per temperature rise. The heat capacity of a wall with different layers is given by:

$Hc_T = \Sigma\, d_i\, \rho_i\, c_i$ .... (28)

It is written in units as J/m^2K.

The way layers of materials are arranged in a wall or roof or floor determines the depth in which heat can travel into the material. Heat waves can be measured in 24hrs cycles and the heat flow flows in such a material is expressed as the **Thermal Diffusivity** of such material. Thermal diffusivity is the ratio between the thermal conductivity and the volumetric heat capacity (m^2/s).

$\propto = \lambda/\rho c$.

Volumetric heat capacity, ρc represents the heat behaviour of any material. Materials with high conductivity lose heat at a greater rate than those with lower conductivity. Hence heat conductivity through a material is directly proportional to the heat Diffusivity and such materials are identified as good materials for short cyclic heat storage as they can store and release heat easily and more effectively when their depth is increased (Yannas & Maldonado, 1995).

Thermal Diffusivity is the extent of heat flux through a cross section of a material. The extent of the heat flux in materials varies according to the material and its physical characteristics and may take different time frames for this movement to occur. The time spent for a heat flux to move within a material is referred to as the **Time Constant**. Time constant is the product of the thermal Resistance of a material and its heat capacity and given by:

$$t = (d/\lambda)\,(d\rho c) \qquad (29)$$

this can further be expressed as:

$$t = d^2 / (\lambda/\rho c) = d^2/\propto \qquad (30)$$

where d = density /depth and $\propto$is the thermal diffusivity.

Thermal Diffusivity is the ability of a material to store and release heat by surface impact. This value increases with the specific heat storage and thermal conductivity. Thermal Diffusivity of any material is given by:

$$b = \sqrt{\lambda\rho c} \qquad (31)$$

($Ws^{0.5} / m^2K$). A modification of this equation was given by (Liman & Allard, 1995) to represent the thermal behaviour of a whole space. The average Diffusivity, b_m of the exposed surfaces was used and is given by:

$b_m = \Sigma (b_i s_i) / s_{tot}$ .... (32)

this considers only s_{tot} which is the exposed surface layers. Where diffusivity captures a non-periodic heat storage which is useful for night ventilation and it also gives a clearer picture of individual material behaviour and influence on the building envelope due to sudden temperature change. This allows for quick character and rearrangements of material compositions to derive desired material properties during calculations for thermal inertia.

To understand and characterize the thermal properties of building materials and components in the field, CIBSE recommends the use of the Admittance method, Heat capacity and mean thermal diffusivity. These parameters will be used to characterise and quantify the thermal properties of the proposed model in this research work.

Diurnal heat capacity is given by (Balcomb, 1983) as:

$dhc = \sqrt{\frac{P\lambda\rho c}{2\pi}}$ .... (33)

Diurnal heat capacity increases with an increase in surface area, as the heat exchange points are increased due to an increase in the exposed surface area. Increasing the thickness of a material will improve the diurnal heat capacity of such a material also. Diaz (1994) presented a detailed and sequential procedure to the derivation of heat capacity calculations.

3.10.6 Factors that affect the use of Thermal Mass.

It is found that thermal mass plays a vital role in the successful application of passive cooling strategy for space conditioning. This is expressed through the controlled indoor temperature, either by reducing rates of heat gain/loss from and to external sources, and the regulation of heat gains by absorbing and exhausting internally generated heat from within the building space. Thermal mass can also supply a targeted space in a building with pre-stored heat energy during winter (seasonal swing) or during cold nights (diurnal swings). In the same manner, overnight stored ‘coolth’ has the ability to absorb greater quantities of heat during the day. The regulatory function of thermal mass is affected by some factors namely: climatic influences, building material and thermal properties, building design, ventilation, insulation, internal and external heat gains and human activities that produce heat and moisture.

Evaporative ventilation uses direct contact of air molecules on the human skin to induce cooling by the occupant sweating. Care has to be taken however not to increase air speeds to the extent that they produce discomfort through the user’s perception of cold draughts.

Increasing convective ventilation overnight when ambient air is cooler can heat flush and lower the core and surface temperatures of thermally massive building fabric, especially when combined with external insulation. The cooling effect can be maximised by keeping windows closed during daylight hours to inhibit the infiltration of external warm air (Givoni, 1991).

The **effects of diurnal heat flushing** is optimised when the cool air is circulated over well positioned thermal mass (Balaras, 1996). Controlled air movement also distributes uniform heat energy within the building space and removes stale air from the interior space to the external environment without sudden drop in the stored energy of the mass. The thermal behaviour of a building fabric is therefore influenced by the rate of airflow through the building. This has to be achieved in a manner where security, user comfort, health and indoor air quality are not compromised (Van der Maas, Flourentzou, Rodriguez, & Jaboyedoff, 1994).

Thermal mass can also be cooled using mechanical systems (Balaras, 1996; Keeney & Braun, 1997). The potentials of night radiant cooling of buildings in the warm humid environment of South Eastern Nigeria was first suggested by Ezekwe (1986). Convective heat transfer in building envelopes have been applied through several innovative approaches, such as the use **hypocaust** floors and walls, **thermal ceilings**. Recently a strategy known as **dynamic insulation** was introduced in France by Anon (1984). Dynamic Insulation is a form of approach where cooler air is passed through insulated building fabrics, thereby picking up heat due to friction between the air molecules and the fibre of the insulation material. Dynamic Insulation dates back to a 1978 prototype design which was later improved on in 1981 (Claridge & Bhattacharyya, 1991). Dynamic insulation reduces heat loss in buildings without the use of massive walls and it has a high potential for air filtration (B. J. Taylor, Webster, & Imbabi, 1998). In an experiment conducted in the UAE termed "Eco- Villa" aimed to demonstrate energy efficiency of new technologies and materials, Elsarrag, Al-Horr, and Imbabi (2012) recorded reductions in the U-Values of walls from 0.24 W/m^2K to 0.05 W/m^2K in a theoretical set up when the ventilation rate was between 0 – 1 $litres/s/m^2$. At the default design ventilation rate of 0.8$litres/s/m^2$ the U-Values moved from 0.063 $W/m^2/K$ compared to 0.125 $W/m^2/K$ recorded in a measured study, hence reducing the wall component conduction by 41% as against the theoretical 38%. Energy loads for air conditioning were reduced by 25% in the dynamic mode.

In addition to the thermal properties of materials discussed in the sections above, application of **insulation** on thermal mass increases the thermal resistivity of the wall on the side the insulation is applied. Therefore, the wall will have good conductivity and as well a high resistance to unwanted heat flow. The position of the insulation layer determines the role that the thermal mass will play in heat storage and heat dissipation. The degree of Resistance of a material to heat gain or storage is represented or expressed by the term U-Value.

3.10.7 Internal heat gains and Heat Sources

When an appropriate ventilation strategy is lacking in an indoor environment, the occupant's health and comfort can be compromised. CIBSE Guide B (2001) recommends a supply range of fresh air at rates between 6 to 8 l/s per person for residential occupants.

There is tendency that internally generated heat will rise and hence, this will affect the rate of radiative cooling sensation due to convective heat transfer on the occupants of the room as well as radiation from any warm appliances (CIBSE, 2006).

The surface area of a material exposed to a heat source has more impact on the ability of material to absorb heat than the depth of the material. Internal walls are prone to perform better than external walls as both sides of an internal wall are exposed to interior spaces. This however implies that the surface area of an internal wall is twice that of an exterior wall. During periods where internal heat gains are high, heat will be absorbed by internal walls at a greater rate than the external wall.

3.11 Designing for Human Comfort and Health

Designing for a balance between health, comfort and energy efficiency is an aspect of passive cooling design consideration that has been somewhat neglected by designers in Nigeria (Hussaini & Abdul Majid, 2015; Nduka & Ogunsanmi, 2015). WHO (Organization, 2018) reports about 4 million premature deaths annually due to diseases that are credited to poor indoor air quality. Recent studies have shown that heat induced death resulting from meningitis has increased in the north and middle belt of Nigeria (Greenwood, 1999, 2006; Moore, 1992). I. Mohammed et al. (2000) reported 109,580 cases of meningococcal meningitis resulting to 11,717 deaths within 6 months in 1996, giving a case fatality rate of 10.7% total. In another study carried out in Zaria, in Northern Nigeria, Sawa and Buhari (2011) projected that meningitis and measles would increase by 6 and 19 persons per thousand respectively, for every 1ºC increase in temperature making buildings very vulnerable during peak periods and at nights. Their findings also disclosed that the highest number of reported cases of meningitis and measles were recorded during the hottest months of March and April.

In the UK alone, respiratory related sicknesses are attributed to building design that have laid more emphasis on air tightness to provide increased energy efficiency (SG Howieson, Sharpe, & Farren, 2014).

In order to achieve health and comfort within building enclosures, it is imperative to put the following factors into consideration in the design process of buildings.

3.11.1 ACH, Air Quality and Air Velocity

Ventilation rates are measured in air changes per hour (ACH). Sherman and Chan (2006) identified building volume, envelope area and floor area as three regulating aspects for air leakages in a building setup. Purpose for which a space is used determines the ventilation rates applicable. These rates are not constant and may vary depending on number of occupants, type of activities they engage in and heat gains (either from users or appliances within the space), humidity levels, pollutants and toxins and other particles off gassing or ingressing from external sources.

Ventilation rates may vary significantly when one or more of these factors change. It is also of interest to note that due to age of building (deterioration), building type, orientation to climate and construction materials, - air infiltration due to the buildings air tightness – may vary (Orme, Liddament, and Wilson (1994). There has been series of debates on the relationship between air tightness and indoor air quality. Parent, Stricker, and Fugler (1996) found no correlation between air tightness and CO_2 levels for 30 Canadian dwellings.

SG Howieson et al. (2014) who monitored a range of new build smaller dwellings across Scotland reported CO_2 levels of 2317ppm (occupied mean peak), and a time weighted average of 1834ppm. Levels peak in some dwellings at 4800ppm indicating poor IAQ during occupied bedrooms. Table 3.8 shows CIBSE recommendations for ACH building spaces. Refer to CIBSE Guide B2 manual for more details (Guide B, 2001).

Table 3. 8 Summary of Recommendations (Guide B, 2001)

Building sector	Section number	Recommendation
Animal husbandry	3.24.1	See Table 3.20
Assembly halls	3.3	See Table 3.6
Atria	3.4	See section 3.4.3
Broadcasting studios	3.5	6-10 ACH (but heat gain should be assessed)
Call centres	3.24.2	4-6 ACH (but heat gain should be assessed)
Catering (inc. commercial kitchens)	3.6	30—40 ACH
Cleanrooms	3.7	See Tables 3.11 and 3.12
Communal residential buildings	3.8	0.5-1 ACH
Computer rooms	3.9	See Table 3.13
Court rooms	3.24.3	As for typical naturally ventilated buildings
Darkrooms (photographic)	3.24.4	6-8 ACH (but heat gain should be assessed)
Dealing rooms	3.24.5	As offices for ventilation (but heat gain should be assessed)
Dwellings (inc. high-rise dwellings)	3.10	0.5-1 ACH
Factories and warehouses	3.11	See 3.11.1 for regulatory requirements
High-rise (non-domestic) buildings	3.12	4-6 ACH for office areas; up to 10 ACH for meeting spaces
Horticulture	3.24.6	30-50 litre.s^{-1}.m^{-2} for greenhouses (45-60 ACH)
Hospitals and health care buildings	3.13	See Table 3.15
Hotels	3.14	10-15 ACH minimum for guest rooms with en-suite bathrooms
Industrial ventilation	3.15	Sufficient to minimise airborne contamination
Laboratories	3.16	6-15 ACH (allowance must be made for fume cupboards)
Museums, libraries and art galleries	3.17	Depends on nature ofexhibits
Offices	3.2	See Tables 3.2 and 3.3
Plant rooms	3.18	Specific regulations apply, see section 3.18
Schools and educational buildings	3.19	See Table 3.18
Shops and retail premises	3.20	5-8 litre.s^{-1} per person
Sports centres (inc. swimming pools)	3.21	See Table 3.19
Standards rooms	3.24.7	45-60 ACH
Toilets	3.22	Building Regulations apply; opening windows ofarea 1/20th. of floor area or mechanical ventilation at 6 litre.s^{-1} per wc or 3 ACH minimum for non-domestic buildings; opening windows of area 1/20 th. of floor area (1/30th. in Scotland) or mechanical extract at 6 litres^{-1} (3 ACH in Scotland) minimum for dwellings
Transportation buildings (inc. car parks)	3.23	6 ACH for car parks (normal operation) 10ACH(fire conditions)

3.11.2 Relative humidity

Relative humidity is the proportion of vapour pressure to saturation vapour pressure at a given dry bulb temperature and is expressed as a percentage (% RH) (CIBSE, 2006). It varies considerably inclining to its daily maximum values at dawn when the air temperature is at its lowest and gradually decreases as the air temperature rises. The decrease in relative humidity towards mid-day is predominant during summer. In areas with high relative humidity levels, the transmission of solar radiation is marginally reduced because of atmospheric absorption and scattering.

High relative humidity reduces evaporation rates from the surface of the body. When humidity is low, sweating becomes more effective in cooling down the body.

High RH values are also known to catalyse the process of corrosion of metals; decay timber-based components and reduce the performance of insulation materials. British Standard (2002) suggests a typical daily moisture production rate of 6 litres for a family of 5 persons. This excludes clothes washing and other moisture production related domestic activities which may produce up to 9 litres.

McIntyre (1980) notes that increased perception to smells, irritation due to cigarette smoke and other fine particles - which may cause nuisance and static discharge from occupants - are common in prolonged exposure to low humidity environments of 30% RH or below. Contrarily Fang, Clausen, and Fanger (1998) argued that the concept of freshness is linked to low humidity levels.

3.11.3 Humidity

The humidity of room air is expressed as mass of water vapour per unit mass of dry air ($kg \cdot kg^{-1}$) or vapour pressure (partial pressure of water vapour (Pa)). High humidity levels stimulate microbiological growth, decay of building materials and the reduction of static electricity. Bathrooms and kitchens are most vulnerable to high room humidity.

3.11.4 Mould growth

When buildings are exposed to high humidity levels for an extended period, problems such as airborne fungi and house dust mites may arise. Studies have shown that moulds can germinate and grow under steady state conditions if the relative humidity at a surface is above 80% (Husman, 1996). Mould growth greatly depends on the length of time a surface is exposed to high humidity; longer the time of exposure, the greater the likelihood of mould growth (CIBSE, 2006).

CIBSE (2006) discusses some factors that control surface condensation and mould growth within buildings and their effects on building performance. It also presents methods for predicting surface and interstitial condensation and guidelines to minimising them. High humidity levels in dwellings can result in condensation and this in turn can foster mould growth. After germination, fungi thrive on damp organic material and as such do not essentially require either high air humidity or high air temperature to continue growth. This is because moulds can sustain their own moist environment by becoming more hygroscopic, and as such reducing the humidity cannot alone stop their growth. 15% base level of mould growth in most dwellings is not affected by the internal RH in such dwellings (Altamirano-Medina, Davies, Ridley, Mumovic, & Oreszczyn, 2006).

The risk of mould germination in interior wall surfaces according to CIBSE (2006) depends on the combined effects of its surface temperature and internal humidity. The surface temperature of surfaces in a building interior most especially the walls, floors and ceilings and roof members in the attic determine the level at which moulds germinate and grow in such an instance. Materials that have a quick response to temperature changes, for example light weight construction components of a building fabric, will likely limit the rate at which internal humidity rises when exposed to vapour and a heat source. On the other hand, thermally massive walls - especially those insulated externally - will be less responsive under the same conditions. CIBSE (2006) suggests that internal humidity levels should be below 60%, noting that if the RH in an indoor space stays above 70% for an extended period, capillary movements of moisture may increase the RH of the external walls which will consequently sustain mould growth on the opposite side of the wall.

Many moulds are toxic and can produce health problems for the occupants. Air condition systems can develop the conditions that allow specific types of mould to grow. Legionaire's disease was first documented at a convention in Philadelphia in 1976, where 184 people developed symptoms of the disease with 29 case proving fatal (Fraser et al., 1977). It is known to be caused by the bacteria now known as *Legionella pneumophila* that thrive in warm and humid environments. The enabling environment for the bacteria is most typically provided by poorly maintained components in mechanical air conditioning and water supply systems in buildings (Hines, 1993).

3.11.5 Dehumidification Techniques

Materials that attract and hold water vapour are known as desiccants. They are applied in passive dehumidification strategies and processes that commonly make use of salts/liquids with high affinity for water or actively by use of mechanical dehumidifiers. Some commonly used salts for passive dehumidification are alumina gel, silica gel, activated alumina and some liquids such as *triethylene glycol* and *sodium chloride* solution (NaCl).

Dehumidification of air before it is supplied is essentially required to side-step the condensation of water vapour on cooled surfaces. This is commonly achieved by a process of adiabatic drying of outdoor humid air by channelling it through a purpose designed dehumidifying component containing desiccants before introducing it into spaces where the conditioned air is required, however, running this process over time leaves the desiccant material saturated with moisture, and at this point, regeneration of the desiccant material becomes inevitable. Regeneration may be achieved by means of oven drying or through solar energy at temperatures between 50ºC and 260ºC (Nayak & Prajapati, 2006). Studies show that most materials used for interior finishing of buildings attract and hold water vapour for example, wood, natural fibres, clays, and many other synthetic materials, however their level of affinity to moisture may not be as strong as commercial desiccants. Woollen carpet fibres have been found to attract up to 23% moisture equivalent of its dry weight, while nylon attracts up to 6% of its weight. Commercially produced desiccants continuously absorb moisture even in dry surrounding air conditions with more absorbing strength varying between 10% and 1,100% depending on type and how much moisture is available in the atmosphere. Desiccant materials can also adsorb hydrocarbon vapours and can therefore be used to purify the air in living spaces (Hines, 1993).

Charcoal (activated carbon) is known to be a good air filter in polluted air purification scenarios and is applied in evaporative cooling as a desiccant. In an experiment conducted in Botswana by Vanessa (2014) under Royal Botanic Gardens, KEW to demonstrate the viability of the use of charcoal for moisture reduction during seed drying, it was found that the equilibrium relative humidity (eRH) of maize seed was reduced from 56% to 20% using charcoal as a desiccant. Making use of charcoal as a desiccant is a practicable approach as it can be re-used until it fails to absorb moisture (Gold, 2014).

Activated charcoal has footprints in the medical world because of its application in various aspects of medicine and drug administration. All desiccants behave in a comparable way in that they attract moisture until they reach a balance with the surrounding air, which can be removed from it by a process of heating to temperatures between 48ºC and 260ºC and/or exposing it to an indirect evaporative cooling process (scavenger airstream). These temperatures are attainable in building attics and may be used effectively to regenerate desiccants as evident in Areemit and Sakamoto (2005) application of solar dehumidification where they used solar heat to regenerate saturated attic plywood used as a desiccant medium. Effective dehumidification COPs of more than 15 was achieved by this approach, three times better than the best mechanical dehumidifier. In 2008, a similar approach was applied by Parker et al. (2008) by using solar heat during the daytime to dry wood in the attic and a clay desiccant with enthalpy controlled ventilation intended to remove moisture. It was found that the system provided a daily usable moisture adsorption potential of 5-10% in addition to reduced daytime sensible cooling loads across the insulated ceiling, due to the lowered temperature of the attic space. Fig 3.19 presents a comparative result between a normal roof ventilation and an enthalpy based attic ventilation in mid-January, showing the effects of the implementation of enthalpy based attic ventilation which also controls the interior relative humidity in the proposed system (Parker et al., 2008).

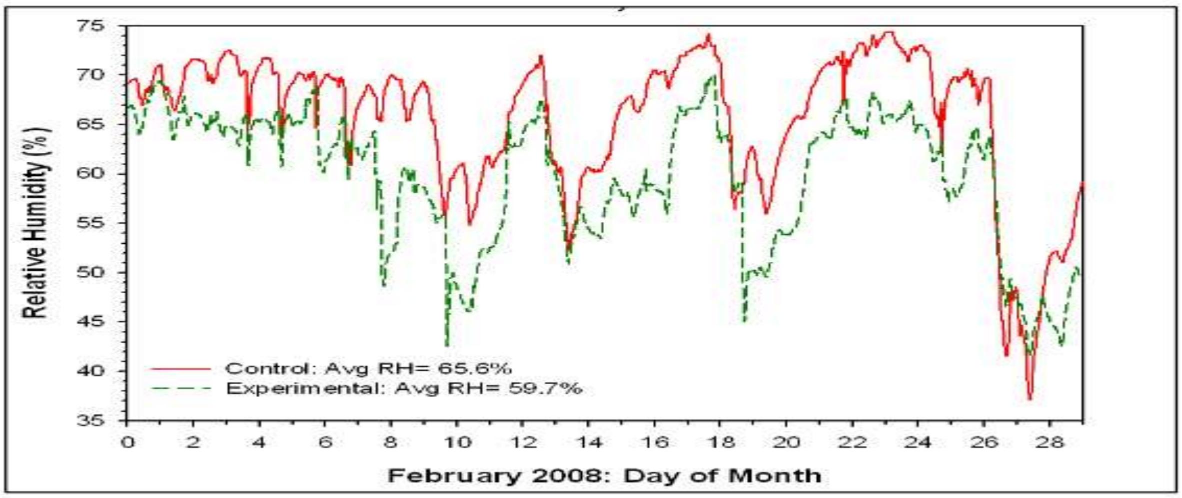


Figure 3. 19 Comparative Main Zone RH with Enthalpy Controlled Solar Attic Ventilation. Source (Parker et al., 2008).

3.12 Recommendations on Active and Passive Cooling Systems in Nigeria

Various cooling techniques have been presented in the review which could aid thermal comfort within building envelopes. Passive cooling techniques are those natural approaches which does not require the use of a conventional cooling system. Most passive cooling approaches in the real sense does only extend the tolerance limits of the occupant's thermal comfort in a given space, and not a reduction in cooling loads of such spaces. It is however imperative to encourage initiatives that would practically incorporate innovations that would optimize passive cooling in Nigerian buildings. On the other hand, active cooling systems will require the application of a power source to drive fans, pumps or compressors and evaporators. Mechanical air-cooling systems have become the most applied technical solution for keeping within comfort boundaries in Nigerian buildings. However, its popularity comes with a negative impact which is high energy/ electricity consumption.

While buildings running on natural ventilation systems in a general context are assumed to use little or no energy, they may not be able to completely maintain indoor thermal conditions in a warm humid climate like South Eastern Nigeria. The efficiency of these systems needs to be critically evaluated hence, it becomes important and worthwhile to balance the cost of passive ventilation systems against the capital operating savings achieved by reducing the size of HVACs required.

Good passive design solutions can only be achieved when Architect's and other designer's building specifications align with the climatic characteristics of individual sites or microclimate. Most passive cooling grounded on bioclimatic strategies when well-integrated into buildings through Architect's design and specification can increase cooling and hence, significantly reduce the overall energy demand.

Cook (1989) has demonstrated that passive cooling systems in most cases can save both energy and money than active cooling systems, and when it comes to effectiveness, passive cooling systems becomes limited to climatic influences especially during the summer peaks and in zones with limited air movements.

Givoni (1994) suggested that in circumstances where passive cooling and design is not adequate to meet user comfort needs, then an application of an add-on mechanical cooling can be provided, signifying the possibility of an integration of the two systems in a hybrid/synergistic module which will boost the performance of the passive cooling system and at the same time reduce energy usage of the mechanical systems to deliver comfort to users.

Since a complete indoor thermal comfort can hardly be achieved by sole application of passive cooling techniques, especially in a warm humid climate, and mechanical cooling on the other hand is not cost effective, the task then is to ascertain a synergistic module for an optimal operation of both systems in a hybrid form that will take advantage of the two major natural heat sinks: the earth, and the sky to provide sufficient cooling capacity. The hybrid system may involve two or more cooling technologies in a way that will beat the limitations of any single cooling system while demonstrating its potential to reduce or completely displace the use of air conditioning systems (Cook, 1989; Givoni, 1998a).

Hybrid cooling systems stand out from the conventional cooling systems because of their intelligent control systems that can automatically switch between natural and mechanical modes in order to achieve minimal energy consumption (Ashwood & Bharathan, 2011; G. Clark, 1981; Cook, 1989).

There are no records of attempts of these combination in warm humid South Eastern Nigeria. However, there are limited research in the following passive cooling strategies which includes: solar, wind, evaporative cooling, radiant cooling, and ventilative cooling strategies. There has however been attempts on the use of design measures e.g. Roof overhangs, court yards, window fins/hoods, etc., but none yet has tried to encompass an all design and retrofitting strategies as it relates to thermo physical performance, which could be adopted for energy management in a building with little or no need for mechanical means of cooling (Ogunsote, Prucnal-Ogunsote, & Adegbie, 2010).

Most buildings in south eastern Nigeria have been built in the last few decades, while majority of these buildings were designed and constructed with little or no consideration of local climate or energy conservation. Substantial amount of energy can be saved by minimizing the thermal transmission of the building fabric. Also, an intelligent selection of thermo physical suitable walls, floors, ceilings, windows and roof materials for buildings constructed in south eastern Nigeria can drastically reduce cooling energy consumption (Ajibola, 2001; Akadiri, Chinyio, & Olomolaiye, 2012).

3.13 Critical Discussions and Knowledge Gap

Mostly all the areas reviewed reveals a scope for further research as it pertains to the climate in South Eastern Nigeria. Few researches have discussed solar utilization and wind energy in the Nigerian context (Hussaini & Abdul Majid, 2015; Iloeje, 1985; Lawal, Akinbami, & Akinpade, 2012; Ojosu et al., 1988), while innovations like geothermal, biomass, clear night sky radiation, ground pipe ventilation and so many other technologies adopted worldwide are yet to be introduced in Nigeria.

There is scope for research on identifying materials and ways to assemble them in order to boost a “fabric first” approach to energy efficiency in building envelopes. One of the weaknesses identified is external walls with U-values of 2.68W/m^{2}k and above. Such walls will easily allow heat waves into the indoor environment in a climate such as found in South Eastern Nigeria. Studies show that energy savings of up to 30% can be achieved when external walls are properly designed to respond to the immediate climatic influences. Innovations involving novel envelope materials and design which has been proposed for similar climates needs to be studied in a Nigerian context. Application of insulation in warm humid climate with different structural materials is also a vast research area to explore.

The concept of ‘roof ventilation’ to capture recommendations by previous studies on the potentials of clear night sky radiant cooling for buildings in South Eastern Nigeria is another potential area for research and needs to be explored. There have been few researches (Ezekwe, 1986, 1990; Ogueke, Onwuachu, & Anyanwu, 2011; Okoronkwo et al., 2014) that have studied the circumstances of the sky cooling potentials in South Eastern Nigeria. The results from these studies have demonstrated potentials for the applicability of sky's capacity for cooling of buildings in Nigeria. However, there is a gap as these innovations have not been explored in any Nigerian building as an alternative to the customary window ventilation. There is therefore a large scope of research identified to investigate and apply the capacity of clear night sky radiant cooling as a means to supply cool and clean air into buildings at night. The identified research scope will also cover innovations to store excess coolth derived from overnight clear sky radiation into the building fabric to be later used for sensible cooling when it is needed.

Few researches have shown that the ground can provide sufficient cooling ability at certain depths (Florides & Kalogirou, 2007; Givoni & Katz, 1985; Jacovides et al., 1996; Jafarian, Jaafarian, Haseli, & Taheri, 2010; Kusuda, 1975; Mihalakakou et al., 1995; Pfafferott, 2004; Sanusi, 2012). This method of cooling for buildings has not been explored in any Nigerian environment. Hence, there is a vast scope of research in this area to verify its applicability in a Nigerian situation by concentrating for starts in the warm humid South Eastern Nigeria.

The South Eastern Nigeria has low wind speeds coupled with diurnal temperatures that are circa 6ºC. However, researches have shown that air movements can be induced using low energy fans or methods. Secondly, surface temperature of radiating bodies exposed to clear night sky can be reduced by up to 30ºC below the ambient. Therefore, another research scope is open to identify and harmonise air movements under radiating roof surfaces exposed to the clear sky for improved indoor conditioning which will also aim at charging strategically placed thermal walls for sensible cooling which will be harvested during peak periods. There is also a gap in the study area to harmonise day cooling by means of underground pipe ventilation and night cooling via clear night sky radiant cooling methods. Harmonsing both methods to work in a single system identifies another research opportunity. Most studies on radiant cooling have used water as the heat conveying fluid. Only few researches have tried to use air as a heat fluid (Parker, 2005; Parker et al., 2008). This study identifies a gap in this area and will attempt to achieve optimal heat transfer from radiating surfaces exposed to the sky into the building by using air as a heat exchange medium.

Further to this, the present study has identified many weaknesses in the architectural design of Nigerian buildings which are dominated by light weighted materials that hardly retain, resist or radiate heat effectively. Insulation in vital areas such as roofs and attics are lacking and most of the indoor spaces are unnecessarily large in volume. Therefore, additional research on these areas to incorporate architectural design and other passive design considerations such as natural ventilation, shading strategies, appropriate building orientation, size, shape and volume will be explored. Givoni (1998a) acknowledged that the effectiveness of clear night sky radiant cooling using the roof as a radiator by passing ambient night air into the building will depend on the roof material and the clearness of the sky and could be suitable for warm humid environments when the sky is clear. The use of effective sky temperature to increase the diurnal temperature swing to enhance night ventilation, and the use of coolth in the earth to supply cool breeze into the building during peak periods of the day could be optimized in a research prospect that will encourage the use of intelligent sensors to track the clearness of the sky and maintain ventilation through earth pipes at temperatures within the acceptable comfort limits.

Therefore, the primary goal of the current investigation is to evaluate the potential of two low carbon semi passive cooling systems as an alternative to the conventional mechanical air conditioning systems. This present study aims to fill the gap in the shortcomings identified by developing prototypes that could combine natural passive means with low energy active cooling applications in a mixed mode system, and in combination with 'fabric first' design approaches to optimize user comfort in Nigerian buildings.

3.14 Chapter Summary

The review of relevant studies has demonstrated that a proportion of required energy for cooling in buildings can be saved by the application of passive cooling strategies which in turn will reduce the rate of CO_2 emission. However, the efficiency of these approaches is limited to climate as they most times fail in maintaining indoor comfort in warm humid climates especially during the peak periods, hence active cooling systems such as air conditioners are becoming popular since they can deliver within comfort targets. The active systems of cooling have their shortcoming which are linked chiefly to environmental issues and expenses accrued to run them.

Some authors have taken the argument a step further by suggesting that the application of these passive solutions on a building with an enhanced fabric may further reduce energy use in such buildings. Mixed mode solutions have been found to be efficient in climates with limited air movements.

The principles and physics of heat gain, heat storage and heat loss, distribution and dissipation as it affects the building envelope, were reviewed in order to understand the thermo physical properties of building envelopes and materials. Some basic principles of air movement and the effects they have on user comfort and wellbeing was also identified. It was found that the nature of the building envelope affects the quality of comfort within such an enclosure. Other factors such air pollution, insects, dust, privacy and security were also identified as some reasons for limited use of openings (doors and windows) for natural ventilation in South Eastern Nigeria. The earth crust and Sky were identified as natural heat sinks applicable for passive cooling in buildings. Other heat sinks identified but classified as man-made are: heavily massed walls (thermal mass) and geo thermal piles in foundations.

Finally, comfort limits were identified and will be adopted as the target comfort parameters for this sub-region of Nigeria. The outcome of the review in this chapter provides the basis for which the field measurement and physical monitoring of existing situation in the study location is conducted.

4. ENERGY STATUS AND PERFORMANCE OF EXISTING BASE BUILDINGS: FIELD MEASUREMENTS

4.1 Introduction

This chapter studies the thermal potentials of existing buildings in the study area. The thermo-physical properties of typical construction practices will be described and assessed in the context of the climate on indoor temperature and humidity. The sky and soil thermal properties of the study area were also accessed to verify their potentials as reviewed in relevant literature.

4.2 Strategy for Field Measurement

The field-work plan is divided into 4 phases which are as follows: The first phase is a collection of (micro) primary measurements and data in the study area (ambient air temperature, outdoor humidity, indoor temperature, indoor humidity, ground temperature and sky temperature). Longitudinal spot measurements of temperature and humidity were taken in 3 residential buildings in 3 locations. These locations are in Enugu, Isuikwuato L.G.A and Port Harcourt. On the map, these locations run from the coastal region of Nigeria towards the Northern Part of Nigeria as shown in section 2.3.

The second phase of this research is to collect data from existing situation in the chosen location. Energy usage in the selected building types were also examined. Other variables identified are: the thermo-physical properties of the building fabric, including sizes and construction methods of walls, floors, roofs and ceilings, windows and doors.

The third phase is the strategic design of hybrid energy conservation systems that can integrate well with a ‘fabric first’ approach.

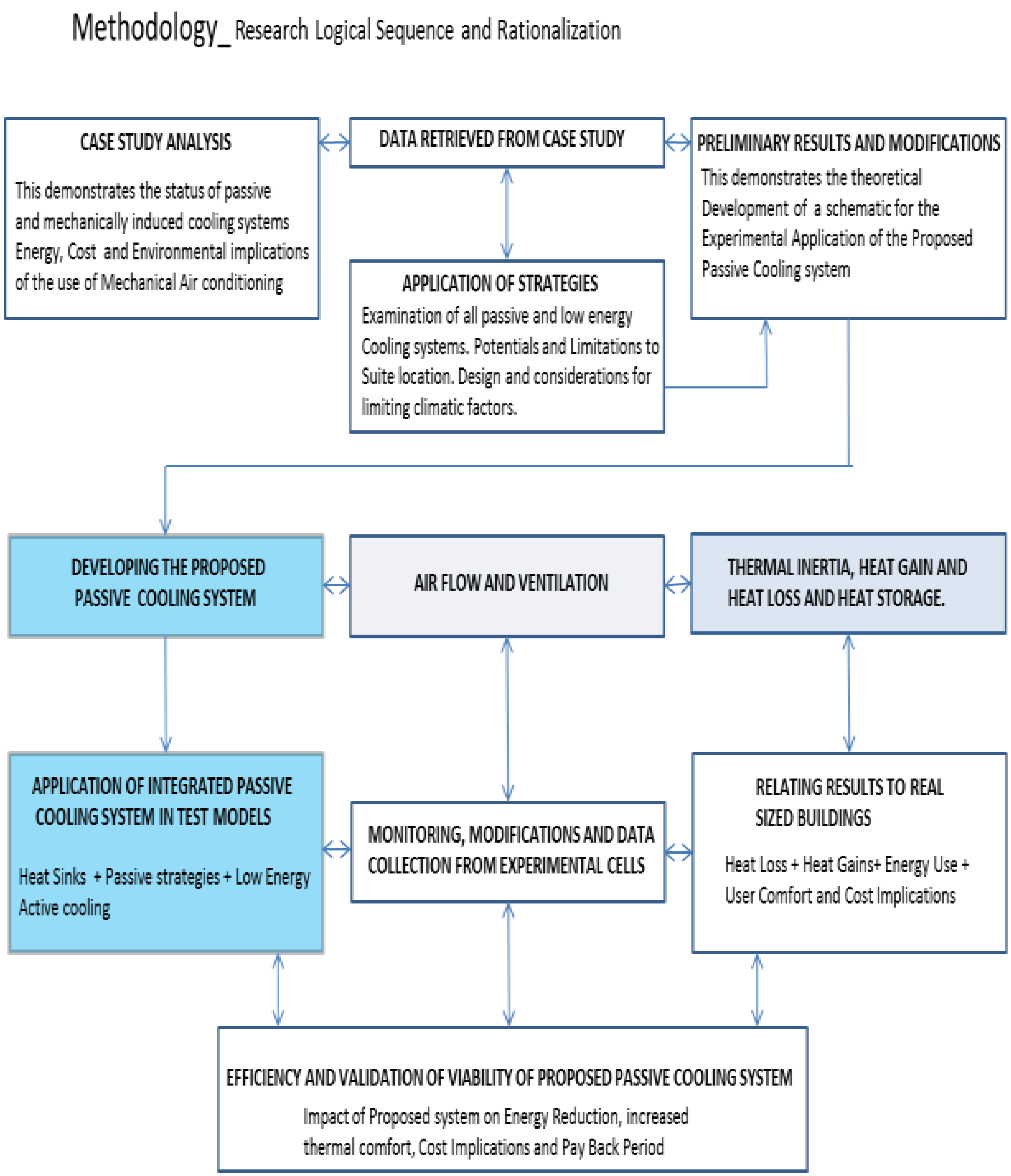


Figure 4. 1 Research Method and Approach to Data Collection from Field Work

4.3 Housing Availability and Affordability in Nigeria.

In 1991 an estimate of 700,000 housing units was projected to be constructed each year in Nigeria in order to alleviate housing shortage by the turn of the century (Vincent I Ogu & Ogbuozobe, 2001). Out of this figure, an average of 437,000 units was needed yearly in the urban areas. Twenty-eight years later, Nigeria's housing deficit still stands at 17 million units. To bridge this gap, the industry once again has estimated N59.5trillion (US$363 billion) in cost, which implies that 100,000 new houses[4] are to be built each year in Nigeria, as against the estimated demand of over700,000 units. The role of the Nigerian government to provide for housing over the decades have been faulted. Some researchers have offered comprehensive studies and arguments on the let-down of public housing in Nigeria (Agbola, 1990; Awotona, 1990; Etiosa et al., 2009; Ezinwanne Udechukwu, 2008; Ikejiofor, 1999; Vincent I Ogu, 1999; Ogunshakin & Olayiwola, 1992).

Unlike in most advanced countries where private firms play a major role in housing production, it is a different scenario in the Nigerian cities and sub urbans where individuals are responsible for the construction of a large percentage of houses, and most times these houses are casually built. In Benin City, one of the major urban centres in Nigeria, over 96% of the housing stock was delivered through private initiatives (Vincent Ifeanyi Ogu, 1996; Vincent I Ogu, 1999). Individuals, households, communities, small scale builders, firms and commercial estate developers/agencies are the leaders in most housing development in Nigeria (Vincent I Ogu & Ogbuozobe, 2001).

Unfortunately, the government at both the federal and state levels in the country tend to focus on public housing to the detriment of the private sector. For instance, in a document that focused essentially on promotion of public housing delivery efforts, encouragement of private sector involvement in housing development was the last of four-point objectives

[4]. If the Nigerian population continues at its annual growth rate of 3.5 percent, this becomes extremely insufficient because at least 700,000 – 1,000,000 units will be needed yearly to bridge the 17 - 20 million housing deficits by government's target date of 2033.

of the national housing policy, and out of 18 extensive strategies designed to realise the housing policy, only one was explicitly targeted to the private housing sector (Vincent I Ogu & Ogbuozobe, 2001). Individual self-help is the main source of housing development in the country. These categories of house developers: individual (self-help) owners, small-scale housing providers and housing firms are probably going to be major players in the housing process in the country in the future.

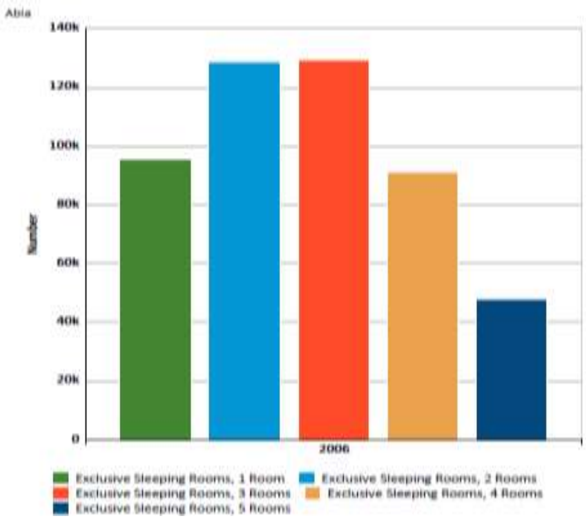
Nigeria's mortgage sector is still very small hence, loan is not a possibility for a greater number of Nigerians due to limited access. House ownership rate in Nigeria is about 25%, which is very low when compared to that of South Africa (56%), Kenya (73%), and Indonesia (84%). Inadequate access to finance, sluggish managerial procedures, and the high cost of land acquiring process are identified as some key issues against progressive housing in Nigeria (CAHF, 2018).

Given the various limitations, the predominant housing delivery method lies on a house by house basis, which in some cases, may take up to 10 years to complete. As such, the majority of homes in Nigeria are financed through personal savings, cooperative societies or inheritances. In addition, most households find it cheaper to buy lands at outskirts of major cities.

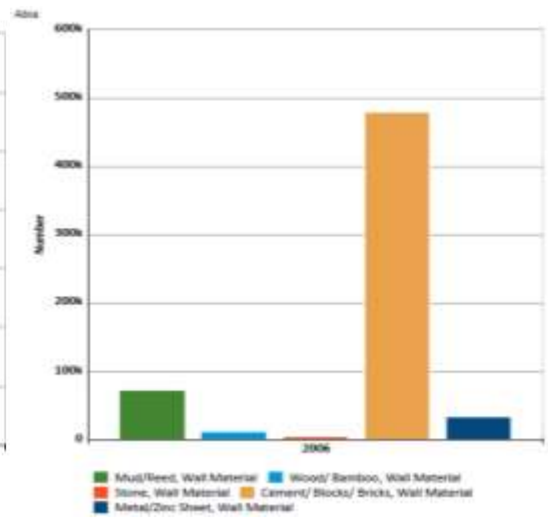
4.4 Buildings Typology, Ownership Profile and Selection Criteria

This section thus presents the predominant house types in the study area. It also presents the monitoring procedure of selected existing buildings in Ahaba Imenyi, focusing on the structure of the building envelope.

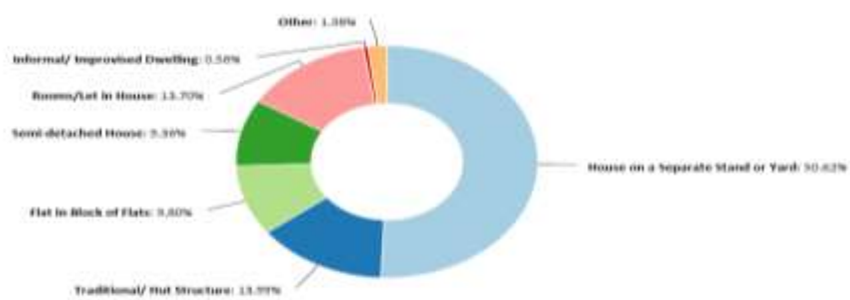
A vernacular building was also monitored because of its unique structure of heavy thermal walls. This was compared with a contemporary building with a 'light weight' fabric configuration. The results obtained produced the initial preliminary conclusions. Vernacular buildings in South-Eastern Nigeria are known for their ability to moderate the effects of the external environment without the use of any mechanical means. Small doors and window openings are typical of this type of architecture (Coch, 1998; Elleh, 1997; Fathy, 1986; Givoni, 1976; Meir & Roaf, 2005; Singh, Mahapatra, & Atreya, 2009).



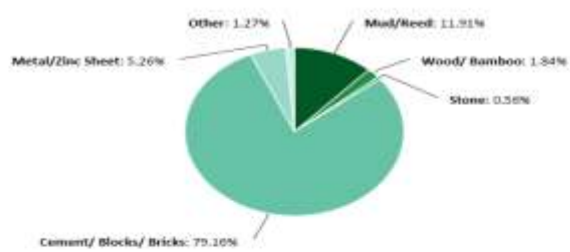
(a): Different House Types in Abia State, Nigeria (Knoema, 2012).



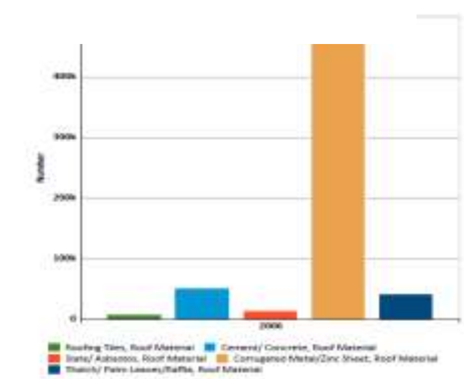
(b) Walling Material Inventory



(c): Households by Type of Housing Unit



(d): Common Walling Materials



(e): Roofing Materials

Figure 4. 2 An overview of housing stock in Abia State of Nigeria (Knoema, 2012).

On the other hand, contemporary buildings in the study area are built with lightweight walls and have larger door and window openings as well as floor areas. These buildings are generally known to follow the amplitude of the external climate more closely, hence large indoor temperature swings are common. They therefore mostly depend on some mechanical means for cooling for a significant part of the year (Givoni, 1994).

Fig 4.2 (a-e) presents an overview of housing stock in Abia State of Nigeria, in a survey carried out by Knoema (2012) showing predominant building types and construction materials. The common building types comprises of 1-bedroom units (95,000 units), 2-bedroom units (130,000 units), 3-bedroom units (135,000 units), 4 bedroom and 5 bedrooms 90,000 and 44,000 units respectively. 50.62% of these houses stand on a separate yard or fenced., while 13.99% are traditional huts mostly found in the villages. The graphs depict that the largest number of housing units are under the 3-bedroom category and followed by the 2-bedroom category both at above 120,000 units. The 1-bedroom apartments are also found to be more popular than the 4-bedroom apartments and the least popular is the 5-bedroom category. Under the building materials, the most commonly used material is cement, sandcrete blocks and bricks which represent 79%, while red mud for walling was at 11.9%, and metal roofs, stones and wood/bamboo were at 0.56%, 5.2% and 1.84% respectively, with other building materials around 1.27%.

There are different building typologies in the study area, mainly commercial and residential buildings. All the residential area within the study area are privately owned by individuals as a result of the flaws in public housing in Nigeria. Most of the residential buildings are bungalows because they are cheaper and easier to construct while maintaining luxury and durability (CAHF, 2018; Damilola, 2018).

Given all these factors especially that of affordability and quick access to shelter, bungalows are the predominant residential building type in the study area. Also considering the average family sizes, 2- and 3-bedroom bungalows are on the top rank of household types in the study area. This study will hence evaluate the thermophysical properties of a typical bungalow and will attempt to apply the results of a proposed passive cooling system on a modified bungalow fabric in Ahaba Imenyi.

4.5 The Experimental Set up and Measurement Methods

Measuring Tools

In order to monitor the temperature and humidity swings within the period of the experiment, temperature and humidity were measured with Tinytag Ultra 2 (TGU-4500) Gemini loggers, Figure 4.3. The temperature measurements will be taken for both external conditions (ambient) and the indoor conditions in all the test compartments.

Figure 4. 3 Tinytag Ultra 2 Temperature/Relative Humidity Logger (-25 to +85ºC, 0 to 95% RH)

TGU4500 has the capacity to record up to 32,000 readings. The reading resolution of temperature for the data logger is ±0.01ºC, while the reading resolution of the relative humidity is ±0.3%.

Testo 925 digital thermometer with thermocouple probes, (Figure 4.4) were used to measure surface temperatures of walls, roofs, ceilings, floors and all exposed surfaces of interest in the duration of the study. This gadget was also used to measure the temperature of the soil during the field work.

Infrared thermometer (Figure 4.5) was used to measure the sky temperature at intervals between early morning hours and late-night hours. Apart from late night and early morning measurements, daily sky temperature in the afternoon between 12pm and 3pm was also observed and recorded during the study. All measurements in the study area started in June 2014.

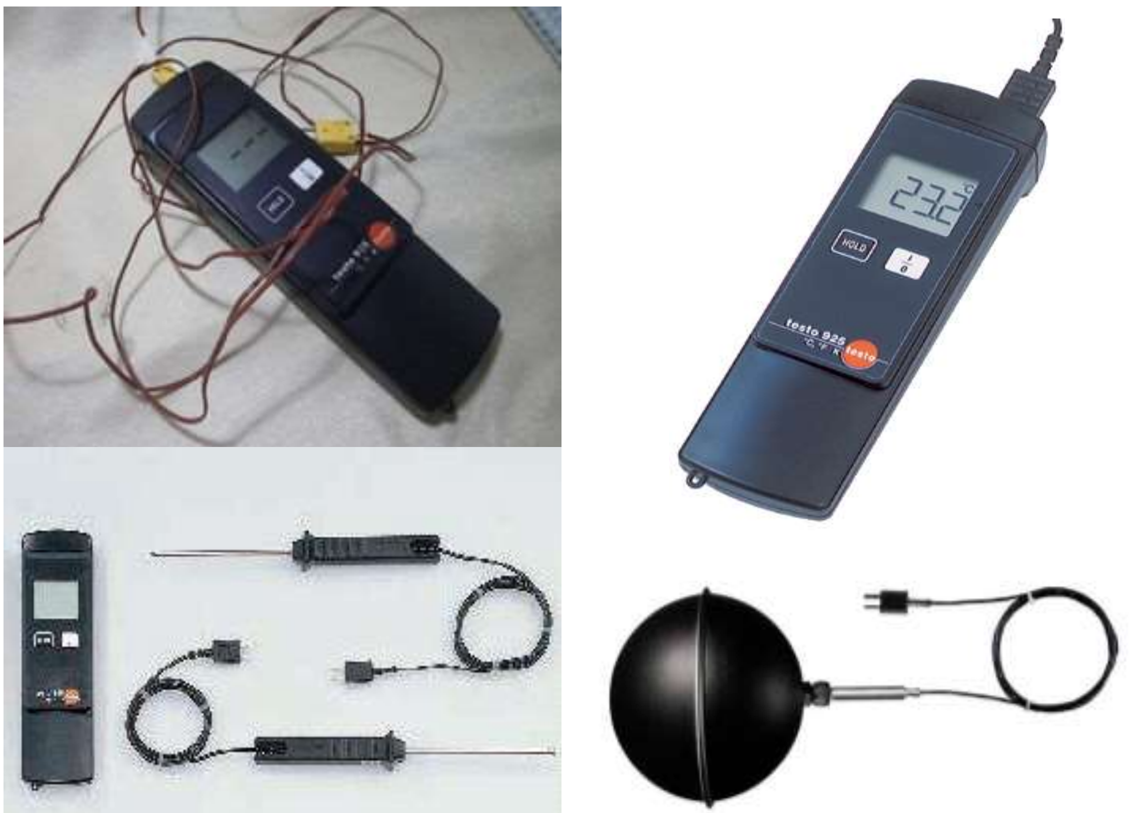


Figure 4. 4 Testo 925 Digital Thermometer: -50ºC to 1000ºC, Accuracy ±0.7ºC ± 0.5% (-40ºC / +900ºC, ±1ºC ± 1% (Remainder) showing Probes and a Globe sensor

Figure 4. 5 Digital Handheld Laser Infrared Thermometer. Temperature range: -32ºC to 1150ºC, Accuracy: ±1.5% or ±1.5°C, Spot Ratio: 20:1, Emissivity: 0.1 to 1.00 adjustable, Resolution: 0.1ºC, Response Time: 500ms, Wavelength: 8-14µm.

The following parameters were measured with Tinytag® data loggers, thermocouples and globe thermometer. Spot measurements were also taken for air velocity.

- Ambient air temperature and humidity (Tinytag® data loggers)
- Sky temperature (Digital Infrared Thermometer)
- Ground Temperature at different depths (Testo 925 Digital Thermometer)
- Indoor air temperature and humidity (Tinytag® data loggers)
- Air temperature at the attic space (Tinytag® data loggers)
- External wall surface temperature (Testo 925 Digital Thermometer)
- Internal wall surface temperature (Testo 925 Digital Thermometer)
- Partition surface temperature (Testo 925 Digital Thermometer)
- Ceiling surface temperature (Testo 925 Digital Thermometer)
- Floor surface temperature (Testo 925 Digital Thermometer)
- Roof surface temperature (Testo 925 Digital Thermometer)

4.6 Measurements of Existing situation in Study Area

Three locations in south eastern Nigeria were sampled namely Enugu, Port Harcourt and Ahaba Imenyi. It was necessary to choose one out of these three locations after comparisons between their climatic characteristics (ambient air temperature and outdoor RH). The test location chosen is in Ahaba Imenyi, a small village about 27.3 km from Okigwe. This location was chosen for easy access as it is in-between Enugu and Port Harcourt. The temperature and humidity readings of a 3-bedroom occupied bungalow is measured. The micro climate is also measured, and data is collected and analysed. The building was built in 1983.

4.7 Field Measurements: Micro Climate of Study Site

The sections below present the profiles of climatic data, soil and sky characteristics at the study site. The site measurements were carried out between June 2014 and September 2014. The results from the 3 locations were plotted alongside each other and there appeared to be a close similarity and agreement with the macro climate meteorological publications. However, closer observation showed some disparities in their individual characteristics.

The annual variations of soil temperature at various depths from January to December were studied. Comparisons were made between calculated values and measured values. Soil temperature at different depths were calculated using Kusuda Equation (2), the results were also compared with the mean ambient temperature.

This section also presents measured and calculated sky characteristics in Ahaba Imenyi. Data presented shows 7-day measured sky temperature readings each in the months of December (2015), January, February and June (2016) respectively. The coolest sky temperature measured on site was -9.0°C[5] in January. Mean sky temperature in January is -5.5°C in the early morning hours around 7am and -6.3°C around 11.30pm at night.

4.7.1 Ambient Temperature and Humidity of Study Site

On site measurements were taken for some climatic data and results are presented. Figure 4.6 presents temperature readings in 3 locations that was taken to ascertain their similarity with meteorological records. The graph shows similarities in daily temperature swings, however the outdoor temperature in Ahaba Imenyi is usually higher than Enugu by an average of about 1.5°C in the daytime, while at night the ambient temperature drops lower than that in Enugu and Port Harcourt. The outdoor temperature of Port Harcourt which lies in the Coastal region in southern Nigeria is circa 27.6°C in the daytime and at night it is around 25.6°C, the diurnal swing in this region is about 3°C. Enugu presents diurnal swings of up to 6°C while Ahaba Imenyi presents diurnal swings of up to 8°C in August. The diurnal swings in December and January can be as high as 22°C, with a gradual reduction from March onwards. The outdoor relative humidity was also measured. Figure 4.7 presents the relative humidity reading in the 3 locations namely Enugu, Port Harcourt and Ahaba Imenyi. The records show that humidity levels were highest in the nights in Ahaba, with readings as high as 96.1% at cool nights. This is followed by Enugu at 93.4%, and then Port Harcourt at 90.3%. Humidity levels in the afternoons are lowest at 61.9% in Ahaba, followed by Enugu at 66.6%, and then Port Harcourt at RH 77.8%. Ahaba Imenyi presents the largest diurnal temperature swing and the highest and lowest relative humidity at night and in the afternoon in the 3 locations respectively.

Due to proximity, limited funds and time constraint, measurements of soil and sky characteristics including the thermo-physical properties of building envelopes were

[5] Although these temperatures were obtained by point measurements at time 6 hourly intervals, there is great potential for even cooler sky temperature readings if an automatic logging device is employed to capture the effective sky temperature all through a week.

concentrated on Ahaba Imenyi to represent other warm humid regions within the South Eastern Nigeria.

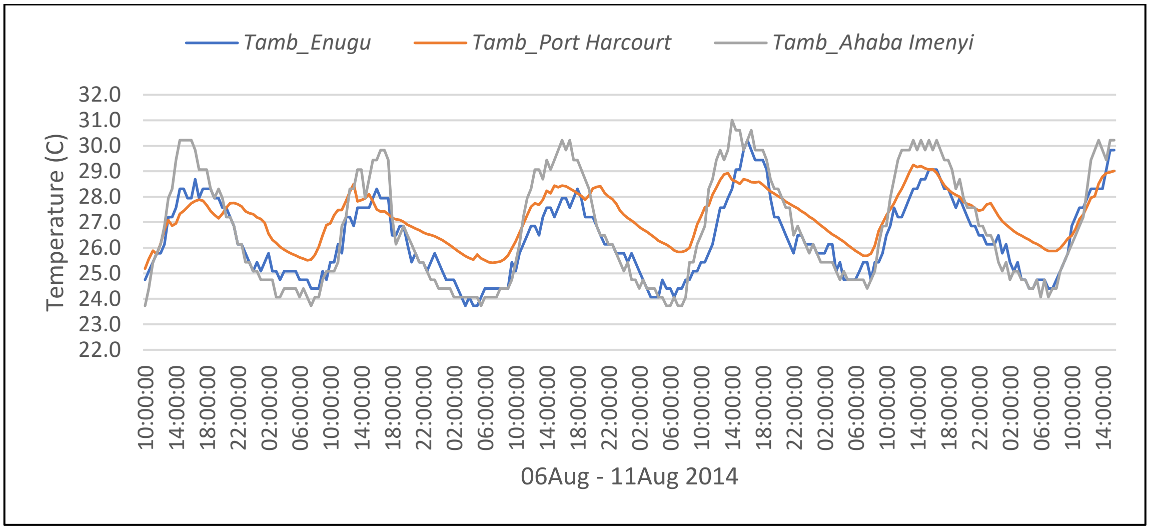


Figure 4. 6 Ambient air temperature reading in the month of August in Locations namely; Enugu, Port Harcourt and Ahaba Imenyi.

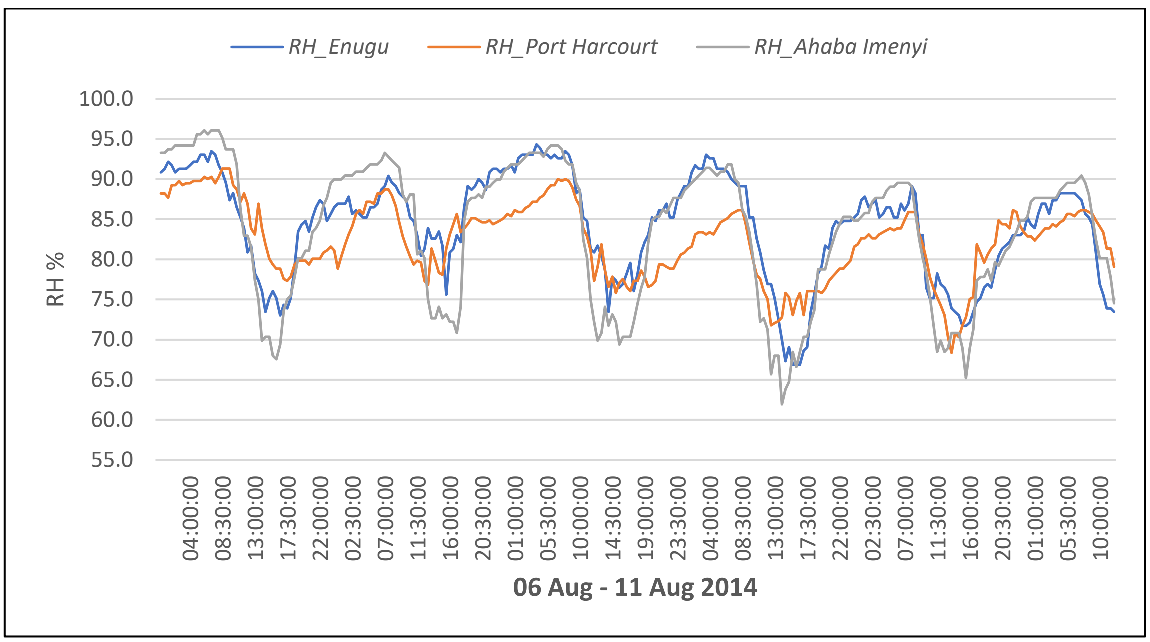


Figure 4. 7 Outdoor Relative Humidity reading in the month of August in 3 Locations namely; Enugu, Port Harcourt and Ahaba Imenyi.

4.7.1.1 Soil Condition and Characteristics of Study Site

The soil in any location has to be analysed for its unique characteristics such as physical appearance, heat regulatory quality (influenced by moisture content/water table) and ability to dampen the temperature amplitudes as depths increase below the surface. The undisturbed soil has the ability to maintain stable temperatures at depths up to 12m. The temperature amplitudes reduce as the depth increases (Kusuda, 1969, 1975; Kusuda & Achenbach, 1965).

There is not much documented temperature data of the soil beyond 0.5m in the study area hence, it was necessary to perform some tests and measurements to obtain the temperature profile at different depths and times. Hand drilling equipment was hired for a week and holes of 1m, 2m, 3m and 4m was drilled in a secured site. Probes were put in place at the base of each of these holes which were wired to the outside to connect to a Testo 925 Digital Thermometer (-50ºC to 1000ºC, Accuracy ±0.7ºC ± 0.5%), these holes were then covered with concrete slabs and earth to reduce the effects of sun's radiation on the readings. Weekly measurements were taken for a period of 12 months starting from January 2015 to December 2015.

The soil temperature of every location is affected by solar radiation, rainfall, ground cover/vegetation, soil type, and the thermo-physical properties of the soil.

The thermal conductivity of the soil determines the soil's ability to absorb heat from a source, retain, and release heat energy later to a cooler body or surrounding boundaries. The thermal conductivity and diffusivity of soil types found within the study area is presented in Table 4.1. In order to ascertain the soil temperature at different depths within the study area, a mathematical model known as "Kusuda Equation" developed by Kusuda and Achenbach (1965) is applied, see Equation (2). The soil temperature at depths of 1m to 4m was calculated from January to December by putting the climatic values in the equation. The results are presented in Fig 4.8.

Table 4. 1 Thermo-Physical properties of soil found within study area

Soil and rock	Thermal conductivity (w/m-k)	Thermal diffusivity (m^2 day^1)
Sandy soil (dry)	0.43 - 0.69	0.023
Sandy soil (moist)	0.87 – 1.04	0.044
Sandy soil (soaked)	1.9 - 2.42	0.065
Silty sand	1.4 - 1.72	0.056
Clayey sand	0.74 - 1.18	0.042
Clay soil (dry)	0.35 - 0.52	0.036
Clay soil (moist)	0.69 – 0.87	0.038
Clay soil (wet)	1.04 - 1.56	0.045
Gravel	0.9 – 1.25	0.047
Gravel (sandy)	2.51	0.079
limestone	1.3	0.044
Sandstone	1.63 – 2.08	0.059

At the depth of 1m, the mean soil temperature was 24.7°C in January and 25.6°C in December. The lowest soil temperature recorded at this depth was in February at 24.4°C and the highest soil temperature at this depth was in August at 30.5°C.

At 2m deep, the temperature of the soil was 25.5°C in January and 26.9°C in December. The lowest temperature at this depth was recorded in February and March at 25.5°C, while the highest soil temperature was recorded in August and September at 29.5°C.

The month of March presented the lowest soil temperature of 26.1°C at the depth of 3m, while it was at 28.9°C in September being the hottest recorded average temperature at that depth. In January 26.9°C and in December 27.7°C was recorded. At the depth of 4m the soil temperature was at an average of 27.5°C, and 28°C in December. The highest temperature reading was in October with an average of 28.5°C and the lowest reading was in April with an average soil temperature of 26.5°C.

A second experiment was carried out in the study area. This experiment aimed at verifying the results obtained from calculations at the different depths from 1m to 4m respectively. The results were aligned against each other and there was an obvious co-relation between the calculated values and the measured values. Average monthly soil temperature at each depth were plotted against the ambient temperature. The amplitudes dampened with increase in depth as argued by Kusuda and Achenbach (1965).

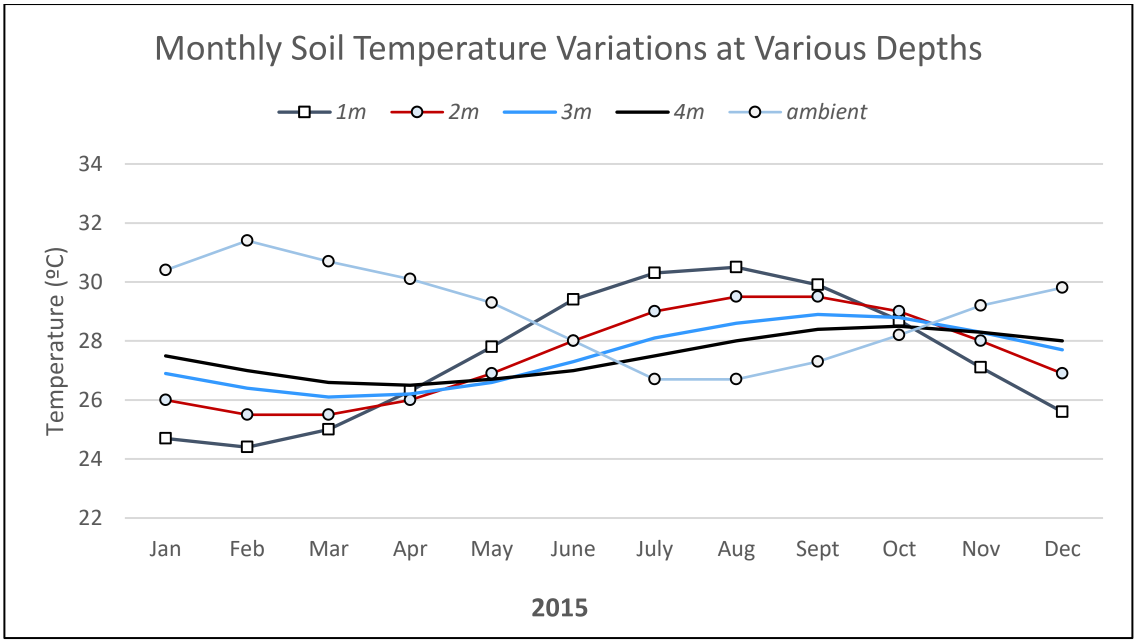


Figure 4. 8 Average monthly Soil Temperature at Various Depths in Ahaba Imenyi

Fig 4.9 presents a comparison of the calculated average monthly soil temperature and the measured soil temperature at a depth of 3m. There is an agreement in both curves. Although both results maintained almost the same shape, there were small disparities between the months of June and November where the calculated temperature gave higher values than the measured temperature.

Apart from the thermo-physical properties of a soil type, some other factors have been found to affect ground temperature. They include; water level, shading and vegetation cover, or by other materials such as rocks, which may protect the soil from direct impact of sun’s radiation.

In Poland, Popiel et al. (2001) compared the effects of covered and uncovered soils on temperature distributions at a depth of 1m. Results retrieved after analysis was in agreement with results of (Givoni, 2007; Jacovides et al., 1996; Mihalakakou, Santamouris, Asimakopoulos, et al., 1994) and showed that the covered soil was 4^{o}C cooler than the bare soil.

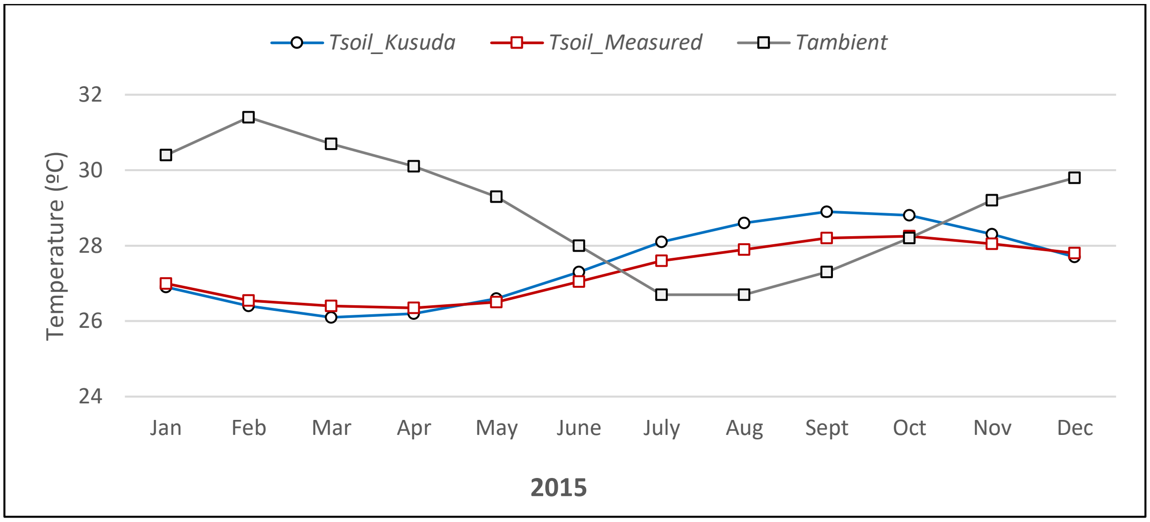


Figure 4. 9 Comparison between Measured Soil Temperature and calculated Soil Temperature at a depth of 3m

4.7.2 The sky condition and characteristics of Study Site

The sky is a natural heat sink that transfers heat by long-wave radiation. The clear dark sky temperature can be very close to absolute zero, when there are no obstacles like radiating gases, water vapor and dust. Higher temperature differences "ΔT" between the sky and ambient temperature increases the effective temperature or the cooling potential of the sky through heat radiation on exposed surfaces. Under clear sky conditions, the effective sky temperature can be 25˚C lower than ambient air (Bliss, 1961).

Some factors are known to affect the effective temperature of the sky and hence the cooling ability of sky for instance, water vapor and carbon dioxide concentrations and cloud cover (Paul Berdahl & Fromberg, 1982). Dew point and site conditions are among other micro conditions that may affect the effective temperature of the sky.

Clear skies are seen in the study area between November and March and these clear conditions last for about 4 months. December presents the clearest days in the year. During this period, the sky varies between clear, mostly clear and partly cloudy 47% of the time and mostly cloudy or overcast for the remaining 53% of the time.

The months of April to October presents cloudiest periods that lasts for about 8 months. During this period, the sky is cloudy 87% of the time and varies between clear, mostly clear or partly cloudy 13% of the time.

In order to understand what the average sky temperature within the study area is, the sky temperature was simulated through calculations using a formula proposed by J. H. Lienhard (2013) see equation (5), while the Goforth et al. (2002) modification of Swinbank formula was used to calculate the thermal down-welling sky irradiance as a function of temperature, relative humidity, cloud height, and percentage cloud cover with a claimed operational error of 9.7%, see equation (19).

Figure 4.10 presents the calculated results and measured results on 22nd December 2015, the results were plotted against each other. The graph shows some agreement between the two results. The measured sky temperature between 9pm and 7.30am was between 10.7^{o}C and 1.4^{o}C respectively, while that of the calculated sky temperature was 12.8^{o}C by 9pm and 3.2^{o}C by 7.30 am. Figure 4.11 presents a comparison between the calculated net radiation of the sky and measured results on 22nd December 2015. The graph shows some agreement between the two results. The down-welling of the measured sky radiation was between 79.2 W/m^2 and 87.5 W/m^2, between 9pm and 7.30am, the calculated net radiation of the sky was between 70.7 W/m^2 and 77.7 W/m^2, there was also an agreement between the calculated and the measured sky radiation.

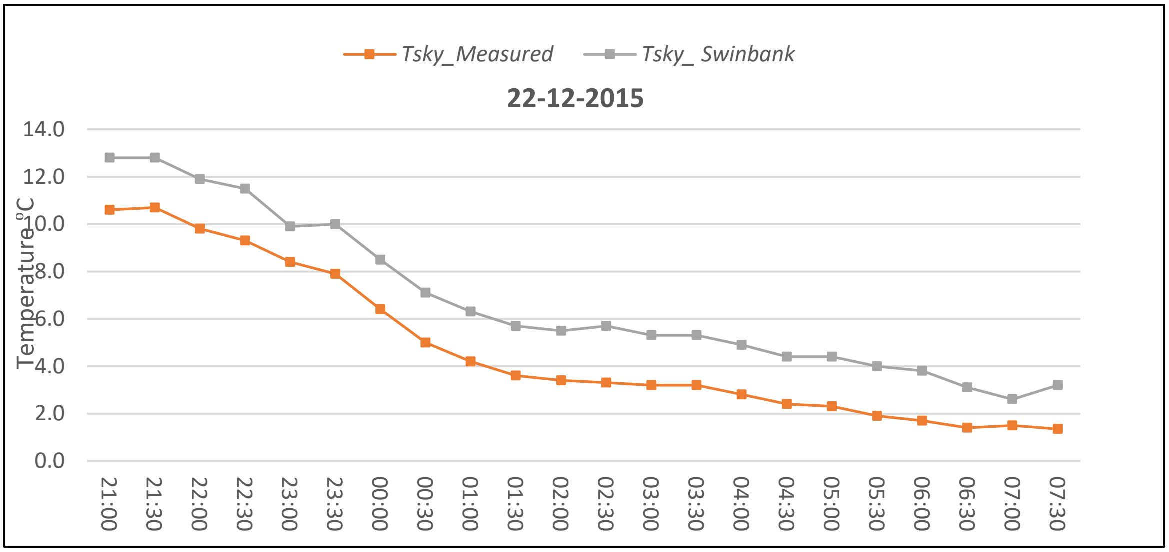


Figure 4. 10 Comparison between Measured and Calculated Sky temperatures

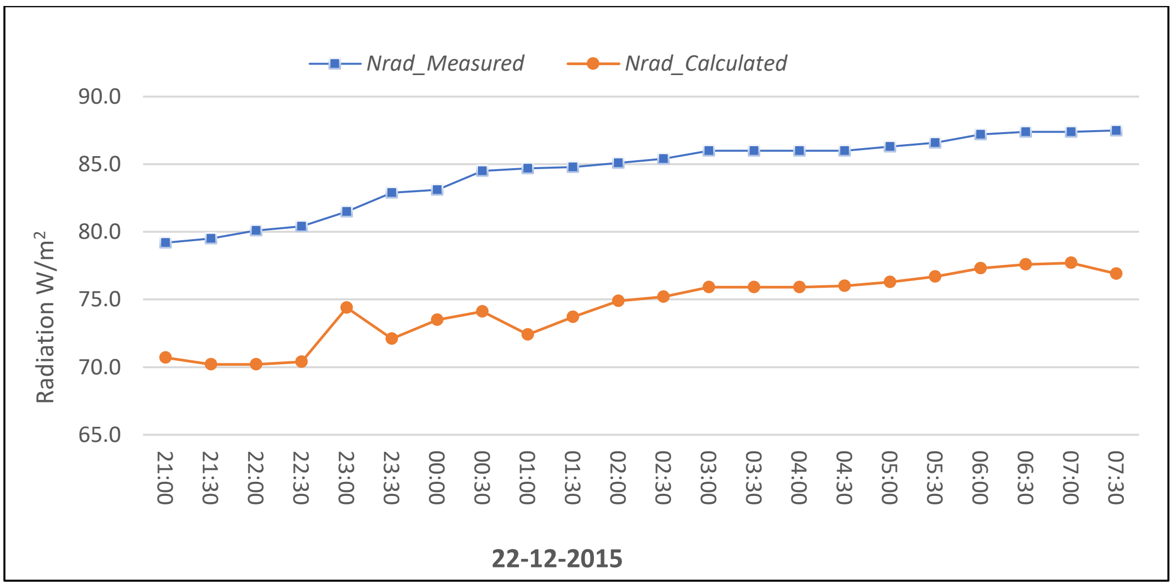


Figure 4. 11 Comparison between Measured and Calculated Sky downwelling

Fig 4.12 presents a screen display of different sky temperature readings on an infrared thermometer that was taken within the study area under different sky conditions. The lowest measured sky temperature throughout the study was -9°C in the morning of 1st January 2016. This measurement was taken when the sky was reasonably clear. The highest sky temperature recorded was 30.5^{o}C on the 9th and 10th of June 2016. The sky measurement is presented for the months of December 2015, January, February and June 2016 respectively, Figures 4.13 to 4.16. Readings were taken by 6am, 12pm and 12am during each batch of 7 days measurements. The first batch of sky temperature measurements was taken from 25/12/2015 to 31/12/2015, Figure 4.13.

Readings taken showed that the lowest sky temperature readings around 6am is at 1.4^{o}C on 27th, and highest reading was 13.5^{o}C on the morning of the 25th. The average sky temperature recorded in December was 4.5^{o}C at 6am. The measurements taken around 12pm revealed a much higher sky temperature between 18.7^{o}C and 21.2^{o}C. The average sky temperature in the month of December 2015 was 19.8^{o}C. Measurements taken by 12am presented much lower sky temperatures than those taken at 6am. The lowest sky temperature recorded at this time was 1.5^{o}C, while the highest temperature was 12.8^{o}C. The mean sky temperature recorded in 7 days in December around 12am was 3.97^{o}C.

Another batch of readings was taken in January 2016. The data was collected over a 7-day period starting from 01/01/2016 to 07/01/2016. The records presented in Figure 4.14 showed the lowest sky temperature readings around 6am at -7.8^{o}C, while highest reading was at -3.8^{o}C. The average sky temperature recorded in January around 6am was -5.5^{o}C. The measurements taken around 12pm revealed a much higher sky temperature in the January batch of measurements with the lowest at 13.8^{o}C and highest at 21.1^{o}C. The average sky temperature within the 12pm range in the month of January 2016 was 17.1^{o}C. Measurements taken at 12am presented much lower sky temperatures than the 6am. The lowest sky temperature recorded at this time was -9^{o}C, while the highest temperature was -4.8^{o}C. The mean sky temperature recorded in 7 days in January 2016 around 12am was -6.3^{o}C. The third batch of readings was taken in February 2016 and presented in Figure 4.15. The readings were taken over 7 days starting from 04/02/2016 to 10/02/2016. The lowest sky temperature readings at 6am was 10.8^{o}C, with the highest at 14.4^{o}C.

Figure 4. 12 Sky Temperature readings under various sky conditions using a Digital Handheld Laser Infrared Thermometer

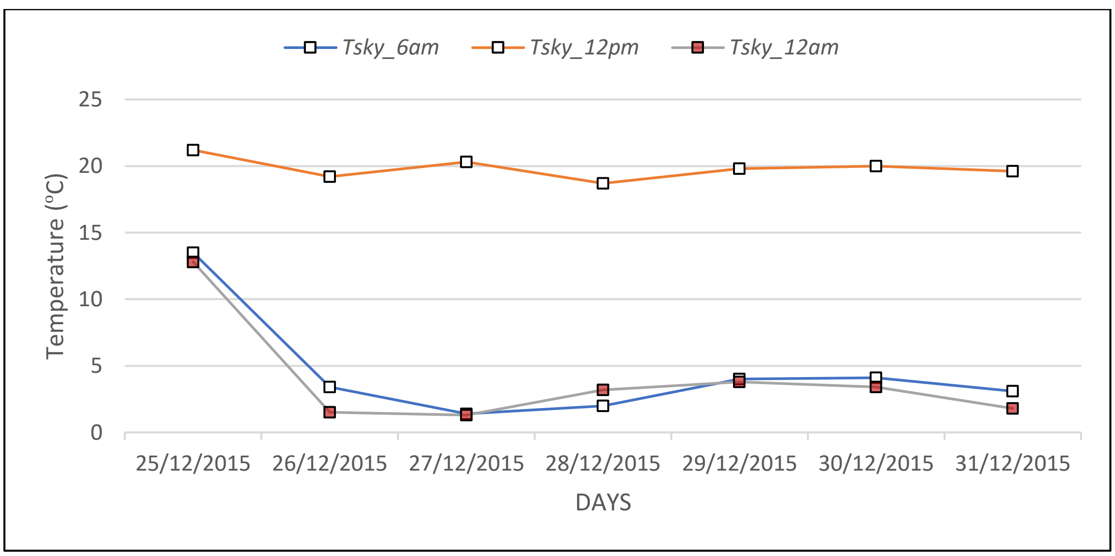


Figure 4. 13 Sky Temperature Fluctuations from 25/12/2015 to 31/25/2015

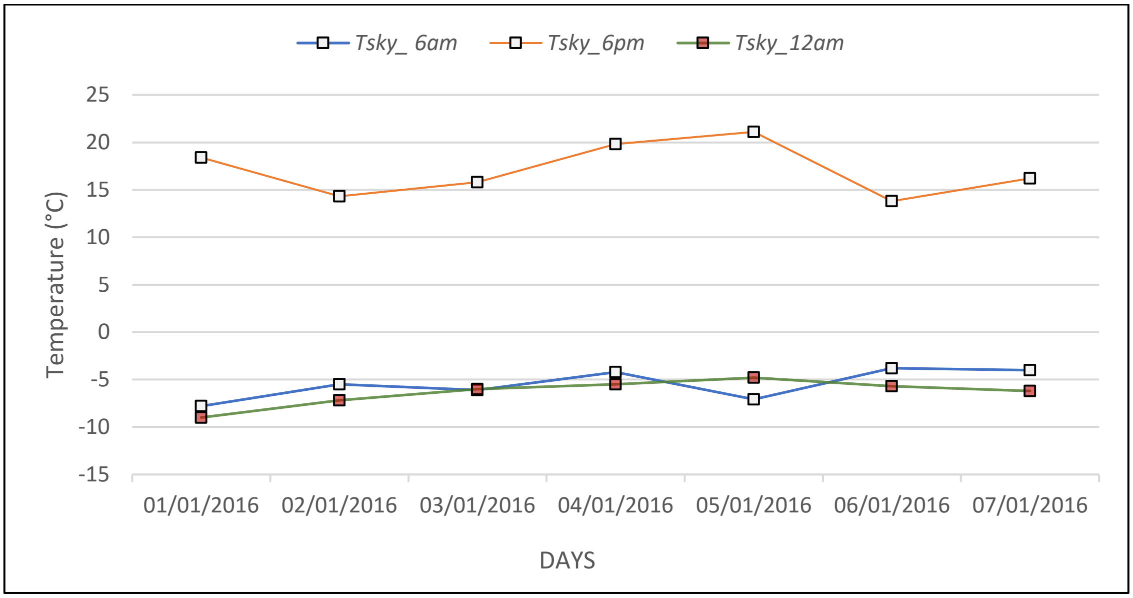


Figure 4. 14 Sky Temperature Fluctuations from 01/01/2014 to 07/01/2014

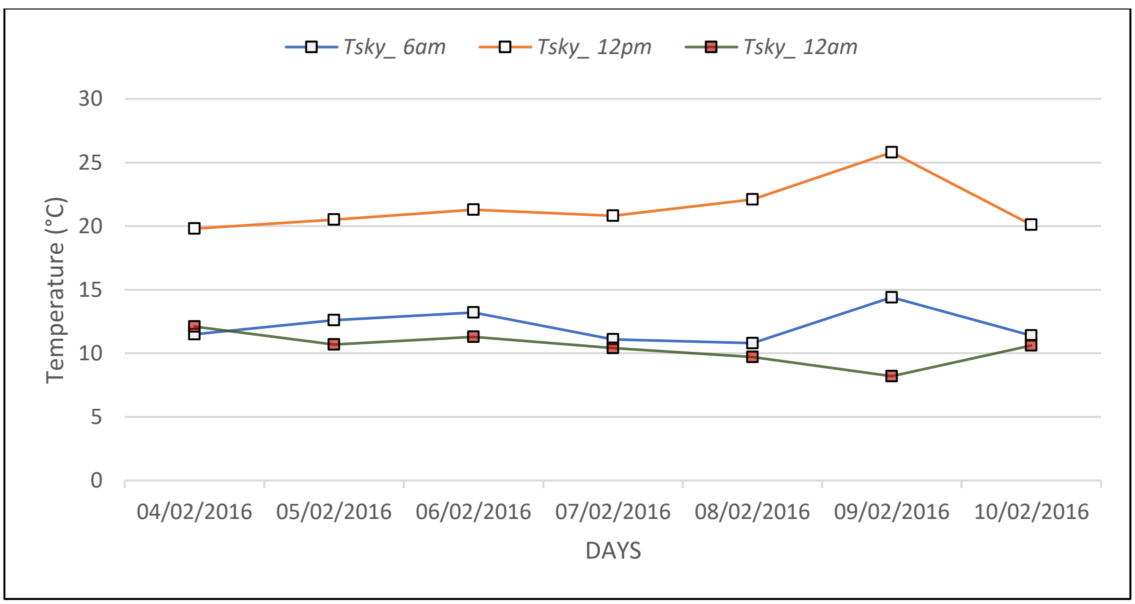


Figure 4. 15 Sky Temperature Fluctuations from 18/02/2015 to 25/02/2015

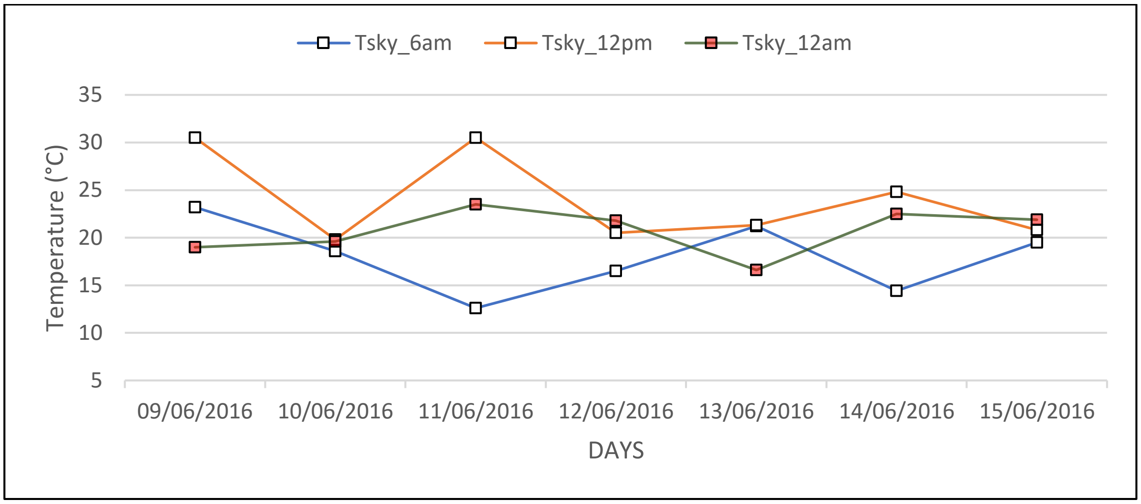


Figure 4. 16 Sky Temperature Fluctuations from 18/06/2015 to 25/06/2015

The average sky temperature recorded in February around 6am was 12.2°C. The measurements taken around 12pm revealed a much higher sky temperature as in the December and January. The lowest sky temperature recorded in the afternoon in February was 19.8°C and highest was 25.8°C. The average sky temperature within the 12pm range in the month of February 2016 was 21.5°C. Measurements taken at 12am as usual presented much more lower sky temperatures than the 6am batch of measurements. The lowest sky temperature recorded at this time was 8.2°C, while the highest temperature was 11.3°C. The mean sky temperature recorded in 7 days in February 2016 at 12am was 10.4°C.

Finally, Figure 4.16 presents a fourth batch of 7 days sky temperature readings that was taken in June 2016. The readings started from 09/06/2016 and lasted till 15/06/2016. The lowest sky temperature readings at 6am was 12.6°C, while the highest reading was 23.2°C. The average sky temperature recorded in June around 6am was 18°C. The measurements taken around 12pm had the lowest sky temperature recorded in the afternoon at 19.8°C and highest was 30.5°C. The average sky temperature within the 12pm range in the month of June 2016 was 24°C. Measurements taken at 12am were lower than the 6am average.

The lowest sky temperature recorded at this time was 16.6^{o}C, while the highest temperature was 23.5^{o}C. The mean sky temperature recorded in 7 days in June 2016 around 12am was 20.7^{o}C.

The sudden fluctuations (see Figure 4.15 and Figure 4.16) can be attributed to the effects of sky condition on effective sky temperature. These sharp drops and rises can be seen in all the graphs, however, it becomes more pronounced in the months of February and June, which agrees with the meteorological reports on cloudiness within the study area at these periods of the year.

The data presented in Figures 4.13 to 4.16 were further analysed using a statistical tool in excel known as "descriptive statistics". According to Investopedia (2018), *"descriptive statistics are brief descriptive coefficients that summarize a given data set, which can be either a representation of the entire or sample population."* Descriptive statistics are broken down into measures of central tendency (the mean, median, and mode), and measures of variability or spread (the standard deviation, variance, the minimum and maximum variables, and the kurtosis and skewness).

This tool was used to determine an upper and lower monthly mean sky temperatures for the months of December 2015, and for January, February, and June 2016 respectively. The results from the descriptive analysis are presented below. Tables 4.2 presents the results from the analysis for the months of January and February respectively. From the figures presented, it could be accepted that the mean sky temperature in the study area in the early morning hours (6am) in January ranges between -7^{o}C to -4.1^{o}C, while in the afternoon (12pm) it is between 14.5^{o}C and 19.6^{o}C and -8^{o}C and -5.1^{o}C at night usually between 10pm and 6am. From these results, it could also be said that January presents maximum mean sky temperatures in the afternoon at about 19.6^{o}C and in the mornings, it has minimum sky temperatures around -8^{o}C depending on the sky conditions. The month of February presents 10.9^{o}C to 13.3^{o}C in the mornings and 19.5^{o}C to 23.4^{o}C in the afternoons while at night, it ranges between 9.3^{o}C and 11.6^{o}C respectively. The monthly sky temperature range for the month of February according to results of descriptive statistics is between 9.3^{o}C and 23.4^{o}C.

The results for the months of June and December 2015 are presented in Table 4.3. Monthly sky temperature for June ranges between 14.5^{o}C and 28.4^{o}C with sky temperature swinging between 14.5^{o}C and 21.5^{o}C in the mornings, 19.7^{o}C and 28.4^{o}C in the afternoons and 18.5^{o}C and 23^{o}C at nights.

In the month of December, the sky temperature drops again as seen in Table 4.3. Morning hours present sky temperature swings of between 0.7^{o}C and 8.3^{o}C, and 19.1^{o}C to 20.6^{o}C in the afternoons while it drops again at night with temperatures ranging between 0.3^{o}C and 7.8^{o}C. The monthly sky temperature swing in December is between 0.3^{o}C to 20.6^{o}C Table 4.3.

The results from the descriptive statistics therefore show that the sky temperature can drop as low as -8^{o}C when the sky is clear and may rise to as high as 28.4^{o}C when the sky is overcast. The rise in sky temperatures occurs in the afternoons and may be attributed to other influences such as ambient temperature and the suns radiant energy. The low sky temperatures identified during this survey could be utilised overnight for indoor conditioning if black body roofing material is used. The results also suggest that although the sky in the month of June is mostly overcast, sky temperatures as low as 18^{o}C and 14^{o}C are attainable when the sky is partially clear. These temperatures are well below the ambient and can be used for radiant cooling of the building through the roof when such an opportunity for clear- sky cooling arises. This can be utilised if temperature sensitive thermostats are used to trigger active measures when sky temperatures provide a significant source of 'coolth'.

Table 4. 2 Results from a Descriptive Statistics Analysis Showing Upper and Lower Sky Temperature limits in the Mornings, Afternoons and at Night for the Months of January and February 2015

		January			
Morning (°C)		*Afternoon(°C)*		*Night(°C)*	
Mean	-5.5	Mean	17.05714286	Mean	-6.34285714
Standard Error	0.598410593	Standard Error	1.048776417	Standard Error	0.521836109
Median	-5.5	Median	16.2	Median	-6
Mode	#N/A	Mode	#N/A	Mode	#N/A
Standard Deviation	1.583245612	Standard Deviation	2.77480158	Standard Deviation	1.380648571
Sample Variance	2.506666667	Sample Variance	7.69952381	Sample Variance	1.906190476
Kurtosis	-1.616833126	Kurtosis	-1.461093786	Kurtosis	1.887913356
Skewness	-0.352410342	Skewness	0.338622097	Skewness	-1.31304982
Range	4	Range	7.3	Range	4.2
Minimum	-7.8	Minimum	13.8	Minimum	-9
Maximum	-3.8	Maximum	21.1	Maximum	-4.8
Sum	-38.5	Sum	119.4	Sum	-44.4
Count	7	Count	7	Count	7
Confidence Level(95.0%)	1.464257972	Confidence Level(95.0%)	2.566263444	Confidence Level(95.0%)	1.276886961
upper	-4.035742028	upper	19.6234063	upper	-5.06597018
lower	-6.964257972	lower	14.49087941	lower	-7.6197441

		February			
Morning (oC)		*Afternoon(oC)*		*Night(oC)*	
Mean	12.14285714	Mean	21.48571429	Mean	10.42857143
Standard Error	0.49466542	Standard Error	0.775035659	Standard Error	0.46686099
Median	11.5	Median	20.8	Median	10.6
Mode	#N/A	Mode	#N/A	Mode	#N/A
Standard Deviation	1.308761683	Standard Deviation	2.05055161	Standard Deviation	1.235198075
Sample Variance	1.712857143	Sample Variance	4.204761905	Sample Variance	1.525714286
Kurtosis	-0.284852473	Kurtosis	4.089497448	Kurtosis	1.282989662
Skewness	0.889431126	Skewness	1.942971375	Skewness	-0.755114
Range	3.6	Range	6	Range	3.9
Minimum	10.8	Minimum	19.8	Minimum	8.2
Maximum	14.4	Maximum	25.8	Maximum	12.1
Sum	85	Sum	150.4	Sum	73
Count	7	Count	7	Count	7
Confidence Level(95.0%)	1.210402678	Confidence Level(95.0%)	1.896443938	Confidence Level(95.0%)	1.142367688
upper	13.35325982	upper	23.38215822	upper	11.57093912
lower	10.93245446	lower	19.58927035	lower	9.28620374

Table 4. 3 Results from a Descriptive Statistics Analysis Showing Upper and Lower Sky Temperature limits in the Mornings, Afternoons and at Night for the Months of June and December 2015

		June				
Morning (oC)		*Afternoon(oC)*			*Night(oC)*	
Mean	18	Mean	24.02857143		Mean	20.7
Standard Error	1.416400535	Standard Error	1.776528756		Standard Error	0.90816403
Median	18.6	Median	21.3		Median	21.8
Mode	#N/A	Mode	30.5		Mode	#N/A
Standard Deviation	3.747443573	Standard Deviation	4.700253286		Standard Deviation	2.402776172
Sample Variance	14.04333333	Sample Variance	22.09238095		Sample Variance	5.773333333
Kurtosis	-0.987971494	Kurtosis	-1.434933626		Kurtosis	-0.24919302
Skewness	-0.135353606	Skewness	0.829130587		Skewness	-0.74551466
Range	10.6	Range	10.7		Range	6.9
Minimum	12.6	Minimum	19.8		Minimum	16.6
Maximum	23.2	Maximum	30.5		Maximum	23.5
Sum	126	Sum	168.2		Sum	144.9
Count	7	Count	7		Count	7
Confidence Level(95.0%)	3.465807256	Confidence Level(95.0%)	4.347009268		Confidence Level(95.0%)	2.222197327
upper	21.46580726	upper	28.3755807		upper	22.92219733
lower	14.53419274	lower	19.68156216		lower	18.47780267
		December				
Morning (oC)		*Afternoon(oC)*			*Night(oC)*	
Mean	4.5	Mean	19.82857143		Mean	3.971428571
Standard Error	1.546424447	Standard Error	0.302933503		Standard Error	1.518569861
Median	3.4	Median	19.8		Median	3.2
Mode	#N/A	Mode	#N/A		Mode	#N/A
Standard Deviation	4.091454509	Standard Deviation	0.801486714		Standard Deviation	4.0177582
Sample Variance	16.74	Sample Variance	0.642380952		Sample Variance	16.14238095
Kurtosis	5.753947434	Kurtosis	0.671544966		Kurtosis	5.678777812
Skewness	2.314291209	Skewness	0.449331756		Skewness	2.313618366
Range	12.1	Range	2.5		Range	11.5
Minimum	1.4	Minimum	18.7		Minimum	1.3
Maximum	13.5	Maximum	21.2		Maximum	12.8
Sum	31.5	Sum	138.8		Sum	27.8
Count	7	Count	7		Count	7
Confidence Level(95.0%)	3.783964307	Confidence Level(95.0%)	0.74125158		Confidence Level(95.0%)	3.715806589
upper	8.283964307	upper	20.56982301		upper	7.68723516
lower	0.716035693	lower	19.08731985		lower	0.255621983

4.8 Building Fabric Composition and Characteristics

The building fabric is a vital component of the building as it serves as a control for a more stable indoor thermal environment.

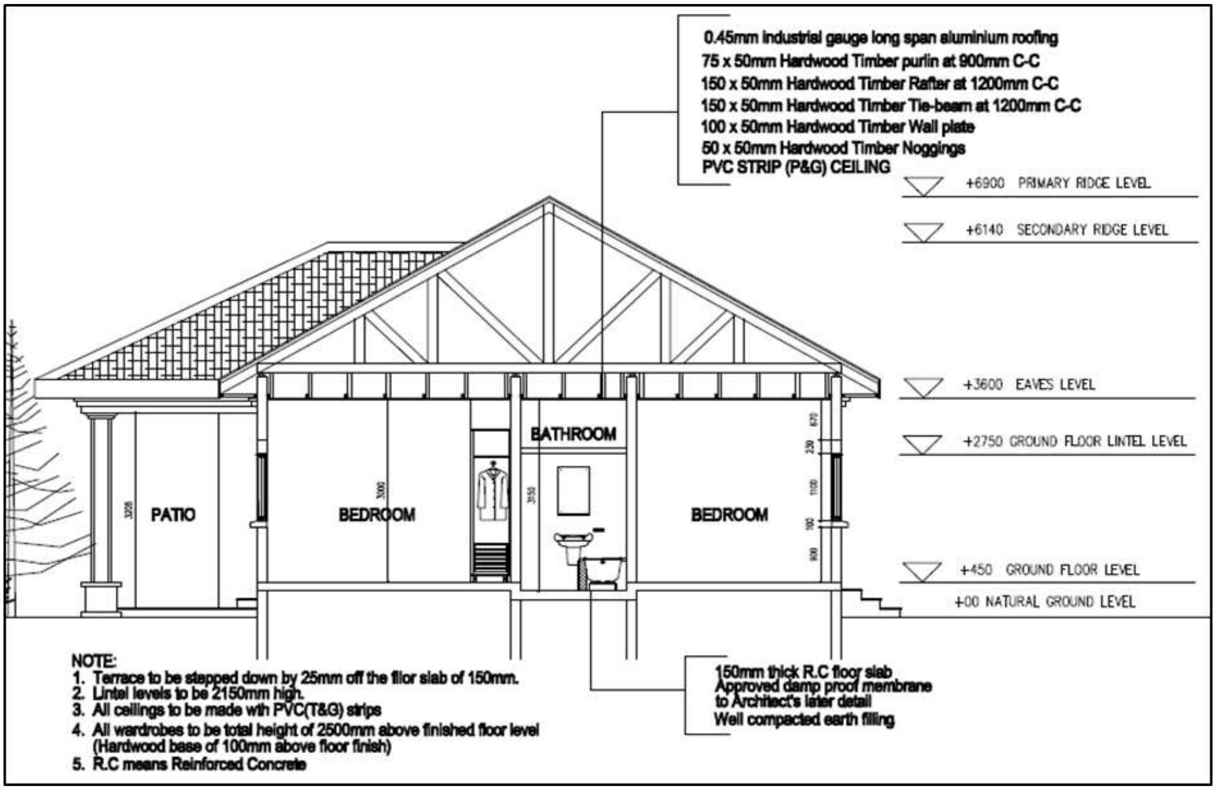


Figure 4. 17 Section of a Typical Bungalow in Ahaba Imenyi.

Measuring the external wall surface temperature will provide data for this study on time lag (capacitance and thermal inertia). The influence and the effects of the external walls on their ability to moderate the effect of the surrounding environment can be harnessed to reduce the amplitude of temperature fluctuations. Measurements of internal wall temperatures will provide data for the analysis of internally generated heat gains and their effect on the indoor environment. Air temperature measurements in the attic space will provide data for the intensity/analysis of the effects of the sun's radiation. Heat accumulation and the amount of heat dissipated from the roof attic to the occupied space below through the ceiling layer can also be ascertained.

There are two types of buildings found in the study area namely: the vernacular buildings which feature clay as the main walling material, timber for columns and thatch for roofs. This type of building is popularly known as thatched or mud houses. They are constructed with thick walls made of clay that measure between 300mm – 400mm and are sometimes reinforced with wooden stakes. Other features of this type of vernacular building are very small windows and doors made from wood. The buildings are predominantly rectangular and lack any ceilings. The roof is made from woven raffia palms. The walls have a measured U-value between 1.16 W/m^2K and 1.01 W/m^2K, while the thatch at 250mm thickness has a U-value of 1.28 W/m^2K.

Figure 4.17 presents a section of a typical contemporary building in the study area. The walls comprise of sandcrete blocks laid with fine mixtures of cement mortar, which are further fortified with reinforced concrete columns and beams. These walls are built in 3 layers that includes: 25 mm thick exterior cement plaster, 150 mm thick solid sandcrete blocks, and 25 mm thick cement plaster in the interior. The total thickness of the wall is 200mm and it has a U-value of 2.68 W/m^2K. The same material is used for the construction of the partition walls.

The roof is made from corrugated aluminum (U-value of 2.13 W/m^2K) laid on wooden purlins and rafters. The roof attic space is usually not deep hence the slope of the roof is considerably gentle as shown in figure 3.30. Externally, the roof has an eaves overhang of 600 mm running around the perimeter walls of the building. The ceiling material is usually asbestos ceiling boards[6] and they have a U-value of 1.86 W/m^2K.

[6] Nigeria still uses asbestos as a ceiling material – This building material is found rampantly in Nigeria's building materials market despite urges from UN to the Federal Government of Nigeria to ban its use as in most other countries

The ratio of wall to floor area is presented in Table 4.4. The total number of users in the measured building is four (4).

Table 4.5 presents the thermo physical properties of some common building materials found in the typical contemporary Nigerian dwelling.

Table 4. 4 Room data and Ratio of Envelope to floor area in Case building

PARAMETER	ROOM 2	MASTER'S ROOM	LOUNGE
Floor Area (m2)	9	12.96	20.16
Ceiling Area (m2)	9	12.96	20.16
Window Area (m2)	2.16	2.16	4.68
Glazed Area (m2)	-NIL-	-NIL-	-NIL-
Openable Area (m2)	2.16	2.16	4.68
Internal Surfaces (m2)	50.4	64.08	88.92
External Surfaces (m2)	16.2	11.34	24.3
Room Volume (m3)	24.3	34.02	54.43
Number of Users	1	1	2
Building Orientation	NW	NW	NW
Glazing to Floor Area	-NIL-	-NIL-	-NIL-
Opening to Floor Area	0.24	0.17	0.23
Wall surface to internal floor	3.6	3.08	2.41
Mass surface to external floor	1.8	0.9	1.21

Table 4. 5 K, R and U-values of various building materials (Givoni, 1998a)

	Common Building Materials in the density of (100 kg/m³)	Conductivity (K Value) (W/mK)	Resistance (R-Value) (M²K/W)	Transfer (U-Value) (W/m²k)
Walls	Brickwork (outer leaf)	0.045	2.22	0.45
	Brickwork (inner leaf)	0.033	3.03	0.33
	Lightweight aggregate concrete block	0.040	2.50	0.40
	Concrete hollow block	0.030	3.33	0.30
	Red clay hollow block	0.026	3.84	0.26
	Concrete (medium density)	0.062	1.61	0.62
	Reinforced concrete (2% steel)	0.104	0.71	1.04
	Mortar (protected)	0.050	2.00	0.50
	Mortar (exposed)	0.053	1.88	0.53
	Gypsum	0.030	3.33	0.30
	Sandstone	0.088	1.13	0.88
	Limestone (soft)	0.061	1.63	0.61
	Limestone (hard)	0.077	1.29	0.77
Surface Finishes	Plasterboard	0.030	3.33	0.30
	Fibreboard	0.025	4.00	0.25
	Tiles (ceramic)	0.056	1.78	0.56
	External sand-cement rendering	0.076	1.31	0.76
	Plaster (dense)	0.043	2.32	0.43
	Plaster (lightweight)	0.030	3.33	0.30
Floors & Roofs	Solid concrete slab	0.032	3.12	0.32
	Hollow core concrete slab	0.028	3.57	0.28
	Tiles (clay)	0.050	2.00	0.50
	Tiles (concrete)	0.071	1.41	0.71
	Wood wool slab	0.020	5.00	0.20
Insulation Materials (100 mm thickness)	Glass Fibre	0.032-0.044	3.10-2.25	0.32-0.44
	Rock Fibre	0.035-0.044	2.85-2.25	0.35-0.44
	Sheep's Wool	0.042	2.38	0.42
	Expanded Polystyrene (EPS)	0.036	2.77	0.36
	Extruded Polystyrene (XPS)	0.029-0.036	3.44-2.77	0.29-0.36
	Polyurethane Foam Board (PUR)	0. 22-0.29	4.45-3.44	0.22-0.29
	Polyisocyanurate Foam Board (PIR)	0.021-0.022	4.76-4.54	0.21-0.22
	Phenolic Foam Board	0.021	4.76	0.21

Table 4. 6 Thermo-physical Properties of a typical contemporary building envelope in the study area

COMPPONENT	THICKNESS (mm)	INSULATIONn (mm)	MATERIAL	U-VALUE	THERMAL RESISTANCERESISTANCE (m_2K/W)	CONDUCTIVITY
ROOF				**2.13**		
Aluminium	12	None	Aluminium sheets		0	205
CEILING	12	None		**1.82**		
Asbestos			Asbestos ceiling Boards			0.15
WALLS				**1.67**		
External Wall	200	None			**Internal Surface= 0.13**	
					External Surface = 0.04	
plaster	25		Mortar		0.156	0.16
Block Exposed	150		Sandcrete Block (solid)		0.124	1.21
plaster	25		Mortar		0.156	0.16
Internal Wall	200	None		**1.67**	**Internal Surface= 0.13**	
					External Surface = 0.04	
plaster	25		Mortar		0.156	0.16
Block Exposed	150		Sandcrete Block (solid)		0.124	1.21
plaster	25		Mortar		0.156	0.16
FLOOR		None		**0.68**		
Plaster	25		Cement Sanscreed		0.156	0.16
Concrete	150		Mass Concrete		0.125	1.2
Soil	900		Top Soil for Filling		0.72	1.25

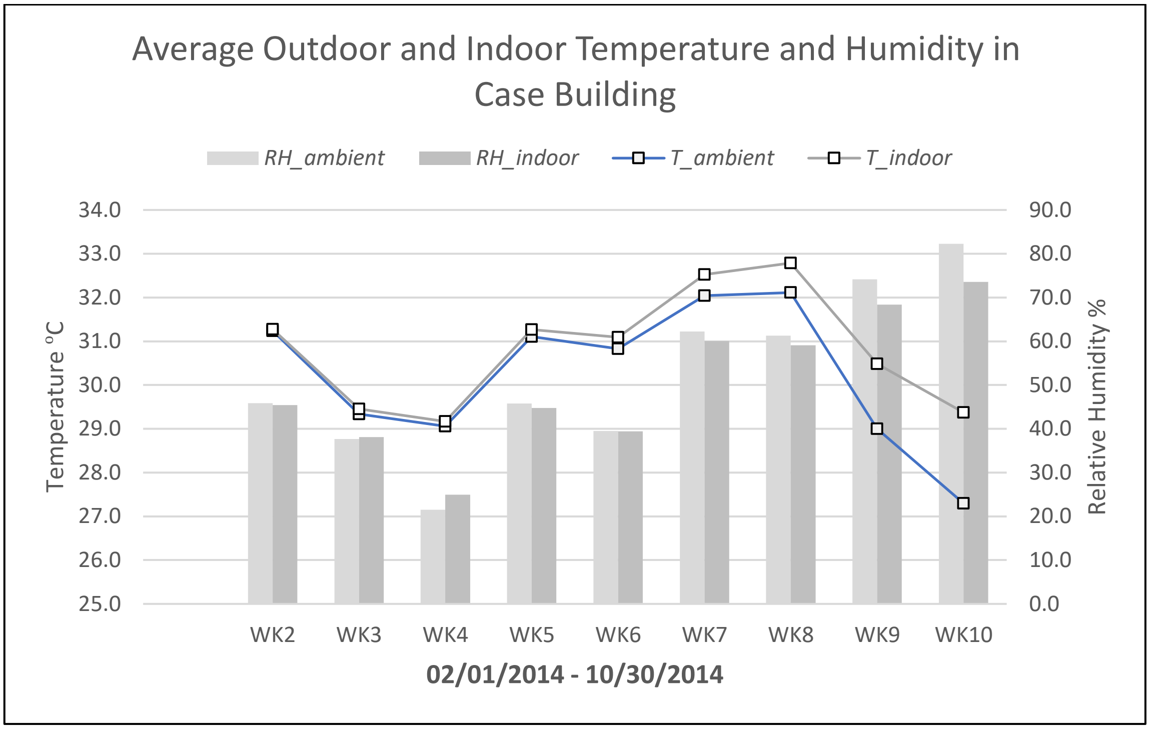


Figure 4. 18 Average Outdoor and Indoor temperature and Humidity in Case Building from 20/01/2014 to 10/03/2014

Figure 4.18 presents a graphical illustration of results from site measurements carried out in the selected 3-bedroom bungalow in the study area. Average weekly indoor and outdoor temperatures and humidity for a 9-week period starting from 02/01/2014 to 10/03/2014 are plotted. The highest weekly ambient temperature was recorded in week 7, when the average ambient was 32ºC and the indoor temperature was 32.5ºC, and in week 8 when the average indoor temperature was 32.8ºC and the average weekly ambient was 32.1ºC. There was a steep fall in average weekly temperatures in weeks 9 (ambient = 29ºC, indoor = 30.5ºC) and 10 (ambient = 27.3ºC, indoor = 29.4ºC). The relative humidity was lowest in week 4 when the outdoor RH was 21.5% and the corresponding indoor RH was at 25%, however there was a gradual rise in RH till week 10 which had an outdoor reading at 82.3% and an indoor reading at 73.6%.

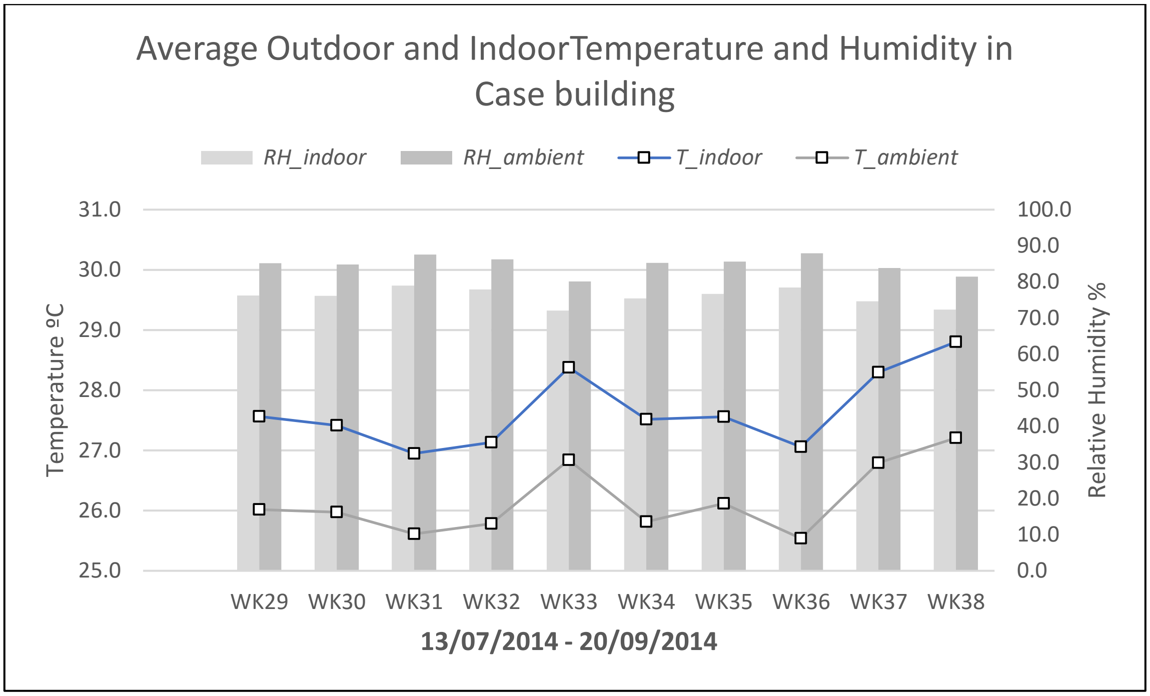


Figure 4. 19 Average Outdoor and Indoor temperature and Humidity in Case Building from 13/07/2014 to 20/09/2014

The RH levels were high in weeks 9 and 10 and there was a large variation between the ambient and the indoor temperature. The drop in the indoor temperature could be noticed from week 6 to 10 as the outdoor and indoor RH increases. This could be attributed to the influence of the building fabric on the regulation of heat/gain in the indoor environment.

Another survey was carried out between July and September Figure 4.19. The measurements lasted for 10 weeks starting from 13/07/2014 to 20/09/2014. A comparison between the results in Figure 4.18 and that in Figure 4.19, shows an increase in RH levels as the weeks progress and a gradual drop in ambient and indoor average weekly temperatures. The outdoor RH ranged from 80.1% to 87.9%, while the indoor average weekly RH was also high and was between 72% and 79%. This period presented lower ambient temperatures that ranged from 25.5ºC to 27.2ºC, while the indoor temperature was between 26.9ºC in week 31 and 28.8ºC in week 38. This observation can be linked to the cooler environment associated with the rainy seasons.

4.8.1 Thermal moderation of the building fabric in case buildings

Diaz (1994) applied a method known as **Temperature Swing Ratio** (TSR) and the **Peak Temperature Difference** (DT_{max}) as analytical indices to study and determine how the building responds thermally to effects due to external temperature changes. These indices allow for the observation on the effects of the building thermal mass by neglecting the resultant temperatures.

TSR, is a quotient of the external and internal temperature swings within a 24-hr period. It identifies the extent to which a thermal mass can modify internal temperature because of external temperature diurnal variations. When the TSR = 1, it implies that the external and the internal temperatures are the same and hence the swing is zero. Figure 4.20 shows a graphical definition of TSR and DT_{max}. TSR, may help in the understanding of thermal characteristics of a building and thermal comfort.

$TSR = T_{so}/T_{si}$

$DT_{max} = T_{o}\,(max) – T_{i}\,(max)$

Where DT_{max} is defined as the difference between the maximum outdoor temperature and the maximum indoor temperature. It is the ability of the building fabric to regulate external temperature when they are at their peak. DT_{max} is most commonly applied when cooling of the indoor is the target of study. Both indices allow for comparisons between buildings regardless of location or the period the measurement was taken.

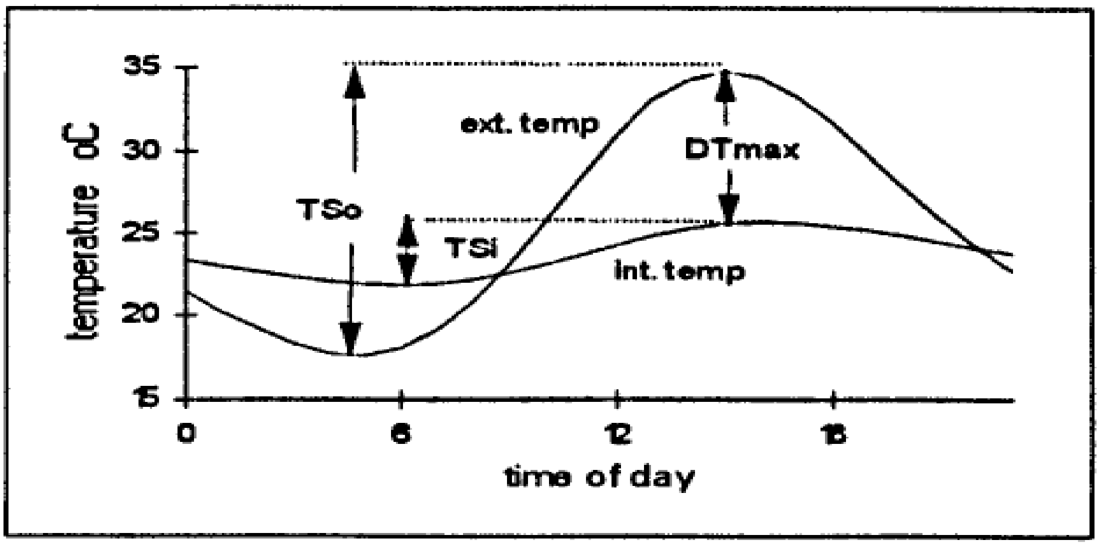


Figure 4. 20 Temperature Swing Ratio (TSR) and Peak Temperature Difference (DT_{max}) (Diaz, 1994)

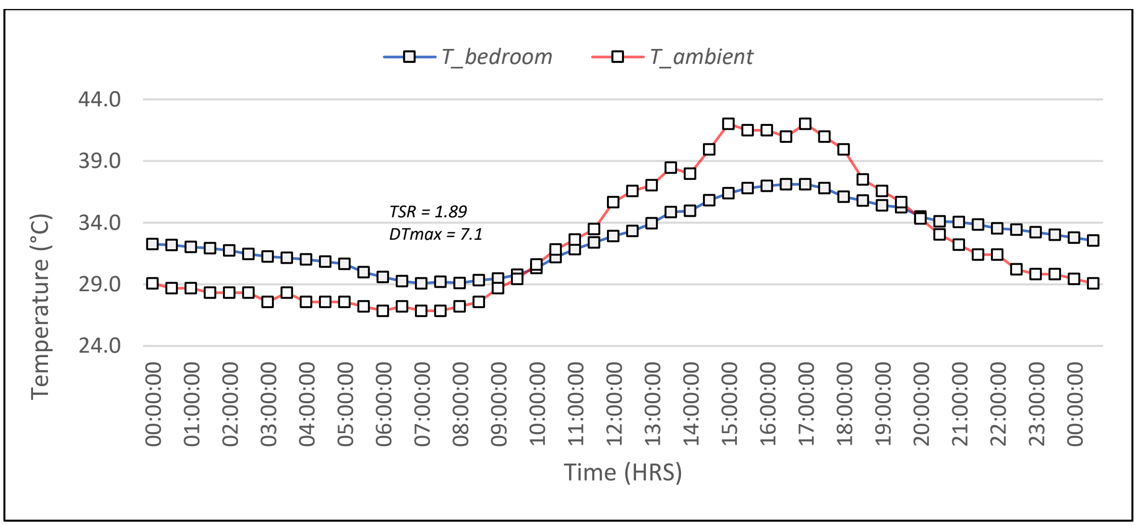


Figure 4. 21 Hourly effects of ambient temperature on indoor temperature in Case Building on a hot day 20/02/2014

Naturally, the building envelope exhibits some level of thermal moderation as can be seen in Figure 4.21. During hot afternoons in February, temperature differences of between 4°C and 8°C are recorded between the indoor and the ambient temperature. During this period, the indoor temperature is within the ranges of 36ºC to 37ºC and may drop to about 28ºC to 29ºC at night while the ambient drops to around 27ºC. This amounts to a temperature drop of between 4ºC and 6ºC during the morning. In the afternoon when the ambient temperature rises, the indoor temperature lags behind the ambient by up to 7ºC, however even this is 8ºC above the upper comfort limit of 29ºC.

Starting as early as 11am heat gradually accumulates in the attic zone. The build-up gradually increases as the sun's radiation intensifies. Temperature differences of 10ºC to 15ºC were recorded. Figure 4.22 shows the temperature rise in the attic zone of the test building in a hot afternoon and its effect on the ceiling temperature.

During the months of July to September the ambient may drop to an average minimum of about 23ºC usually between midnight and 10am. Another comparison was made using data collected on a half sunny/rainy day in July 2014, as shown in Figure 4.23. The aim of this comparison is to determine how much thermal mass in building fabric can affect the indoor temperature of a space due to ambient temperature swings. The measurement was taken on 15/07/2014. A bedroom in a contemporary 3-bedroom bungalow constructed with sandcrete blocks and another in a vernacular mud house were monitored. The buildings are 24m apart. The mud house was able to maintain a smooth curve and hence, indoor temperature was maintained between 25.8ºC and 28.6ºC during the hot afternoon and later went up to 30.8ºC by 15:30hrs after a few hours when the ambient temperature fell. This was maintained at around 28.2ºC till 23:30 hrs. The room in the 3-bedroom bungalow had its lowest indoor temperature at 27.7ºC and highest temperature at 30.3ºC. The room in the mud house maintained an average of 2.4ºC lower than the room in the sandcrete block when the sun was out. There was a sudden drop in the indoor temperature of the contemporary building as the ambient dropped. This was not significant in the mud house, due to the time lag of the clay walls.

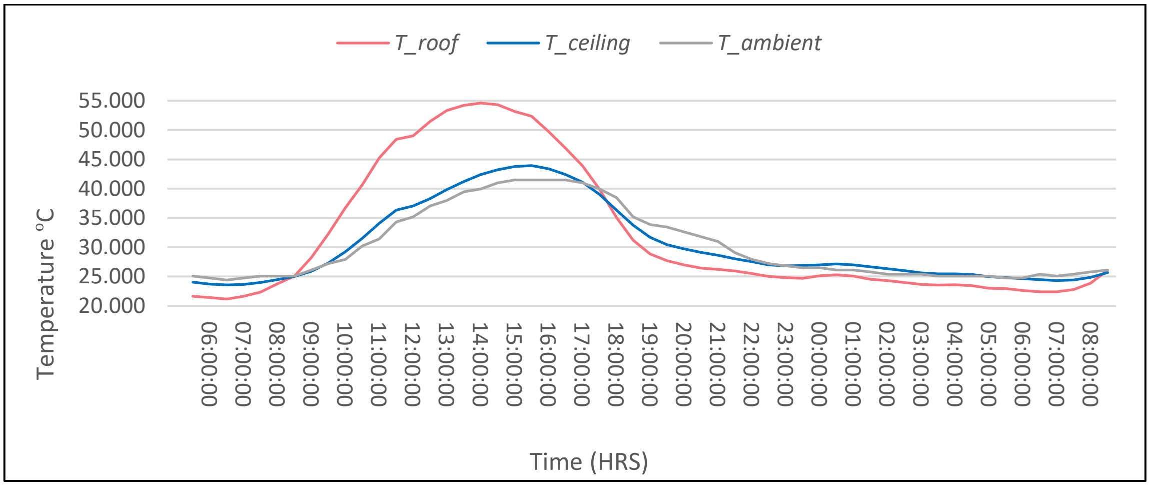


Figure 4. 22 Temperature swings in the roof and ceiling space in case building due to effects of ambient temperature

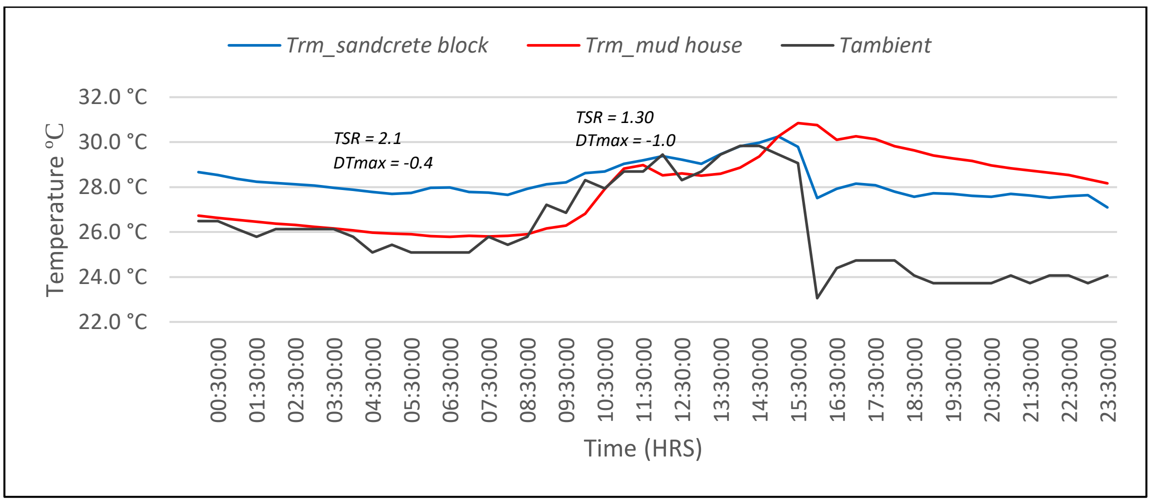


Figure 4. 23 Response of different building fabrics to the influence of ambient temperature on a cold rainy day in Case Buildings on 15/07/2014

4.8.2 Window Openings and Infiltrations

Windows play major roles in the overall energy performance of any building. A good window design will take into considerations floor to window ratio, type of glazing material and the thermo physical properties all window parts (Givoni, 1998a).

The measured building generally depends on natural ventilation for air movement within the building as windows are usually permanently left open to benefit from the cooler outdoor air. The window areas are typically 1.2x1.2m see Figure 4.24 (a) and are made from wood. This window type has an advantage of letting air flow continuously into the indoor space even when the window leaves are shut allowing some background ventilation. A major disadvantage is the high possibility of uncontrolled, unwanted or discomforting air movements directly in contact with the skins of users. Discomfort from draughts are predominant during the early morning hours of the day. Table fans are used as the only mechanical means for the internal cooling of the occupants.

Shading is achieved using roof overhangs and covered patio to the entrance of the building that faces west. Internal shading is achieved using blinds. This method can also reduce solar glare (Givoni, 1994).

The other types of windows found within the study area have aluminum panels (see Figure 4.24 (b)). Aluminium windows are becoming popular in e Nigeria. Most of them have sliding panes while others come as swing windows or top hinged openable window lights.

The opacity of glass plays a significant role in controlling solar gain which may lead to the greenhouse effect and increase indoor air temperatures.

Figure 4. 24 Typical (a) Jalousie and (b) Aluminium panel/glazed window types in study area

4.8.3 Energy Use in Buildings in study Area

Buildings in Nigeria are yet to include any significant layers of insulation in the construction of walls, floors or roofs. U values are therefore relatively high and without insulation the efficacy of internal thermal mass to suppress heat gains and stabilise internal temperatures is less than optimal.

75% of electricity demand is used to cool building interiors (Karsten Ley et al., 2014). To capture the energy use in typical building types located within the study area, 4 buildings (1-bedroom to 4-bedroom bungalows that combines natural ventilation with air conditioning systems) were monitored. These building are of similar construction with the only difference being the window types. Data was collected on the energy use. These building run on both natural ventilation and artificial air-cooling systems using the split unit type. The investigation found that an average building in Ahaba Imenyi depends on air conditioners for a minimum of 16hrs on weekdays and 20 to 24hrs on weekends for space cooling. The minimum room volume measured is $39m^3$, with a maximum of $95m^3$. Figure 4.25 presents the heat gain through the external walls in three spaces in one of the buildings studied. The average heat gain through external walls on a sunny day was 1.2 kW, 1.8 kW, and 2.6 kW for wall areas of $11.3m^2$, $16.2m^2$ and $24.3m^2$ respectively.

The average energy consumption of an air conditioner is 318 Watts and the energy tariff in Nigeria as at 2017 is NGN 30.08 per kWh. Figure 4.26 (a-c) presents the cost of energy in 4 housing types ranging from a 1-bedroom apartment to a 4-bedroom apartment, that are the most commonly constructed house types in south eastern Nigeria.

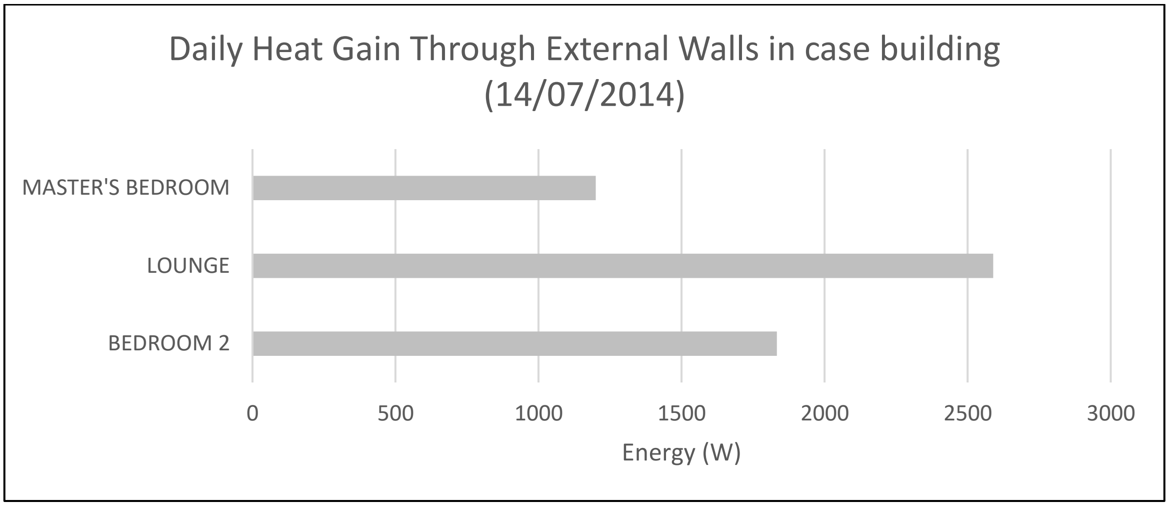


Figure 4. 25 Heat gain through external walls in a two-bedroom apartment

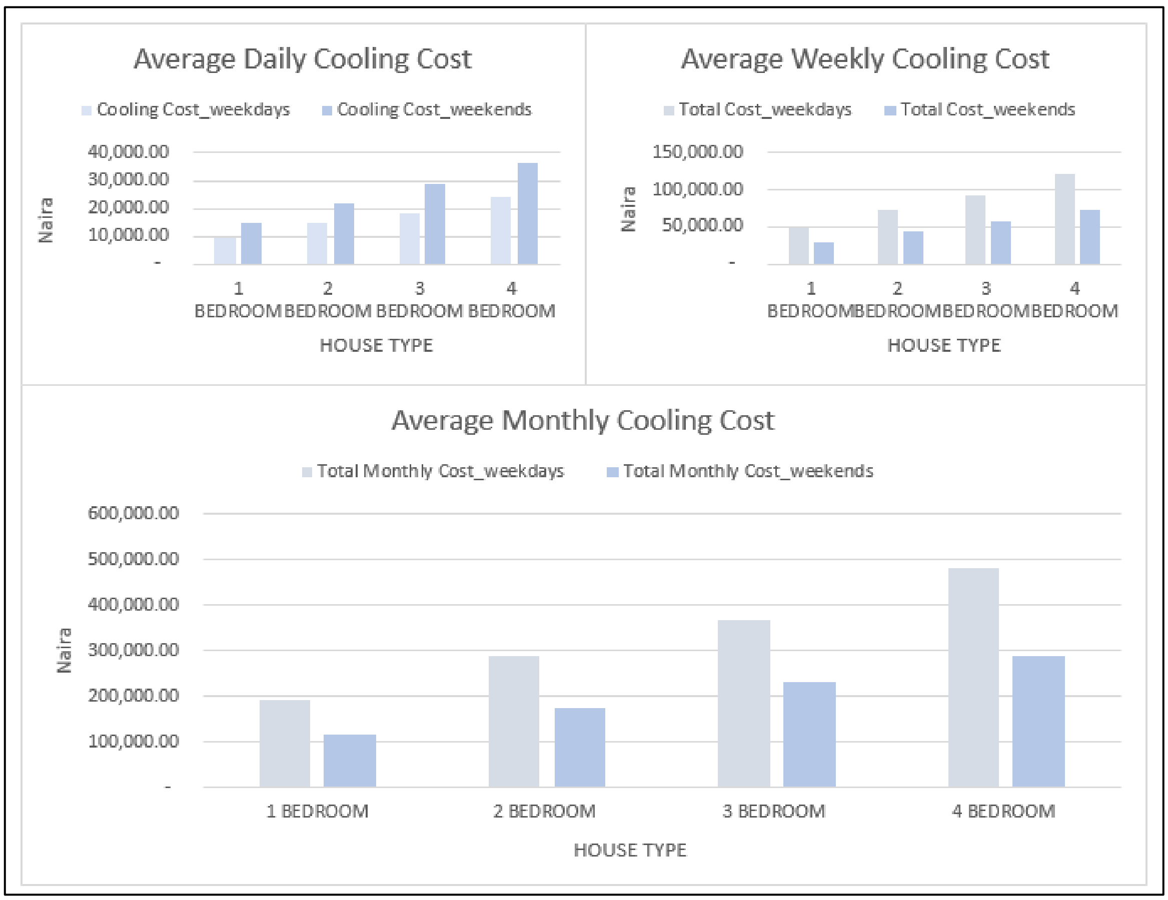


Figure 4. 26 Average Cost of Energy for Cooling in typical housing types in Study area

4.8.4 Thermal Comfort in case building

Fig 4.27 is a psychometric chart comparing the accepted thermal comfort conditions of study area as presented in section 2.6.2 (23°C to 29°C and RH45% to RH75%) and the thermal conditions of the case buildings according to results of temperature and humidity measurements on site. The thermal comfort limit is exceeded daily especially during peak summer. The case building hardly maintains internal indoor temperature below the upper threshold during the daytime. Temperature readings above 29°C usually occur as early as 10:00 hours with daily peaks between 16:00 hours and 17:00 hours, when it starts to decline but remains above the upper threshold until midnight when it starts to drop to within the comfort zone. Temperature above 35°C are recorded especially during the hot seasons (see Figure 4.21) and remain just over 32°C at peak periods between July and September. Most temperature rises recorded in the case buildings can be attributed to the lightweight nature of the walls and roofs which lack insulation rendering the indoor space vulnerable to heat accumulation as a result of solar heat gains. The case building stays above the upper comfort limit for circa 50% of the time.

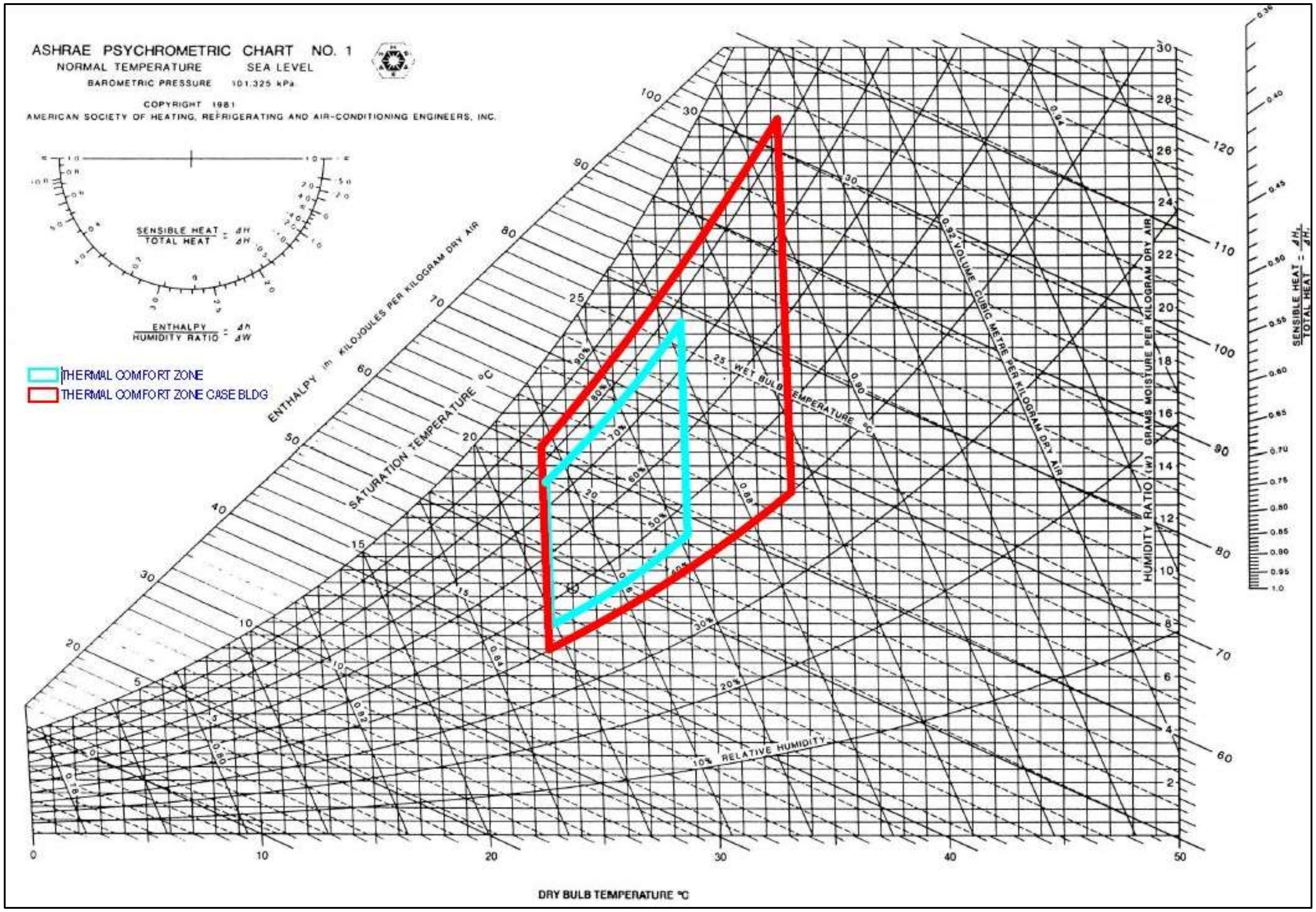


Figure 4. 27 Psychometric chart showing the comfort zone and the thermal parameters of case building

4.8.5 Overall response of measured buildings to the effects of Immediate Outdoor Environment.

The results of the study show that thermal mass contributes to the heat regulation of some buildings found in the study area. Thermal capacity/inertia is key to a dwellings ability to regulate indoor temperature. The study further confirms that the level of heat accumulated and transmitted from the attic space of buildings into the dwelling spaces directly below it is mainly due to lack of insulation in the roof attic, the ceiling level and lack of vents to release heat accumulated in these areas. The heat is usually transferred through convection and radiation. The study also identified the need for control of ventilation and air movement across the dwelling.

Observations and measurements of sky temperature presented net sky radiations within the threshold observed by (Ezekwe, 1986) and (Ogueke et al., 2011). These discoveries indicate that there are potentials for application of clear night radiant cooling by means of exposed surfaces to the sky. The building roof covers almost twice of the total area of a building. This research therefore, will take a step further into the incorporation of metal roofing materials as black bodies to enhance radiation of heat to the clear-sky at night while channeling the chilled air to thermally massive internal walls to help suppress internal temperatures particularly during the hot afternoons and early evenings.

Soil temperature measurements presented data indicating that temperature of the soil at a certain depth remained around the annual average ambient temperature, which is circa 27^{o}C. This is well below the ambient air for most of the year. Using ground pipes for supply ventilation – particularly during the day- is a strategy that could reduce the amplitude of the daily internal temperature swings.

To optimise the heat balance over 24 hours and maximize the night cooling potential of a black body high emissivity roof surface will require the air inputs to be carefully balanced.

There is of course no requirement to ventilate an unoccupied dwelling and hence a dwelling could be effectively shut down during the day with little or no external air infiltration. If occupied, delivering air via a ground pipe will help to reduce internal heat gains. During periods where the night sky is clear increasing air inputs could drive a heat flushing cycle with night time ‘coolth’ being stored in the hypocaust internal thermal mass.

4.9 Chapter Summary

A study was carried out to ascertain the micro climate of a proposed site of study within Ahaba Imenyi, a warm humid location in South Eastern Nigeria. Climatic characteristics of the site (temperature and Humidity) was observed. Maximum temperature during hot seasons (November to mid-May) is circa 37.8°C while it is around 26.7°C during the cool seasons.

Two potential heat sinks for thermal conditioning identified in Chapter 3 namely, the Sky and the Earth crust were studied and measured under the climatic conditions of the study area. It was also observed that during the hot periods, the effective sky temperature drops as low as -9°C and 12.6°C during the cold and cloudy seasons respectively, which is attributed to sky conditions during these periods. The diurnal temperature swing during these months were up to 20°C most of the time. Point measurements at different daily intervals indicated that 77.7 W/m^2 per hour of cooling can be achieved by black body radiation to the clear sky. This value may be exceeded if an automatic logging device could be employed for an effective measurement of the sky temperature even as the cloud conditions changes. The ground temperature was as low as 24.4^{o}C during the hot periods therefore indicating its potential as a heat sink for cooling.

The study went further to assess the potentials in optimizing cooling by targeting time lag and the temperature amplitudes at different depths in the soil and it was found that while the soil temperature at depths of 3m and 4m remain almost stable annually usually around the mean annual temperature of 27°C, shallower depths may provide more cooling effects as temperatures at these depths remain 2°C to 3°C below 27°C during the overheated periods of the year, but rises above 30°C during the cool season when there might not be need for ground cooling.

The thermo-physical properties of the building envelopes as a function of heat moderation was also measured and presented. Indoor temperatures as high as 38.7°C and 54.3°C was recorded in the rooms and attic spaces respectively.

The results obtained therefore suggests the potential for an integrated ventilation system, operating in a modified building envelope with well insulated and strategically placed thermal mass.

5. DEVELOPING AND ASSESSING A PASSIVE COOLING MODEL

5.1 Introduction

This chapter discusses the design and construction of a proposed passive cooling system. The results and findings from the case study are applied with a view to developing prototype test cells to support and validate the modeling of the proposed passive cooling system.

5.2 Theory and practice

To understand how a passive cooling system functions, it is important to have a clear knowledge of how the building envelope responds to the effects of climatic variables because of its fabric arrangement, characteristics, and thermo-physical properties. Prototype test cells will be built to provide scale models of the new insulated envelope. A schematic drawing showing the viability of the proposed passive cooling system has been developed based on results from the case study that was carried out in Ahaba Imenyi in Abia State Nigeria.

Observations from the case study has shown that insulating the walls and roofs can increase the time lag and reduce the amplitude of internal to external temperature differences, however, given the high summer temperatures it is unlikely that such a fabric first approach will provide the complete solution and be able without additional active measures to maintain internal temperatures in the target adaptive comfort zone. A passive cooling system combining ground pipe ventilation and night time black body radiant cooling will be incorporated. Fig 5.1 is a modification of Watson and Kenneth (1983)

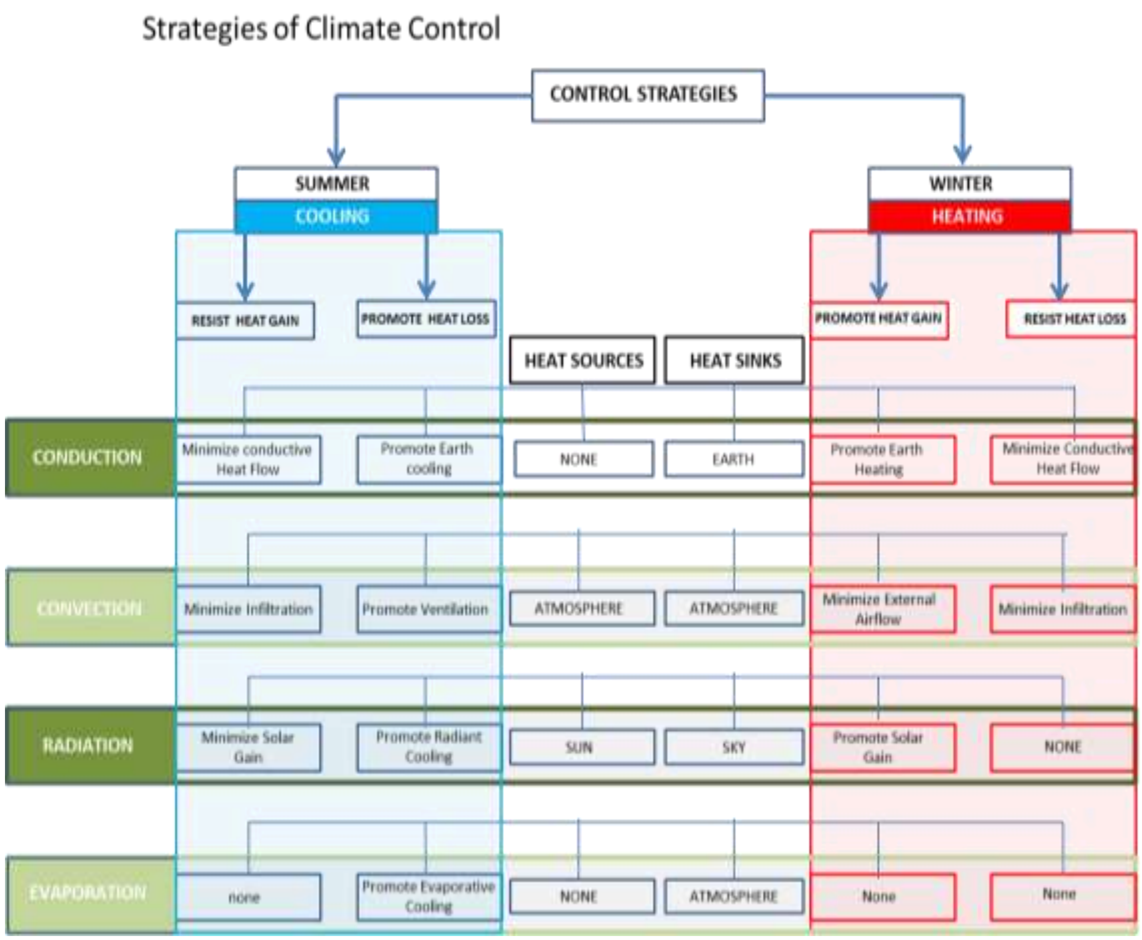


Figure 5. 1 Strategies for controlling climatic influences on buildings in two seasons (Watson & Kenneth, 1983)

strategies for controlling climatic influences on buildings. The figure displays some basic principles of heat gain and loss across the two main seasons. It also defines the major heat sources and heat sinks that affect building envelopes and how the building envelope responds to climatic conditions.

5.3 Approach to the design

A schematic drawing was developed based on observations from field-work. Figure 5.2 illustrates the interaction of the building envelope with external climatic factors. The design is focused on 3 basic strategies namely:

- Thermal mass in combination with insulation
- Ground pipe supply ventilation
- Night sky radiant cooling

The physical properties of air are presented in Table 5.1.

The proposed passive cooling system hopes to achieve above 50% reduction in cooling demand in residential buildings.

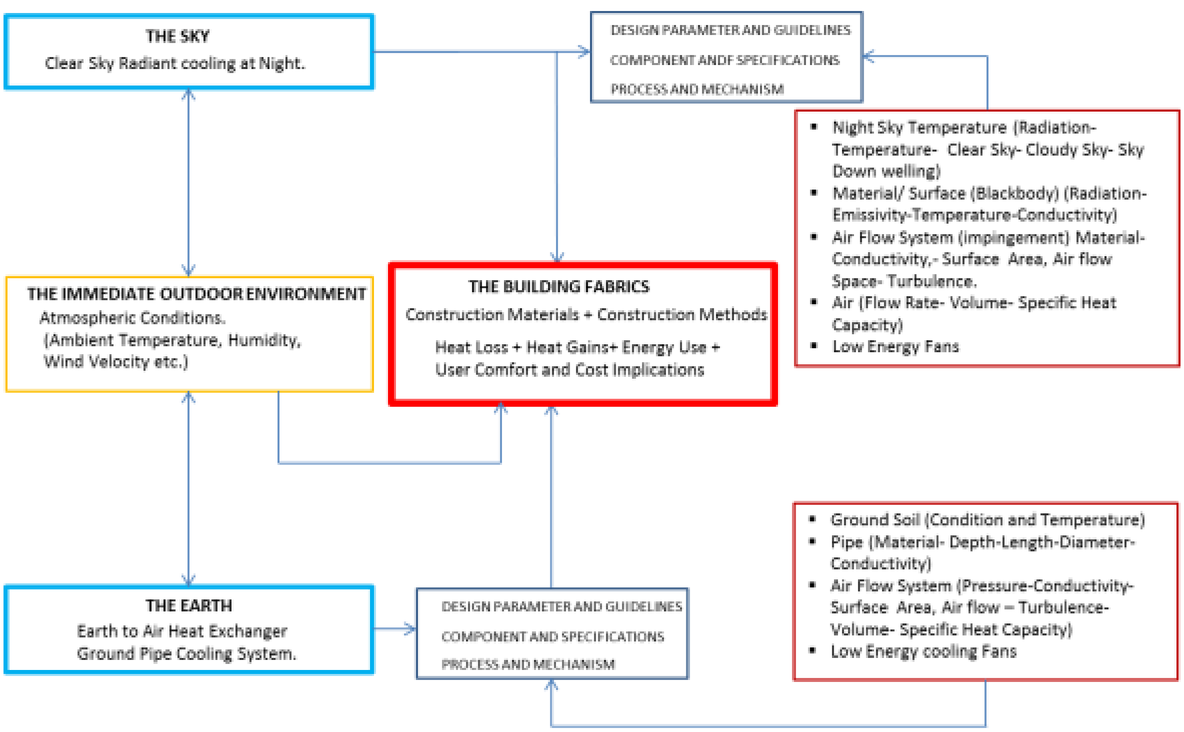


Figure 5. 2 Layout for Proposed Passive Cooling System Developed from Literature Review and existing Situation on Site from Case Study

Table 5. 1 Air density, specific heat, thermal conductivity, kinematic viscosity, expansion coefficient and Prandtl's number - temperatures ranging -150 ºC to 400 ºC (Engineeringtoolbox)

Temperature	Density	Specific Heat	Thermal Conductivity	Kinematic Viscosity	Expansion Coefficient	Prandtl's Number
- *t* -	- *ρ* -	- c_p -	- *k* -	- *ν* -	- *b* -	- P_r -
(°C)	(kg/m³)	(kJ/(kg K))	(W/(m K))	x 10^{-6} (m²/s)	x 10^{-3} (1/K)	
-150	2.793	1.026	0.0116	3.08	8.21	0.76
-100	1.98	1.009	0.016	5.95	5.82	0.74
-50	1.534	1.005	0.0204	9.55	4.51	0.725
0	1.293	1.005	0.0243	13.3	3.67	0.715
20	1.205	1.005	0.0257	15.11	3.43	0.713
40	1.127	1.005	0.0271	16.97	3.2	0.711
60	1.067	1.009	0.0285	18.9	3	0.709
80	1	1.009	0.0299	20.94	2.83	0.708
100	0.946	1.009	0.0314	23.06	2.68	0.703
120	0.898	1.013	0.0328	25.23	2.55	0.7
140	0.854	1.013	0.0343	27.55	2.43	0.695
160	0.815	1.017	0.0358	29.85	2.32	0.69
180	0.779	1.022	0.0372	32.29	2.21	0.69
200	0.746	1.026	0.0386	34.63	2.11	0.685
250	0.675	1.034	0.0421	41.17	1.91	0.68
300	0.616	1.047	0.0454	47.85	1.75	0.68
350	0.566	1.055	0.0485	55.05	1.61	0.68
400	0.524	1.068	0.0515	62.53	1.49	0.68

5.3.1 Ventilation Strategies

A thermal shaft is designed to run from the ground floor of the building to the attic space and then connect to the sheathed and ventilated roof cavity. A low energy fan which has the capacity to produce positive and negative flow is installed at the apex of the shaft where a plenum connects the shaft and the space to the insulated roof air void. The fan in the plenum pulls air by negative pressure at night into the roof space through serpentine channels created between the high emissivity metal roof sheeting and the plywood. This way, air is introduced at controlled volumes and speeds into the attic space. This action is expected to create heat exchange by convection and conduction between the metal roof and the passing air molecules.

As the diurnal temperature swings in the study area are low, this system is designed to operate on days when the sky is clear and deliver cool air into a centrally situated thermal mass wall with a high surface area.

Expanded lightweight clay granules (with a high surface area) are introduced in a compartment between the ceiling and the shaft. These granules are expected to cause turbulence in the air movement and increase the rate of heat transfer. This process will cool the walls in the shaft while delivering nighttime ventilation.

During the daytime, as the heat in the air cavity under the metal roof increases and vents at the apex, a negative pressure is created that will draw air from the internal volumes via the shaft by means of enhanced stack effect. Stored 'coolth' in the thermal mass is sufficient to absorb internal heat gains suppressing internal air temperatures. This system is also designed in such a manner that the flushed heat from the roof attic can be utilised for domestic water pre-heating. See Section 5.2.7 for details of the system for heating water for domestic use.

5.3.2 Clear Night Sky Radiant Cooling

The sky temperature in the study area was found to be as low as -9^{o}C in January and as high as 28.4^{o}C in June. The minimum sky temperature measured in June was 14.5^{o}C. However, measurements carried out between December 2015 and June 2016 presented sky temperature variances between -8^{o}C and 20^{o}C. This agrees with the 7^{o}C range recorded in Ezekwe's (Ezekwe, 1986) measurements in Nsukka. Based on the ability of exposed surfaces to lose part of their heat energy to the clear-sky at night, a passive cooling-oriented roof was designed and incorporated into the schematic drawing as presented in Figure 5.3. The metal roof covering with a high emissivity coating serves as a radiating (black body) surface to a clear night sky.

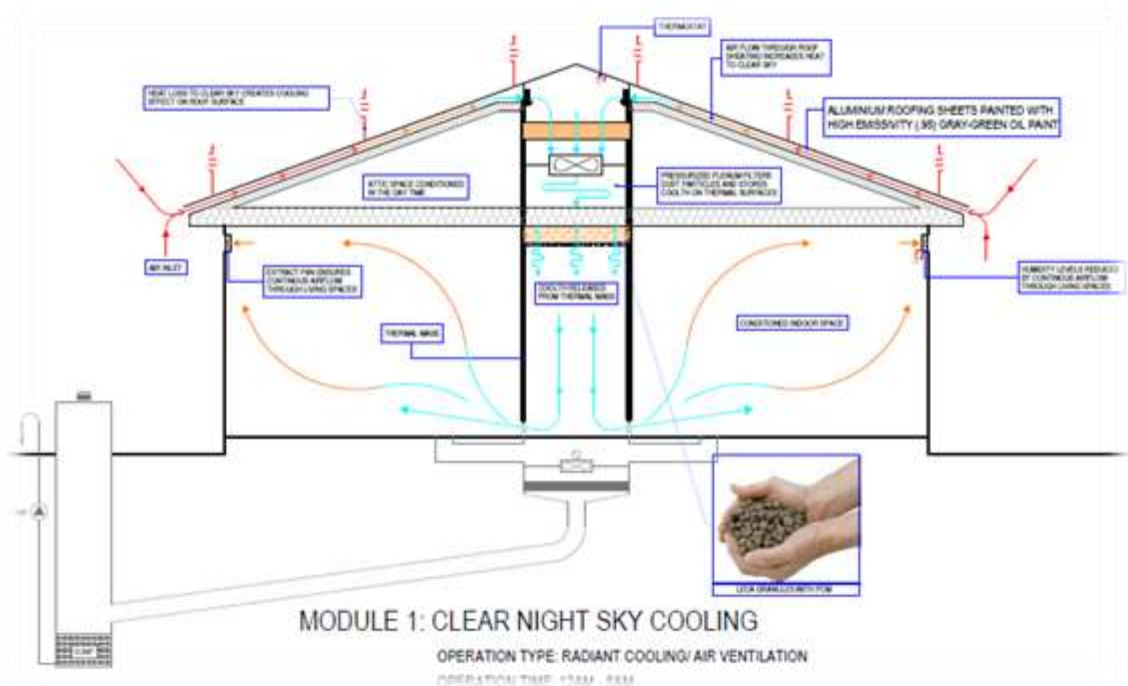


Figure 5. 3 Schematic design for Clear Night Sky Radiative Cooling Using the roof as a blackbody of high emissivity. Air is the heat exchange Fluid and ventilation medium

At night, the air loses heat through convection as its molecules vibrate around the molecules of the roofing sheets under controlled flow rates. This cool air is transferred from the roof cavity into to the dwelling spaces through layers of filters and dehumidification pellets, consisting of activated charcoal and clay granules which are laid in the air shaft as illustrated in Figure 5.4. This ‘coolth’ is stored in the large areas of exposed thermal mass used for the construction of the shaft. The accumulated coolth will subsequently suppress indoor temperatures by convection and occupants will also radiate heat to the cooler walls. The human skin is a radiating surface and has an emissivity of about 0.95 (Mike Luciuk, 2009).

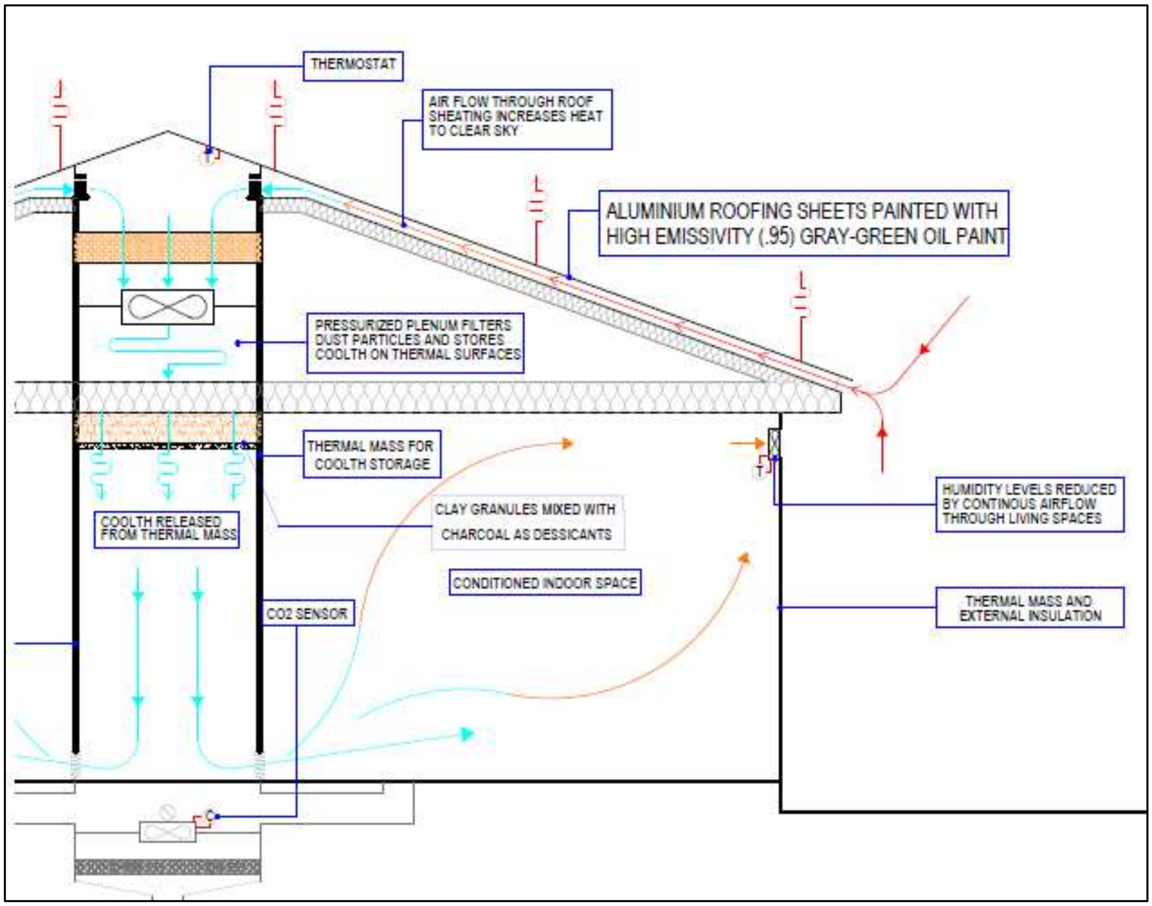


Figure 5. 4 Schematic design showing air movements during a Clear Night Sky Radiative Cooling module

The operation of the clear night sky radiant cooling is triggered by thermostats installed under the roofing sheets. This system effectively monitors the effective sky temperature and activates the fans when conditions are optimal for heat flushing. The system comes on when the temperature of the radiating roof drops to a certain level[7]. The system is

[7]. Very low temperature readings between 21°C and 0°C was recorded on the surface of a radiating plate in the study area. Therefore, there was need to maximize the amount of coolth generated through clear night

deactivated if the temperature at the inlet to the thermal stack is higher than the thermal mass wall temperature. This way the system will moderate and modulate air infiltration and coolth/heat accumulation ensuring that the fan is only activated when cooling potentials are available.

5.3.3The Attic Space Cooling and Heat Flushing

The purpose designed air cavity is achieved by forming an insulated air space (plywood/insulant composite) directly below the profiled metal sheets. At night, the insulated plywood panel serves as a medium to prevent heat gain from the attic space directly below. During hot afternoons, the insulated plywood material will stop heat gain into the attic space from the metal sheets and at night, it prevents heat gain into the air channel when the night air is being cooled by radiant heat losses. The attic space is further separated from the indoor space by an insulated ceiling layer.

5.3.4 Earth to Air Heat Exchanger (EAHX)

The second module is positive pressure ventilation using an earth to air heat exchanger that makes use of the relatively stable ground temperature at certain depths as a heat sink. Figure 5.5 presents the sketch and the operational modes of the model. At certain depths the earth is always cooler than the maximum ambient temperature during the hot afternoons and is always lower than the upper comfort limit of 29ºC.

sky radiation, hence, the use of a thermostat set to pick and trigger the operation of the clear night sky radiant cooling system at temperatures from 21°C and below was necessary to optimize results.

This system is designed to supply air into the house by means of pipes buried at a depth where the Earth temperature is almost equal to the annual mean ambient temperature.

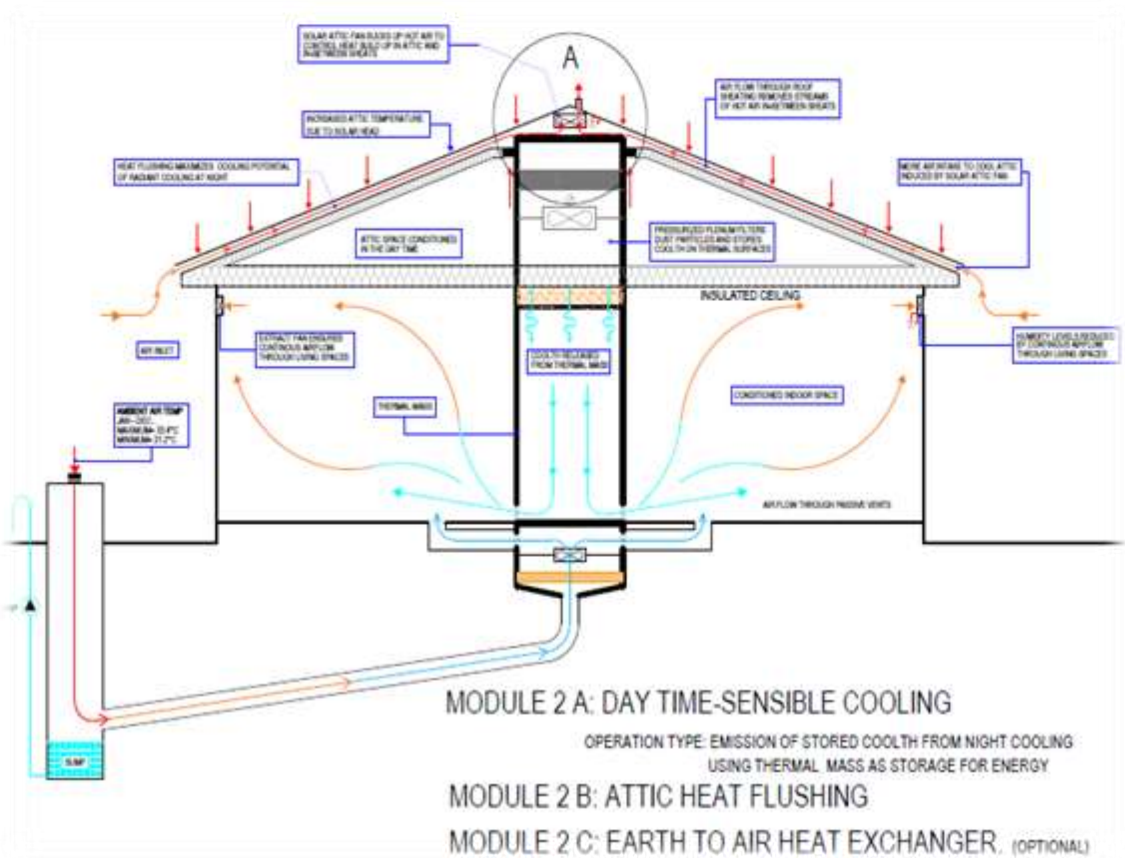


Figure 5. 5 A Schematic design for Earth to Air heat exchanger. This system may not thermally charge walls but will circulate cool air through the building for heat Flushing during overheated periods of the day

At a depth of 3m, the temperature in the soil[8] varies between 25^{o}C and 27.1^{o}C. While at the depth of 1m, the temperature of the soil[9] varies between 24.7^{o}C and 30.5^{o}C. The soil

[8]. The mean annual soil temperature in the study area at depths of 1m and 5m varies between 25.4^{o}C to 29^{o}C and 26.1^{o}C and 27.6^{o}C respectively.

[9]. The soil temperature in the study area at depths of 1m varies between 24.4^{o}C during the periods with hottest ambient to 30.5^{o}C during the periods when the ambient air temperature falls below the annual average.

temperature was, 27.1^{o}C in November 25.6^{o}C in December 24.7^{o}C in January 24.4^{o}C in February, 25^{o}C in March 26.3^{o}C in April and 27.8^{o}C in May. The temperature at this depth is below the annual average temperature during the months considered to be the hottest months. Therefore, for ease of construction for this study, air will be introduced into the experimental cells through pipes that are buried at 1m.

Air change rates will be set to achieve the CIBSE Guide B (2001) recommendation of 8 litres per second/per person (circa 30m^3 per hour). Warm air is removed through vents installed at 150mm below the ceiling level. This is effectively fan enhanced displacement ventilation.

Figure 5.6 presents a schematic showing the air flow and mechanisms of the positive pressure ground pipe ventilation (PPGPV) system. Air is supplied into the building through a plenum. The application of the PPGPV in a warm and humid climate will regularly cause condensation in the ground pipe when the absolute humidity is high. In order not to allow the moisture to pond – which may provide an appropriate environment for the growth of mould and bacteria, any condensed moisture can either be collected for irrigation or allowed to drain from the pipe to earth through weep holes.

The condensed water inside the ground pipe is channelled through pipes buried at an inclined angle into specially designed sumps/ground pipes. The clean water collected in the sump can be sprinkled on the shading zone to enhance the adiabatic cooling and irrigate the soil surface for cooling.

As the PPGPV system has a limit to its heat exchange capacity with the soil it important to optimise the flow rates and thermal interfaces. CO_2 sensors will monitor concentrations[10] and determine if there is a need for ventilation in a space depending on occupant density. This approach will ensure that the system is not activated when there

[10]. The CO_2 sensors are set between 1,000ppm and 1,200ppm. At these concentrations the underground cooling system comes on and is triggered off when the CO_2 concentration drops to a set minimum.

are no occupants in the dwelling/room. The underground ventilation system is deactivated when the nighttime radiant cooling ventilation system activates delivering air at what will invariably be a lower temperature. These systems are in effect mutually exclusive.

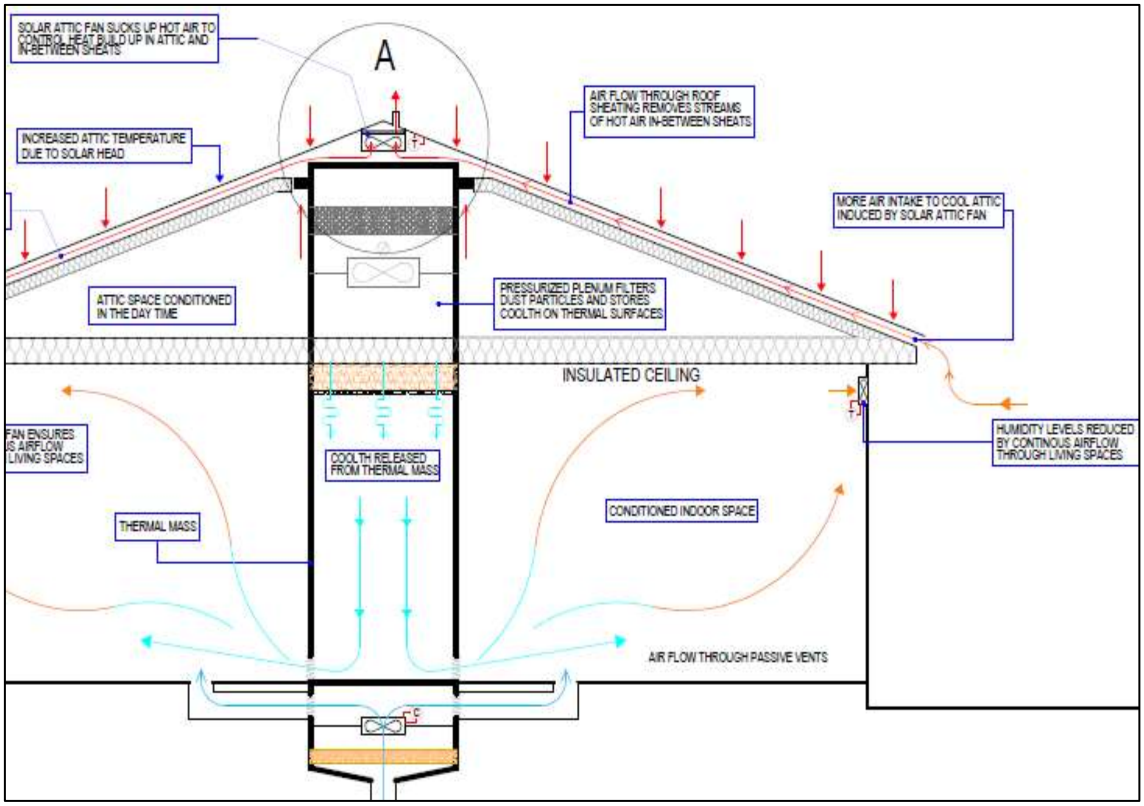


Figure 5. 6 A Schematic design for Earth to Air heat exchanger showing air movement and circulation into the rooms. This system is controlled by CO_2 sensors set at 1000ppm

5.3.4.1 Ground Cover, Shading and Soil condition

Almost all pipes buried in the soil during peak conditions will provide cooler air temperature than ambient from the pipe outlet if efficient thermal interfaces can be engineered. There are other factors that have been identified to influence the level of the earth's ability to absorb and release heat. They include; water table, moisture content of soil, shading and vegetation cover, or by other materials such as rocks, which may protect the soil from direct impact of sun's radiation.

The surface temperature of bare soil is usually higher than the mean ambient temperature on sunny days. Jacovides et al. (1996) compared the effects of the impact of suns radiation on grass covered soil in Greece. The result has shown only a 1ºC difference in soil temperature between the bare soil and grass-covered soil during winter, however temperature differences of up to 7ºC was recorded in summer.

Two years before this, Mihalakakou et al. (1995) studied the cooling potential of multiple earth-to-air heat exchangers (ground pipes) under grass-covered soil and an uncovered soil. The results confirmed that both pipes had the capacity to produce air at temperatures below the ambient, with the short grass-covered soil having a higher cooling capacity than uncovered soil.

A ground shading strategy therefore is one of the techniques applied in the proposed passive cooling system to enhance the cooling ability of the soil.

5.3.5 Domestic Hot Water Passive Heating and Supply System

The air temperature in roof spaces during the daytime is usually high when compared to the ambient temperature. Controlling heat accumulation in the attic could be challenging especially when the same attic space is used for night time cooling (Parker 2005 and 2008). Heat is flushed through the attic zone by negative pressure induced by temperature differences between the air in the roof space and that in the dwelling space. Warm air is removed from the attic space as a result of pressure created by the temperature differences in the two planes. The ceiling between the attic space and the building interior is insulated to maximise this effect. Optionally, the warm air can be blown through air to water heat exchangers, installed in the roof attic for domestic water heating before being expelled through outlets provided in the design as shown in Figure 5.7. The radiators are designed with pipes running into an improvised insulated water reservoir. Hot water pumps are used to run the water through the pipes and hot water radiators, each positioned in the attic space. The main aim is to turn the waste heat into usable heat for domestic water heating before it is finally ejected from the roof attic.

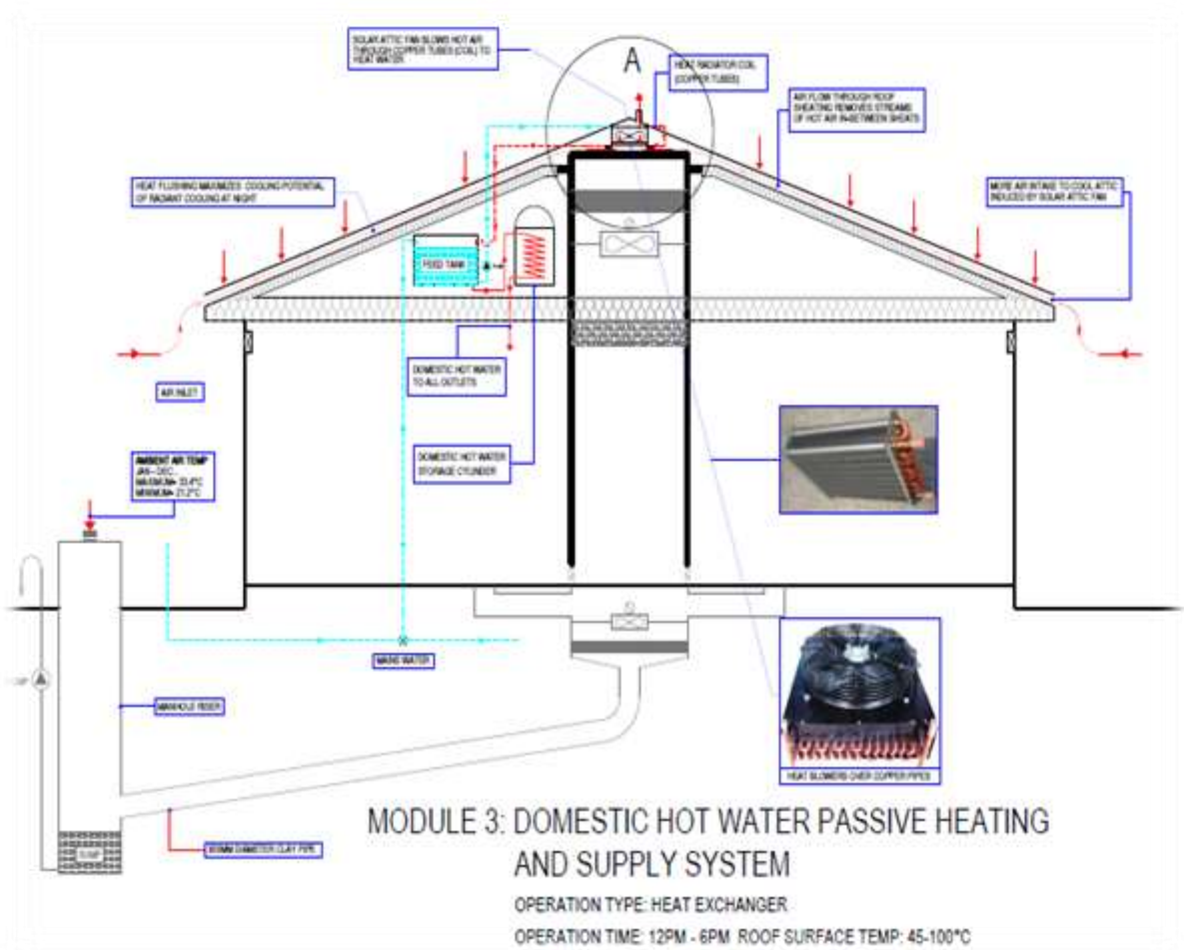


Figure 5. 7 A Schematic design for Attic Heat flushing and domestic water heating and supply system

5.4 The Experimental Cells

Three experimental test cells were designed, namely: Control Cell (CC_1), Passive Cooling System 1 (PCS_1), and Passive Cooling System 2 (PCS_2). The Control Cell 1 (CC_1) is designed to copy the thermal character of an unoccupied bedroom in a 3-bedroom bungalow that was previously measured in the case study (see Chapter 4). The two other experimental cells (PCS_1 and PCS_2) were also designed exactly as CC_1 according to the specifications provided in the schematic design but will be constantly modified to test and compare different variables. Modifications of the different envelopes varied between light, heavy and insulated walls and ceilings. The roof covering is the same in all the cells and the modules for introduction of air was changed depending on the variable being tested.

Figure 5. 8 Location map of Ahaba Imenyi in Abia State, Nigeria showing position of test. Source: Google Map, accessed 02 July 2017)

This included changes in air velocity, volume of air introduced and the Air Change Rates per Hour. Turbulent and laminar regimes were engineered and tested by adding baffles that redirected the air around serpentine loops.

The cells are in Ahaba Imenyi, a town in Abia State in the South-Eastern part of Nigeria which lies within Latitude 5^o40, 5^o49 and Longitudes 7^o29, 7^o57 as shown in Figure 5.8. It is accessible by road networks and settles in a slightly undulating platform. Ahaba Imenyi is in the outskirts of Okigwe town.

The test cells are of the same dimensions measuring 1.2m x 1.2m x 1.5m, the cells are $2.16m^3$ by volume which is 8% the size of a standard 3m x 3m x 3m ($27m^3$) bedroom. The experimental cells are positioned in an open area where they are free from surrounding influences (shade etc). The distance of the cells to the nearest building is 4.2m to the east of the cells. The south and the north of the cells are flanked by existing bungalows at distances 5.8m and 6.2m respectively while the west of the test cells are clear of any existing structures. There are no trees within 20m radius of the experimental rigs. The physical properties and construction of the test cells is discussed in the sections below.

5.4.1 The Frames

The cells were designed in such a way that they could easily be moved from one location to another. A metal framework or skeleton was designed and fabricated to hold the walls and floors that were given an anti-corrosive paint coating. The metal frames are of mild steel components and the details of fabrication are presented in Figure 5.9. Figure 5.10 presents the plan and elevations of the frames for the test cells while, Figure 5.11 shows the finished frame. Figure 5.12 shows the first stage of coupling of the fabric components of the test cell. Figures 5.13 to 5.15 show the construction of walls of the test cell.

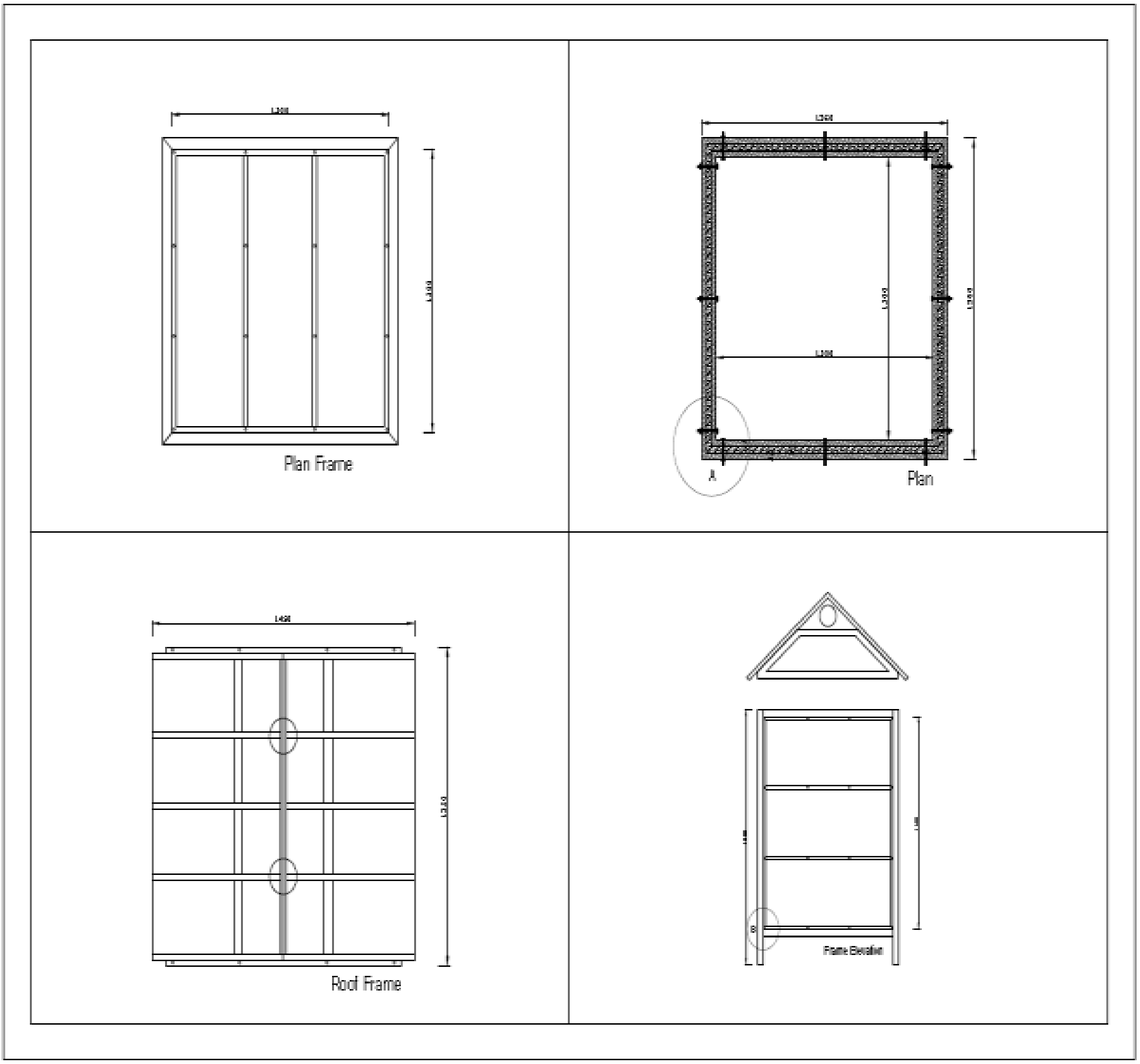


Figure 5. 9 Floor plan of Framework, B -Floor Plan of cooling System, C -Roof Plan of Framework and D - Elevation of Frame Work

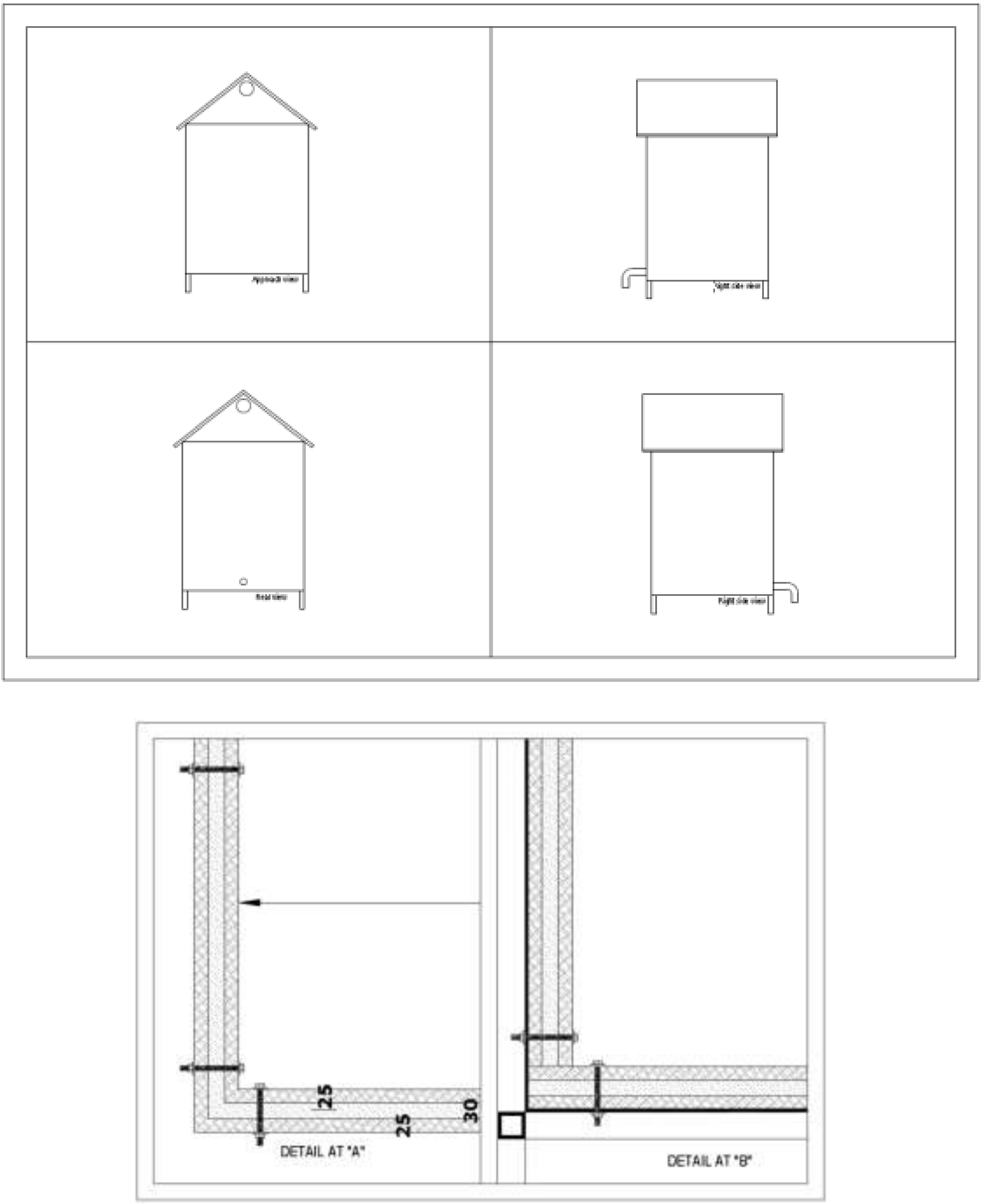


Figure 5. 10 (a) Elevations of Proposed passive cooling system. (b) Details of wall coupling to metal frames

Figure 5. 11 Picture showing a finished metal frame for one of the experimental test cells

Figure 5. 12 Experimental Cell under Construction

5.4.2 The Fabric First Design

5.4.2.1 Wall and Floor Configurations

To test the viability of the design measures, prototypes were constructed, and field trials were undertaken to determine ‘proof of concept’. The key measures and thermal retrofitting strategies include increased thermal mass, solar shading and glazing systems, as well as adding insulation to ceilings, walls, and roofs.

A typical wall in the case study is constructed in three layers which include: 25 mm cement plaster on the exterior, 150 mm solid sandcrete block which is finished with a coat of 25 mm thick cement plaster at the interior wall with a total U-value of 2.68 W/m²K. The roofs are made from aluminium roofing sheets with U-values of 2.13 W/m²K, while the floors are made from a layer of earth, mass concrete slabs and finished in cement-sand screed. The U-value of the floors is 0.68 W/m²K.

This section involves the construction of the fabric for Passive Cooling Systems (PCS) which is expected to perform in isolation or a synergistic combination with other passive cooling measures to provide indoor thermal comfort without suffering high electricity consumption and excessive cost consequence.

The frames were designed and constructed in a way that sheets of plywood boards were assembled on the outer side of the frame. The fabric for the experimental cells was chosen with a choice insulation material and thermal mass to meet the requirements and standards required in wall construction. A total of 3 different test cells were designed with different specifications and are presented in this work.

The control cell (CC_1) is constructed from a light weight wall specification with a U-Value of 2.64 Wm^2K, like that found in the case bungalow with a U-Value of 2.68 Wm^2K. The aim was to design a check test cell with similar thermal behavior between the existing building and the set of constructed test cells. 10mm thick plywood was used to construct the outline of the experimental cell. These pieces are held in place with wood gum and the bond is further fortified with bolts screwed to the metal frame. This method was applied in the construction of both walls and floors of all the experimental cells. 50mm thick sandcrete slabs were laid behind the plywood material to form the walls. The slabs were finished with vitrified ceramic tiles. This wall produced a U value equivalent to that of an existing wall formation of buildings in the study area. The floor was laid with a cement-sand creed of 25mm thick and finished in a layer of vitrified ceramic tiles.

For the second experimental cell PCS_1, the walls were further retrofitted to incorporate 100 mm thick solid sandcrete block with a 25 mm lightweight plaster on the internal wall and vitrified tile finishing which produced a U-value of 0.92 Wm^2K. While the floor was made from a layer of mass concrete slabs, cement-sand screed and finished in vitrified ceramic tiles. The U-value of the floors is 0.48 Wm^2K. The roof was retrofitted to incorporate 20 mm of Polyurethane Foam laid in between 2 layers of 10mm thick plywood, which produced a resultant U-value of 1.28 Wm^2K. The walls of the third test cell PCS_2 is constructed with heavy mass and a layer of 25 mm of Polyurethane Foam insulation. The insulation was applied on the external part of the wall before it was finally tiled. The internal wall was finished in 25mm thick fine cement plaster that was later finished in ceramic wall tiles. The total U-value of the resultant wall was 0.39 Wm^2K. The floors and the roof finishing are the same as in PSC_1, which was retrofitted to incorporate

25 mm thick layer of Polyurethane Foam laid in between 2 layers

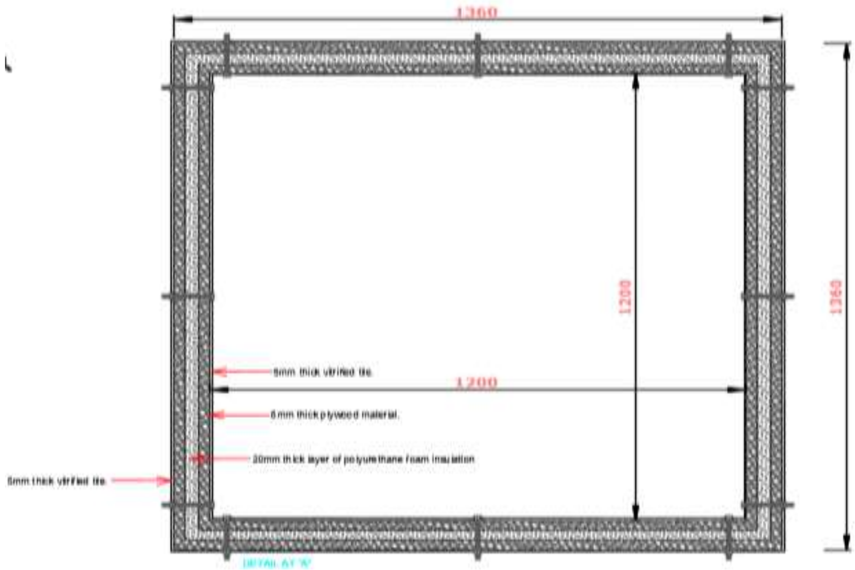


Figure 5. 13 Plan showing CC_1. Walls are finished in U-Value 2.64 W/m^{2}K

Of 10mm thick plywood, that produced a resultant U-value of 1.28 Wm^{2}K. Pictorial views of the test cells under construction are shown in Figure 4.16.

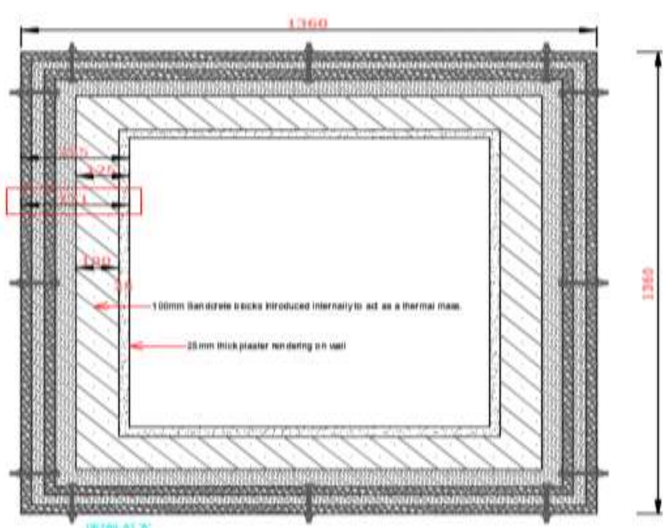


Figure 5. 14 Plan showing PCS_2. Walls are finished in heavy thermal mass for coolth storage U-Value 0.39 W/m^{2}K

Figure 5. 15 Pictorial View of PCS_1 and PCS_2 under construction. Walls in PCS_2 are finished in heavy thermal mass for coolth storage U-Value 0.39 W/m^{2}K

Table 5. 2 Thermo-Physical Properties of Materials used in the Construction of Experimental cells

Material	Form	Density (kg/m^3)	Thermal Conductivity (W/mK)	Specific Heat (MJ/m^2K) *(kJ/(kgK)*
Sandcrete Block	Block	2427	1.3957	0.4751
Clay	Sand	3100	1.875	0.92
Vitrified Tiles	Finishing	1900	0.84	
Plaster	Cement/Sand	1300	0.5	
Mild Steel	Metal	7823	44.117	4.1896
Plywood	Board	697	0.221	0.7258
Polyurethane Foam (PUF)	Insulation	40	0.0372	0.0704
Aluminium	Metal		204	*0.91*

The thermo-physical properties of materials used in the construction of the test cells is presented in Table 5.2 and Table 5.3.

The external envelope of the test cells is finished with vitrified tiles, Figure 5.16, and the internal surface is finished with 25mm thick plastering material. The floors are tiled, and the metal roof covering is coated with a high emissivity paint. These details are shown in Table 5.2.

Table 5. 3 Thermal Properties of experimental test cells

Wall materials and properties

Variables	Case	CC1	PCS1	PCS2
Thickness (mm)	200	100	200	200
U-Value (Wm^2K)	2.68	2.64	0.92	0.39
Thermal Resistance (m^2K/W)	0.60	0.61	1.09	2.56
Exposed Surface Area (m^2)	41.4	8.64	8.64	8.64

Figure 5. 16 External wall finishing on experimental cells PCS_1 and PCS_2

Figure 5.17 is a comparative analysis between the control cell CC_1 and an unoccupied bedroom in a dwelling house. The aim of this assessment is to ascertain if the retrofitted CC_1 will have similar thermo-physical properties as the unoccupied bedroom, which has no source of internally generated heat especially from occupants. The results for 11/03/2016 to 12/03/2016 show a level of agreement in both CC_1 and the unoccupied bedroom. There were however slight disparities in the curves that indicated an average of less than 1ºC difference in the indoor temperatures of both spaces. The test cell CC_1 maintained an average daily room temperature of 29.5ºC, while the temperature in the unoccupied room was maintained at an average of 29.8ºC. The difference between the two daily average temperatures was 0.3ºC. The CC_1 was able to reduce the average room temperature by 1% when compared to an unoccupied bedroom.

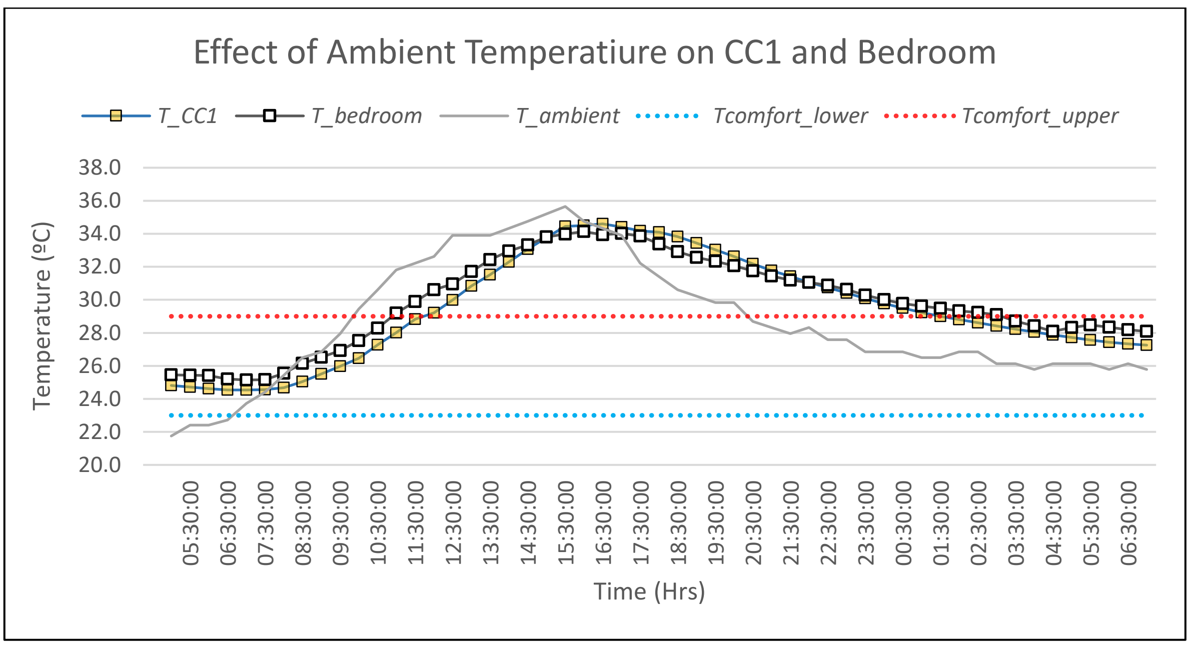


Figure 5. 17 A comparative assessment of temperature swings in CC_1 and an unoccupied bedroom in an existing building

This result will enable us make assumptions that subsequent modifications on CC_1 (as PCS_1 and PCS_2) will be equivalent to modifications on a real sized building.

The wall thickness was then increased by laying 100mm thick sandcrete block finished in fine cement and sand plaster in inner part of the cell. The introduction of thermal mass in the walls of PCS_1 resulted in a decrease in the indoor temperature of the test cell as shown in Figure 5.18. Thick walls increased the ability of PCS_1 to moderate the indoor temperature due to effects of ambient temperature swings. The temperature in PCS_1 remained lower than the temperature in the bedroom by 0.9ºC around 5:30am. The application of thermal mass was able to maintain indoor temperature of PCS_1 below that in the unoccupied bedroom by 4ºC during peak periods.

The minimum temperature attained in PCS_1 was 24.2ºC while the maximum temperature was 32.9ºC. Despite the temperature drop, the upper comfort limit was exceeded between 12:30pm and 1:30am but remained within the comfort range between 2am and 11am, while that in the unoccupied bedroom was exceeded between 11am and 3am and it remained within the comfort range between 3:30am and 10:30am. Temperature readings below the lower comfort limit were however recorded in early morning hours between 5am and 8am in PCS_1.

The experimental cell PCS_1 maintained an average daily room temperature of 28.9ºC, while the temperature in the unoccupied room was maintained at an average of 29.8ºC. The difference between the two daily average temperatures was 0.9ºC. The PCS_1 was able to reduce the average room temperature further by 3%.

The PCS_1 also maintained an average room temperature of 28.5ºC between 5am and 7pm (daytime), while the temperature in the unoccupied room was maintained at an average of 29.9ºC between 5am and 7pm. The difference between the two averages in the daytime was 1.4ºC, and the average room temperature reduction in the daytime was 4.7%.

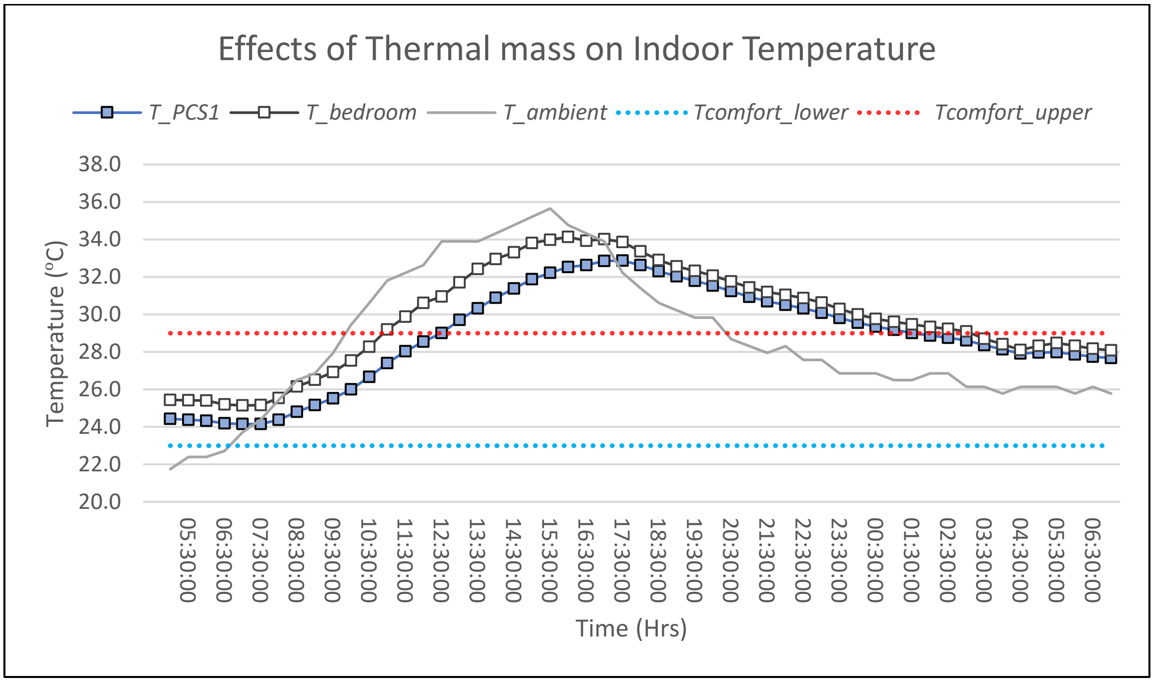


Figure 5. 18 Effects of Thermal Mass on Indoor Temperature

Between 7:30pm and 4:30am (nighttime), the average room temperatures in PCS_1 rose to 29.7ºC, while the temperature in the unoccupied room also rose to an average of 30.2ºC. The difference between the two averages was 0.5ºC, and the average room temperature reduction at night was 1.7%.

An insulation layer was applied to the external walls of the thermal mass PCS_2. The application of insulation produced a further drop in the indoor temperature as shown in Figure 5.19. The maximum temperature difference between the unoccupied bedroom and PCS_2 was 5.1ºC during the afternoon. The PCS_2 produced indoor temperatures above the upper comfort limit of 29ºC by an average of 1.1°C (30.1°C average maximum above comfort limit) between 3:30pm and 11:30pm. The maximum temperature attained in the PCS_2 was 30.8ºC by 6pm, while the lowest temperature recorded was 23.5ºC in the morning hours. PCS_2 was able to keep indoor temperature within the comfort limit from

11:30pm till 3pm. It however sustained room temperatures below that recorded in the unoccupied bedroom throughout the day.

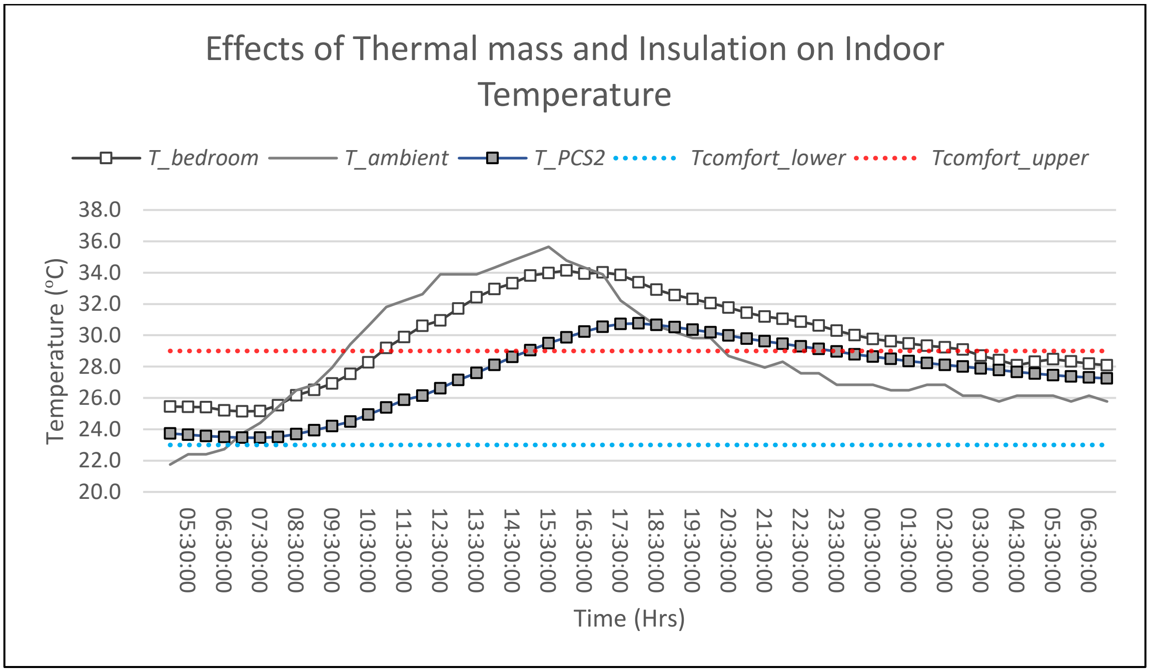


Figure 5. 19 Effects of Thermal Mass and Insulation on Indoor Temperature

The experimental cell PCS_2 maintained an average daily room temperature of 27.5ºC, while the temperature in the unoccupied room was maintained at an average of 29.8ºC. The difference between the two daily average temperatures was 2.3ºC. The PCS_2 therefore was able to reduce the average room temperature further by 7.7% when compared to an unoccupied bedroom.

It also maintained an average room temperature of 26.7ºC between 5am and 7pm (daytime), while the temperature in the unoccupied room was

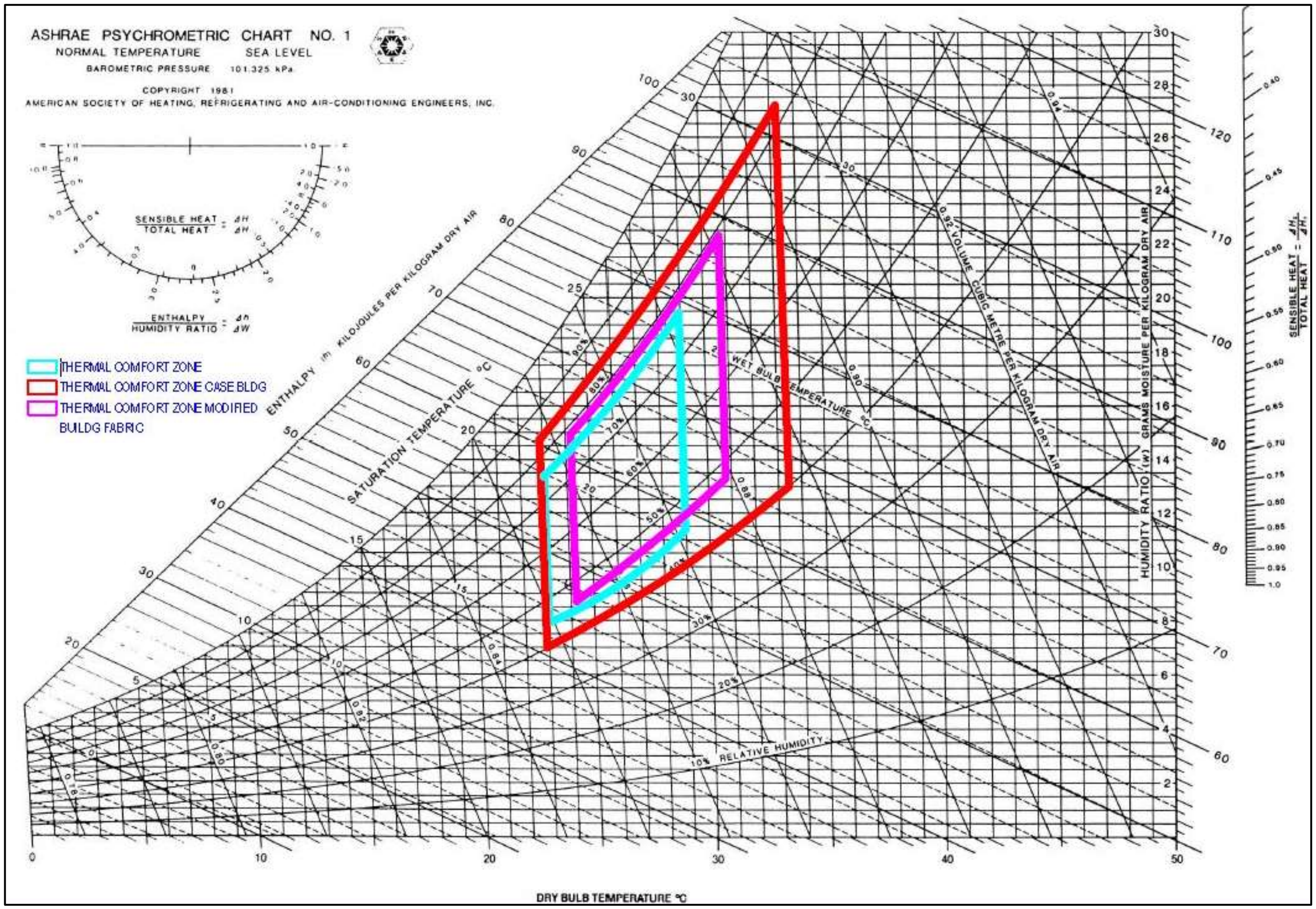


Figure 5. 20 Psychometric chart showing the comfort zone and the effects of modified building fabric on indoor thermal comfort

maintained at an average of 29.9ºC between 5am and 7pm. The difference between the two averages in the daytime was 3.2ºC, and the average room temperature reduction in the daytime was 10.7%. Between 7:30pm and 4:30am (nighttime) in the morning, the average room temperatures in PCS_2 rose to 28.9ºC, while the temperature in the unoccupied room also rose to an average of 30.2ºC. The difference between the two averages was 1.3ºC, and the average room temperature reduction at night was 4.3%.

Figures 5.20 presents a psychometric Chart of the indoor thermal condition in the room space of the modified building fabric. Relative Humidity reading was higher than the acceptable upper range of RH 75% at RH 78.9% when the indoor temperature is around 24.2°C and drops to RH 47.5% when the indoor temperature exceeds the upper comfort limit at 30.8°C. Therefore, it is clearly observed that the temperature rises above the upper comfort limit results to a drop in RH below RH 75%.

The application of insulation on thermal mass however could not sustain indoor temperature below the upper comfort limit during daily peak periods. Figure 5.21 to Figure 5.23 present a summary of temperature swings in the different experimental cells due to adjustments of the thermo-physical properties of walls.

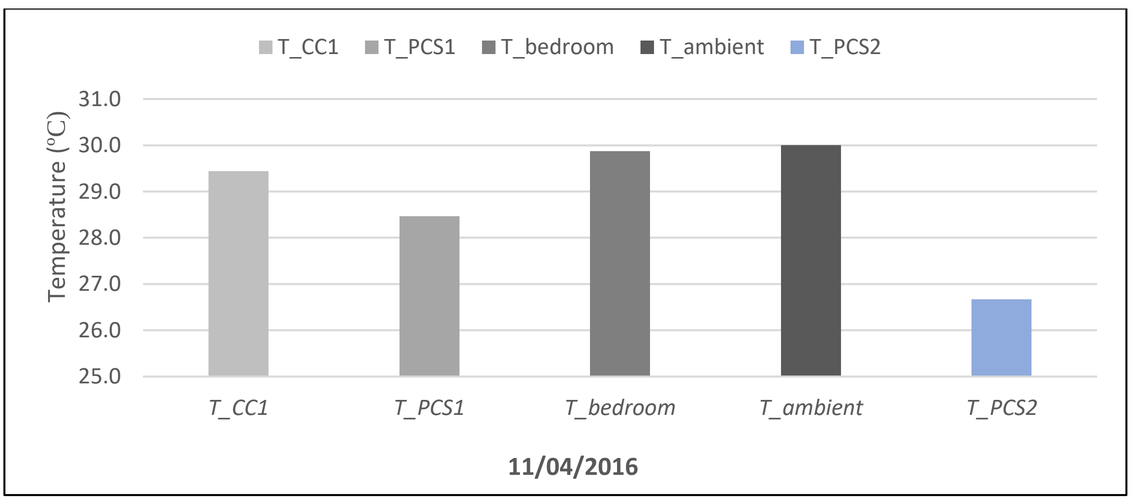


Figure 5. 21 Effects of Fabric design on the mean Indoor Temperature between 5:00am and 7:30pm

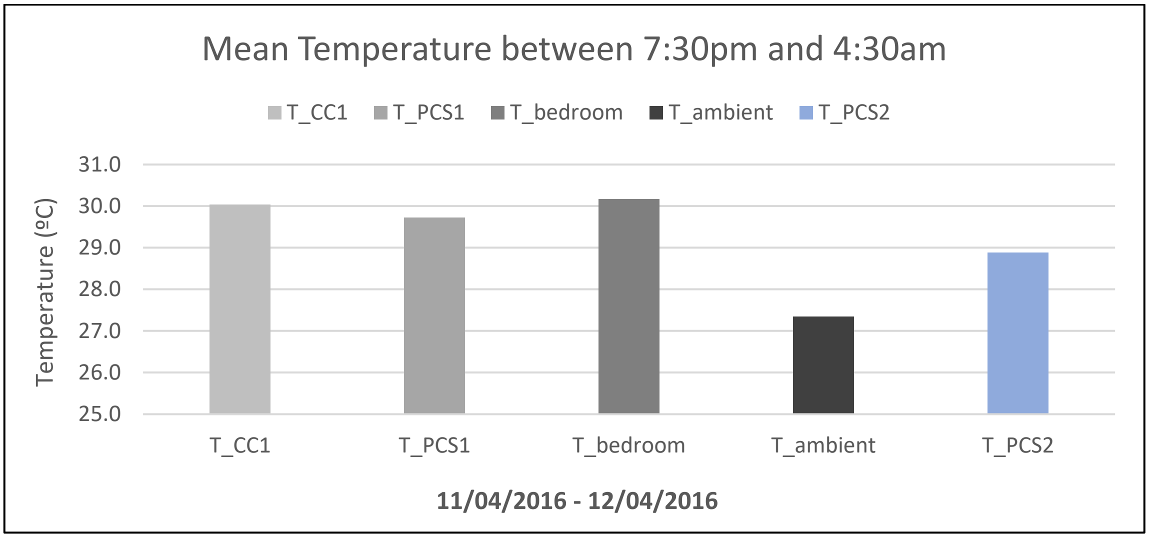


Figure 5. 22 Effects of Fabric design on the mean Indoor Temperature between 7:30pm and 4:30am

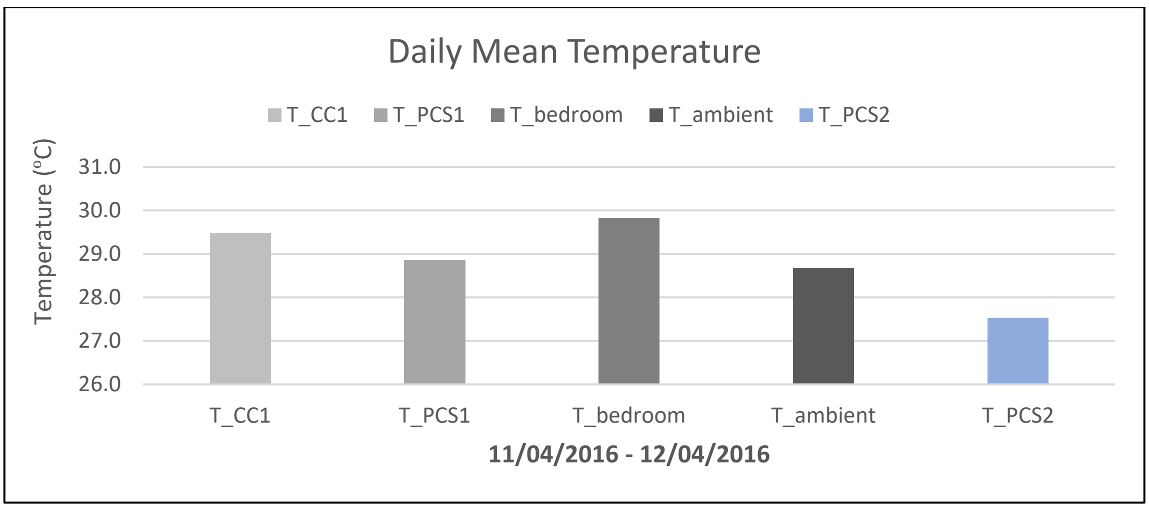


Figure 5. 23 Effects of Fabric design on the mean daily Indoor Temperature

Measurements were taken on the 3 types of wall formation in the experiment to determine the effects of wall formation on heat transfer in building fabrics. Point measurements were carried out using a Testo 925 Digital Thermometer (thermocouple) and surface temperature of the walls were recorded 5 times in a day usually by 7:00hrs, 10:00hrs, 15:00hrs, 18:00hrs and 21:00hrs respectively, these measurements were carried out for a period of 8 days. The external wall surface temperatures for the Bedroom, PCS_1 and PCS_2 were relatively close and were assumed to be the same and was plotted against the surface temperatures in the internal walls of the Bedroom, PCS_1, and PCS_2. Figure 5.24 presents the readings from the measurements that were carried out on a typical day.

The surface temperature of the exterior wall was minimum in the morning around 7:00hrs at 25.8ºC. At this temperature, the surface temperature of the internal wall in bedroom was 27.6ºC, while that in PCS_1 was 27ºC, and the temperature reading on the walls in PCS_2 was 26.5ºC. By 10:00hrs, the surface temperature of the exterior wall rose to 27.5ºC, while the readings on the walls in the Bedroom, PCS_1, and PCS_2 dropped to 27.1ºC, 25.3ºC, and 24.3ºC respectively.

By 15:00hrs, the external wall surface temperature has risen to a maximum of 35.6ºC, the wall surface temperature in PCS_2 has declined to the minimum reading of 24ºC. There was a consequential rise in the surface temperatures of the walls in the Bedroom and PCS_1 to 32.9ºC and 31.7ºC respectively. By 18:00hrs there was a drop in the external wall surface temperature to 33.1ºC while the Bedroom and PCS_1 rose to their maximum temperatures of 34ºC and 34.6ºC respectively, while that in PCS_2 rose to 24.7ºC. There was a further drop in external wall surface temperature to 32.1ºC at about 21:00 hours, while the Bedroom and PCS_1 dropped to 31.8ºC and 33.3ºC respectively, and PCS_2 rose to 26.9ºC. Figure 5.25 shows the energy saving (cooling load reduction) achieved by the application of retrofits on the walls of the test cells. The PCS_2 reduced cooling loads by 2.6 kW around 15:00hrs, while the PCS_1 reduced loads at that time by 0.9 kW, while the cooling load reduction in the Bedroom was 0.25 kW. During morning hours, the loads were reduced by 1.6 kW, 0.4 kW and 0.32 kW in PCS_2, PCS_1 and Bedroom respectively. Cooling load reduction in the evening around 18:00hrs was 1.4 kW, -0.52 kW and -0.3 kW for the PCS_2, PCS_1 and Bedroom respectively.

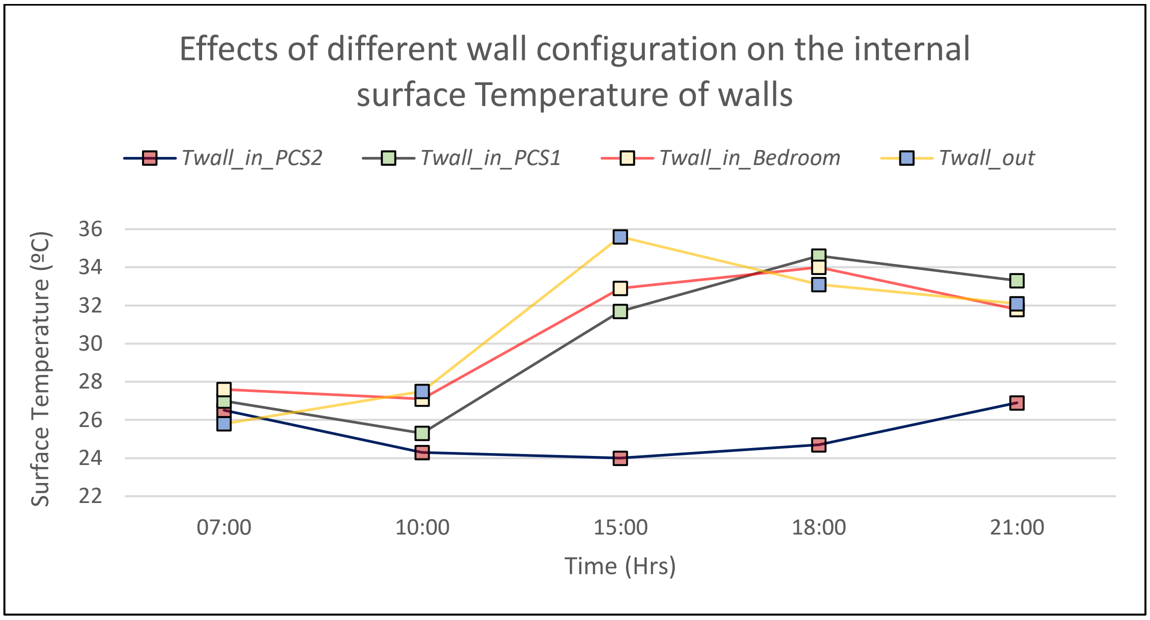


Figure 5. 24 Effects of Thermal Mass and Insulation on the Internal Surface Temperature of Walls

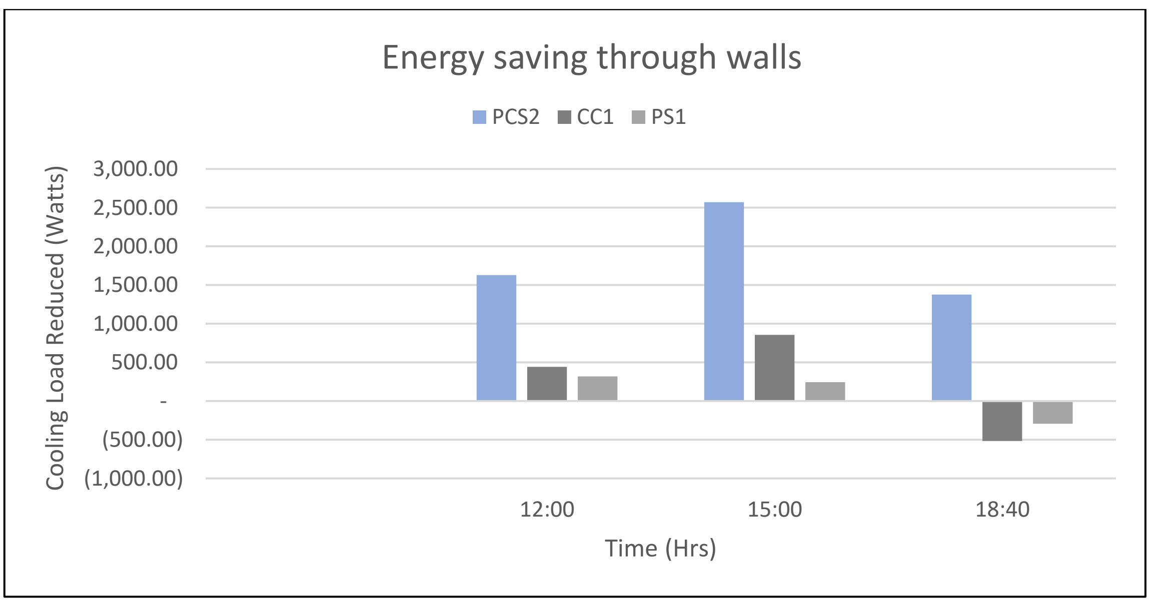


Figure 5. 25 Effects of Thermal mass and insulation on heat energy displacement

5.4.3 Temperature moderation, Cooling Performance, and Energy/Cooling load reduction of fabric modification

The experimentation in the study area identified low thermal capacity of building fabric as the main factor behind the high domestic cooling energy demand and consumption which arises from excessive use of mechanical cooling appliances because of elevated indoor temperatures. This situation was found to be a very common trend especially during the hot seasons (November and April). During these hot months, the ambient temperature rises to daily maximums above 38°C.

Figure 5.26 presents the energy required for cooling a room[11] of 27m^3 in a retrofitted building envelope over the base case scenario. It also presents the temperature reductions in the room space. Upgrading the thermal properties of the building fabric using thermal mass and insulation was able to reduce the indoor temperature of a room by 10.7% during the day and 4.3% during the night over the base case. The reduction in indoor temperature resulted in a drop of the daily energy demand for cooling of the room from 11.6 kWh to 6.7 kWh, which amounts to 42.2% (when a thermostat is set at 25°C) reduction in cooling energy requirement for the space. The energy requirement for cooling is dependent on the thermostat setting at each instance[12]. Building fabric modifications and upgrade displaced 4.9 kWh of cooling energy at a thermostat setting of 25°C daily and 147kWh each month in the hot months. This amounts to a reduction of 1767kWh per annum (4187kWh).

[11]. The test cells measure 1.2m x 1.2m x 1.5m, the cells are 2.16m^3 by volume which is 8% the size of a standard 3m x 3m x 3m (27m^3) bedroom.

[12]. Thermostats were set at different settings 23°C, 25°C and 26°C respectively. It was found that energy demand for cooling in both the case building and the modified building fabric decreased when thermostat was set at 26°C giving the values of 9.4 kWh and 4.9 kWh respectively but increased when the thermostat was set at 23°C giving the values of 16.5 kWh and 10.9 kWh respectively. The values of the thermostat setting for room temperature will also determine the percentage of heat energy displaced.

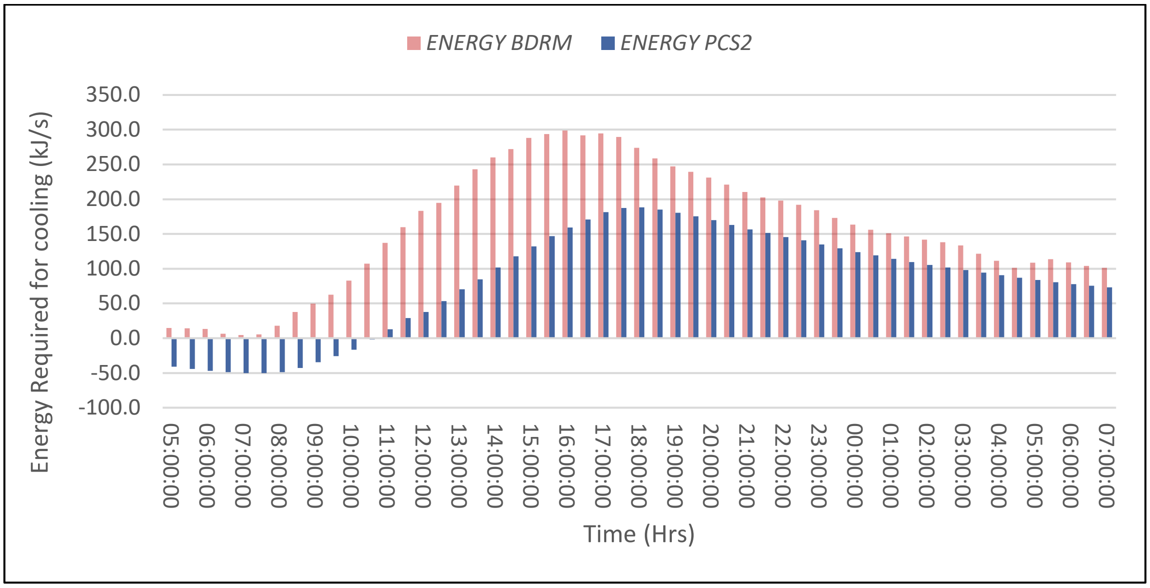


Figure 5. 26 Effects of modification of the building Fabric on Cooling Energy demand in a 27m^3 bedroom with thermostat set at 25°C.

5.4.3.1 Roof and Ceiling Configurations

The roof of the experimental test cells was constructed from metal frames and insulated plywood boards that were coupled as shown in Figure 5.27. The roof was retrofitted to incorporate 20 mm of Polyurethane Foam laid in between 2 layers of 10mm thick plywood that produced a resultant U-value of 1.28 Wm^{2}K. Two holes of 100mm diameter were created for the installation of 2 fans. The roof structure is designed in such a manner that it will minimize heat gains during hot afternoons due to the incident sun's radiation on the roofing sheets - by providing insulation between the hot metal sheets and the roof attic, and permit heat flushing of the roof attic – by providing vents which will displace hot air due to pressure differences. The roofing sheets rest on purlins that are installed on a 50mm plywood/insulant composite. This approach is aimed at controlling heat gains through the attic zone into the main space of the test cells. The air plenum is designed to take air in at night and flush heat out during the hot afternoon.

Figure 5. 27 Roof structure under construction showing details of Insulation and air inlet plenum in the proposed experimental cell

The roof of the control cell is not insulated but is separated from the indoor space by a layer of asbestos ceiling board. Figure 5.27 shows the construction of the roofs for the experimental cell PCS_2. Air is the fluid for heat transfer in the roof design because of its flexibility and ease when it comes to construction and maintenance.

The effects of roof insulation on the attic air temperature were studied by placing Tinytag data loggers in the attic areas of the experimental cells. Figure 5.28 presents the records in the attic spaces in CC_1, PCS_2 and the ambient temperature. The results showed the effects between 9:00 hours and 19:00 hours. The aim is to identify how much of the sun's heat due to solar radiation may be moderated when a layer of insulation is applied under the roofing sheets.

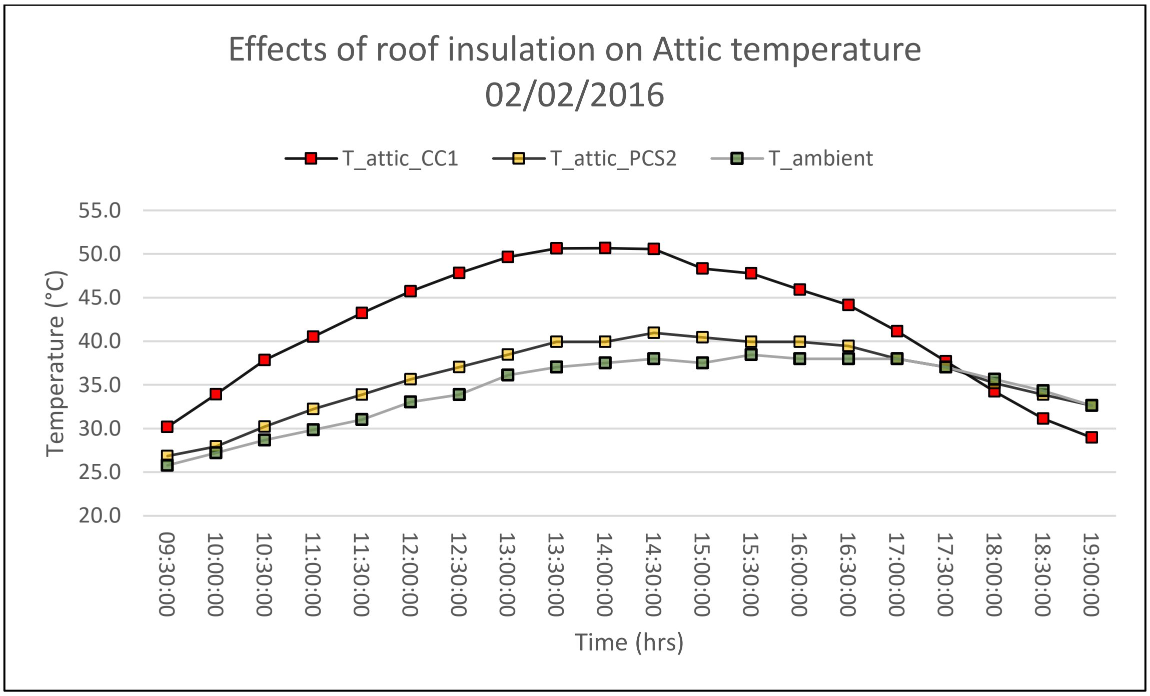


Figure 5. 28 Effects of Roof Insulation on the Temperature of Air in Roof Attic

A temperature rise from 26.9Cº and 30.2ºC was recorded in the attic space of the insulated roof and the uninsulated roof respectively from 9:00 hours in the morning when the ambient temperature was circa 25.8ºC. The ambient temperature reached a maximum at

15:30 hours of 38.5ºC, while the insulated roof followed closely at 39.9ºC, with the uninsulated roof rising to 47.8ºC. The maximum temperature attained in the uninsulated roof attic was 50.7ºC at about 13:00 hours, while the insulated roof produced air temperature of 39.9ºC maximum. The maximum recorded ambient temperature for the day, was 37.0ºC. The average temperatures recorded were 43.9ºC, 36.3ºC and 34.4ºC for the uninsulated roof, the insulated roof, and the ambient temperature respectively.

A maximum air temperature difference of 11.2ºC was recorded between CC_1 and PCS_2 at about 13:00 hours, while the average maximum attic temperature difference between them from 11:00 hours and 16:30 hours (when the intensity of the sun radiation is strongest) is 8.9ºC. The maximum temperature difference between the ambient and PCS_2 was 3.0ºC between 14:30 hours and 15:00 hours. The average temperature difference recorded between the two was 2.5ºC between 11:00 hours and 16:30 hours.

The maximum air temperature difference between CC_1 and ambient air is 13.9ºC that occurred around 12:30 hours, while the average air temperature difference was 11.4ºC between 11:00 hours and 16:30 hours. The temperature in the attic of the uninsulated roof was about 27.6% higher than the ambient temperature, while the temperature of the insulated roof was 4.7% higher than the ambient temperature. The air temperature in the insulated roof was cooler than that in an uninsulated roof by an average of 22.4%.

Another comparison was done between the attic of CC_1 and PCS_2 and the result is presented in Figure 5.29, the aim is to observe the level of heat gain in the attic space due to temperature increase. An average heat gain of 138W was obtained by calculations in an uninsulated roof and 30.2W in an insulated roof at about 12:00 hours. The average hourly heat gain in the attic space of CC_1 between 9:30 hours and 17:30 hours was 94.4 W/h, while the average hourly heat gain in the PCS_2 roof attic was 21.8 W/h. The difference in heat admitted into the attic spaces) CC_1 and PCS_2) at 12:30 hours was 107.5 W (77.5%), while the average daily heat energy prevented between 9:30 hours and 17:30 hours was 72.6 W (76.9%).

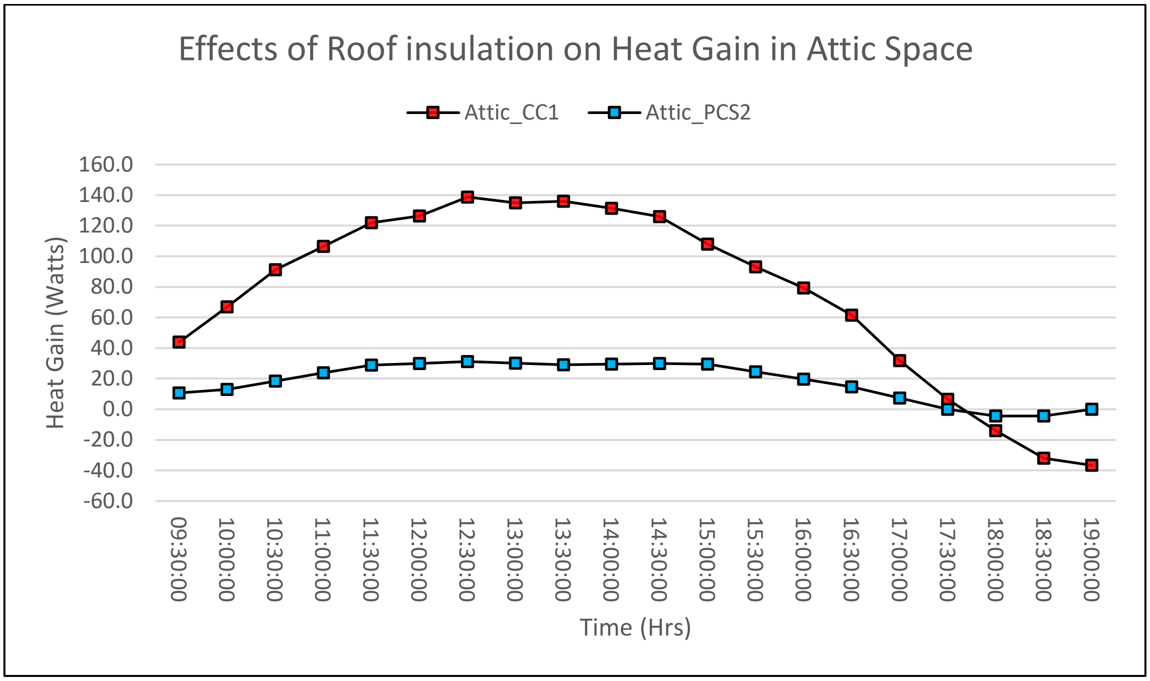


Figure 5. 29 Heat gain in Roof Attics as a function of Roof Insulation

A further investigation was carried out to ascertain the effect of the roof insulation on the surface temperature of the ceiling and on the indoor temperature in CC_1 and PCS_2. The result is presented in Figure 5.30. The surface temperature of the surface of the ceiling in the insulated roof attained a maximum of 35.5ºC, and that in the uninsulated roof was at a maximum of 41.6ºC. The average surface temperatures of the ceilings because of roof insulation were 30.6C and 34.7C for the insulated PCS_2 and the uninsulated CC_1 respectively.

The maximum indoor temperatures recorded were 40.4ºC and 32.6ºC for CC_1 and PCS_2. Minimum room temperatures of 22.9ºC and 23.1ºC were recorded in PCS_2 and CC_1 respectively both cells at about 8:00 hours. The average indoor temperature as a function of roof insulation is 28.9ºC and 33.8ºC in the PCS_2 and CC_1 respectively. Figure 5.31 presents the temperature difference (ΔT) between the attic and the indoor spaces as a function of roof insulation. ΔT was higher in PCS_2 with the maximum recorded at 28.3ºC at about 13:30 hours, while CC_1 was at 14.0ºC. The average ΔT between the attic temperature and the indoor temperature between 8:00 hours and 18:00 hours were 17.7ºC and 7.9ºC for PCS_2 and CC_1 respectively. The difference between ΔTCC_1 and $\Delta TPCS_2$ is about 14.3ºC (50.5%).

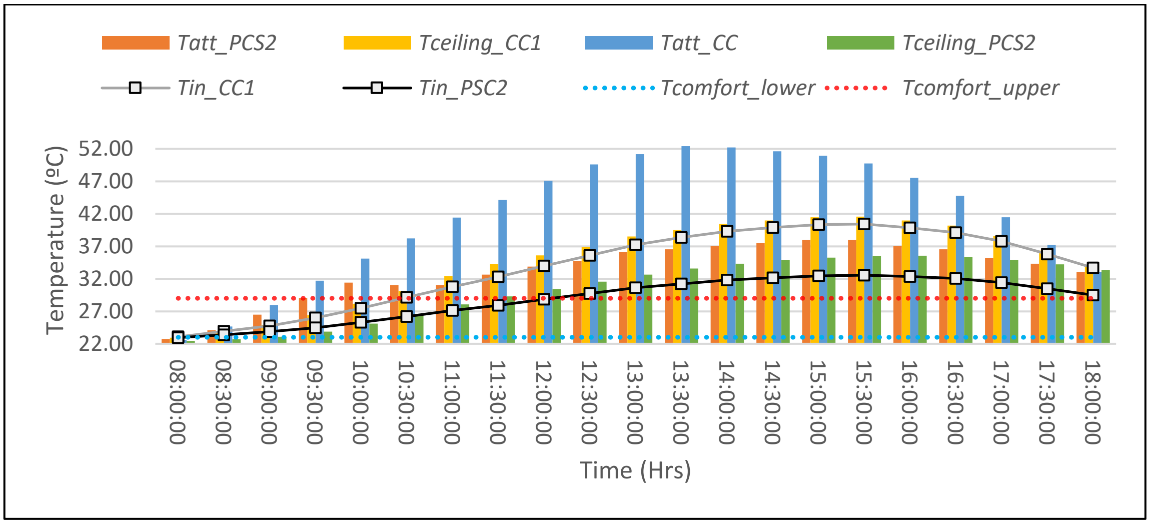


Figure 5. 30 Effects of Roof Insulation on the Surface Temperature of ceiling and Indoor Temperature

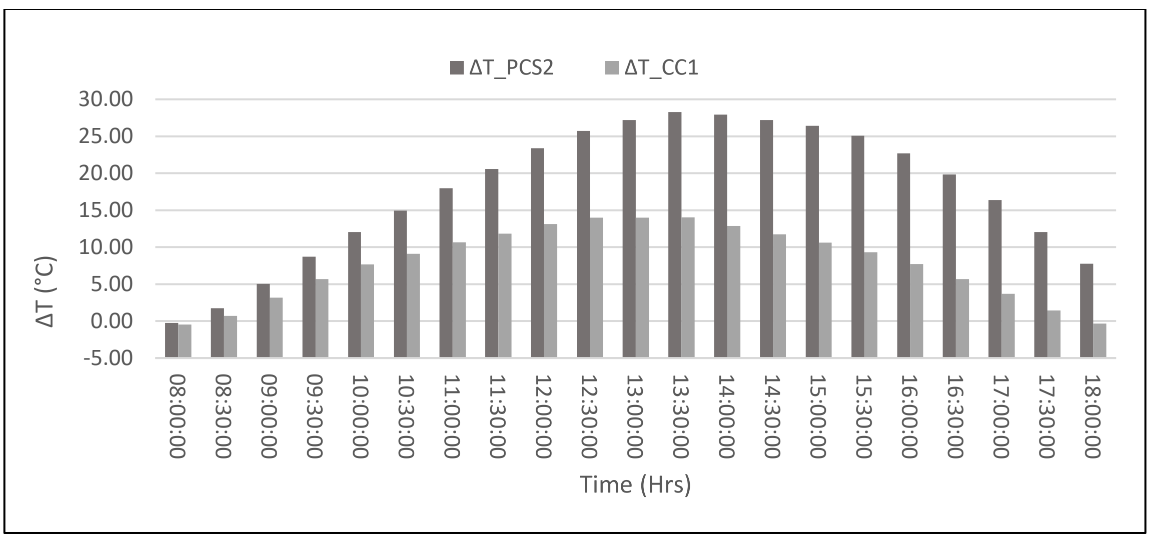


Figure 5. 31 Temperature Difference between the Attic and Indoor spaces as a function of roof insulation

Data obtained from the study was used to calculate the cooling load reductions as a function of roof insulation and was plotted as shown in Figure 5.32. The energy saving/heat displacement per hour shows that at about 13:30 hours, a maximum load reduction of 67.6 W and 33.6 W were obtained in PCS_2 and CC_1 respectively, while Figure 5.33 shows average cooling load reduction between 8:00 hours and 18:00 hours of 0.9 kW and 0.4 kW for PCS2 and CC1 respectively.

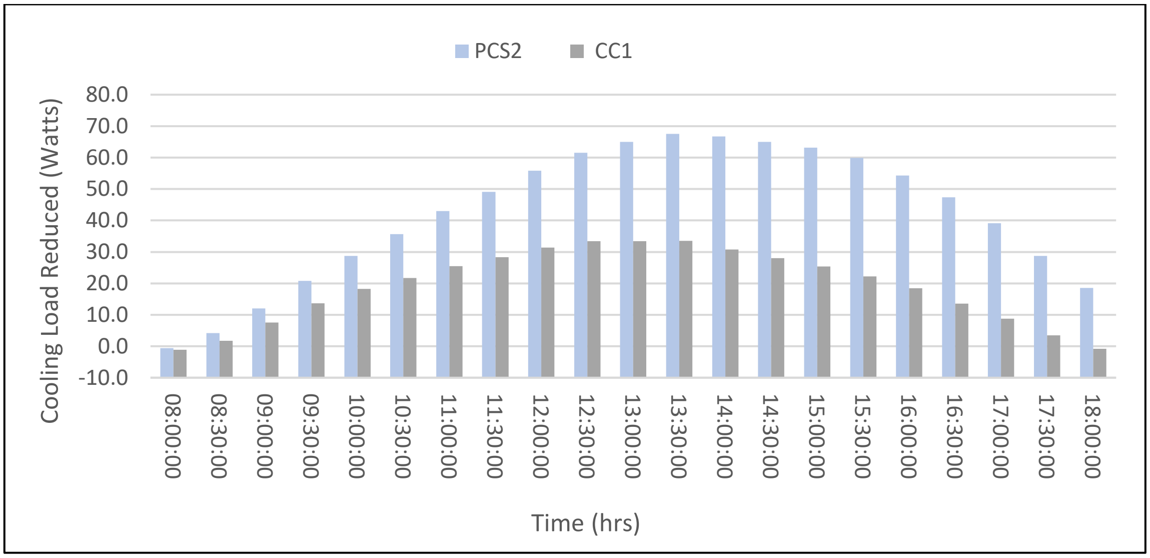


Figure 5. 32 Hourly Daytime heat displacement due to Roof Insulation

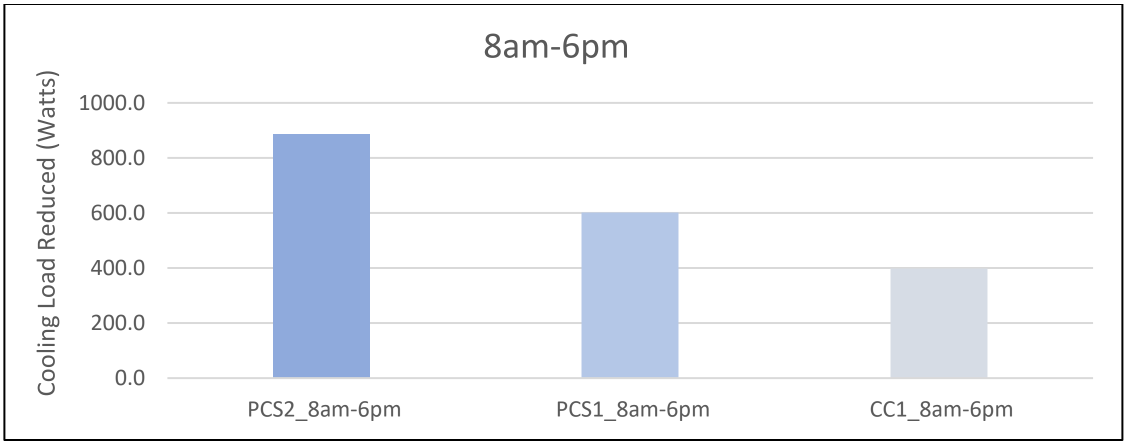


Figure 5. 33 Average Daytime Cooling load reduction for 10 hrs due to Roof Insulation

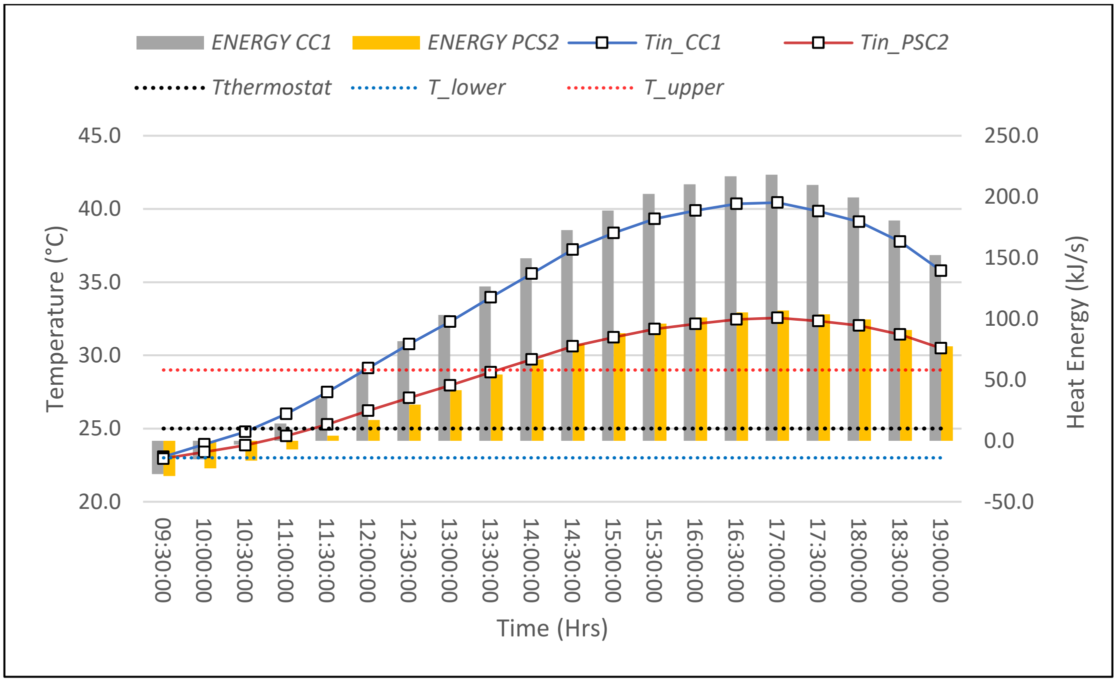


Figure 5. 34 Effects of roof insulation on Cooling Energy in a 27m^3 bedroom with thermostat set at 25°C

Relating the data to a 1:1 sized building[13], the application of insulation in the roof section of the modified building envelope registered a substantial reduction of 22.4% in air temperature in the attic space of 11.7m^3. The application of roof insulation also displaced 2.8 kWh of heat energy in the attic space daily between 9:00 hours and 19:00 hours. The average percentage of heat displaced in the attic space due to the application of roof insulation is about 35.4%. On the other hand, air temperature in the indoor space of 27m^3 was also affected by the application of roof insulation. Heat reduction in the indoor space was from 4.2 kWh to 1.9 kWh daily which is about 53.9% of cooling energy displaced, Figure 5.34.

[13]. The test cells measure 1.2m x 1.2m x 1.5m, the cells are 2.16m^3 by volume which is 8% the size of a standard 3m x 3m x 3m (27m^3) bedroom, the volume of the roof attic becomes 11.7m^3.

Even though there was a significant reduction in indoor temperature, the modification of the building fabric on its own could not sustain indoor temperatures within the comfort range of 23°C and 29°C throughout the day. Additional cooling measures are therefore required.

5.5 Passive Cooling Measures

The building fabric has been measured and redesigned to resist heat gain and promote heat loss by minimizing conductive heat flow from the outer to the inner surfaces of walls and roofs, and to reduce infiltration of warm air into dwelling spaces. It therefore becomes imperative to optimise the ability of the building fabric to efficiently regulate heat flow by applying ventilative cooling systems using both ground and sky as heat sinks.

5.5.1 Ventilation System and Schedule

The air flow and ventilation system applied in this study are designed to conform to the CIBSE standards for ventilation. Low energy direct current (DC) fans were used to induce airflow in the experimental cells. The number of air changes per hour (ACH) is a crucial factor that determines the quality of ventilation in any enclosed space. It is applicable in both naturally and mechanically ventilated systems to achieve the correct balance between the human response to air movement and to improve the methods for designing air distribution in spaces (P. O. Fanger, Melikov, Hanzawa, & Ring, 1988).

Low energy DC fans are the major air movers applied in the experimental cells. Two Excelvan® 12V 3inch in-line blower 2.5A hi-flow 130CFM capacity fans were used in the roof attic and a third installed in the plenum that connects the earth to air heat exchanger in the test cell.

5.5.1.1 Power Supply and Control.

A 12V 150 watts Photo Voltaic Cell (PVC_{solar}) powers all the electrical components used in the experimental cell PCS_2 that included an optional hot water pump. The PVC_{solar} powers all electrical components in the day while it is charging a 12 Volt, 75amp battery which in turn will power the cells throughout the night. A control panel is wired to the test cells and mounted inside a nearby house to protect it against rain and direct sun heat. The panel turns the system on and off, controls the fan speeds by means of speed regulators that were also mounted (Figure 5.35).

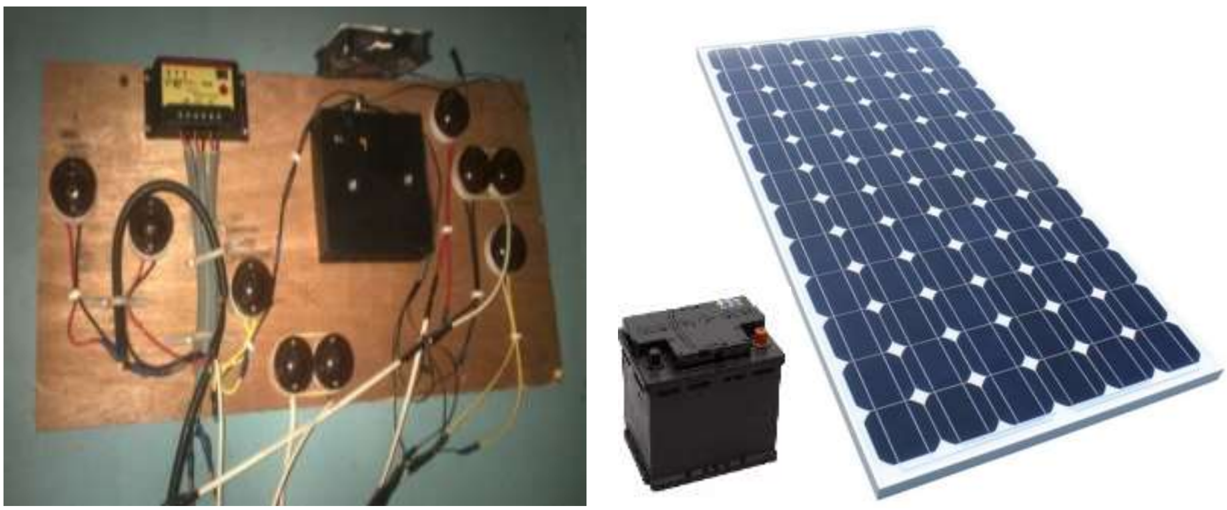


Figure 5. 35 A control panel mounted indoors in a nearby residential building and wired to the experimental cells (a). 12 Volts, 150W photovoltaic cell for power supply (b), 75amp 12 volts battery (c)

5.6 Positive pressure Ground Pipe Ventilation (PPGPV)

Having completed the construction and testing of the upgraded fabric of the PCS_2, design considerations and construction of the positive pressure ground pipe ventilation system (PPGPV) commenced.

An evaluation of ground pipe ventilation and overnight radiant cooling to displace air conditioning in South Eastern Nigeria

It has been demonstrated that the first few meters into the earth crust is cool when the ambient is warm and warm when the ambient temperature is cool. The earth maintains this attribute to depths of up to 12m (Mihalakakou et al., 1995; Pfafferott, 2004; Sanusi, 2012). To utilize the cooling potential of the soil, positive pressure ground pipe ventilation system (PPGPV) is therefore proposed as a method to reduce the temperature of the incoming air.

The performance of a PPGPV system can be influenced by some factors which include pipe length, pipe diameter and depth at which the pipe is buried. It is also affected by air flow rate, thermal properties of the pipe (conductivity) and thickness of pipe. A parametric study was carried out by Jamil Hijazi (2018) to determine the influences of these factors on the performance of a PPGPV by developing a numerical model using Design Builder. The aim was to determine the optimal effect of each of these variables on the output of the cooling system. His findings showed that longer pipes increased the surface area in contact with the cooler soil and increased the length of time the air flows in the system and hence there was more time for heat exchange that resulted in cooler air from the outlet. Cooling effect also decreased when the airflow rate is increased. There was a 1.7ºC increase in outlet air temperature when the airflow rate increased from 2m/s to 15m/s. His findings also claimed that the soil temperature in Saudi Arabia decreased as the depth increases, which contradicts the claims made by Kusuda and Achenbach (1965) that an increase in soil depth will result in an increase in the time lag at that depth. Cooler soil temperatures are a function of season, depth and time lag.

The ongoing study has reviewed the temperature variations and patterns within soil depths varying from 1m to 4m under the earth surface in a location in South Eastern Nigeria. It was found that time lag in the first few meters into the ground are large enough to maintain an almost constant temperature equivalent to the mean ambient at such depths throughout/during the hot periods of the year, this observation agreed with the reports of Kusuda and Achenbach (1965) and Givoni and Katz (1985).

Figure 5.36 presents the results of soil temperature measurements from the study. It is observed that soil temperatures at 1m (24.9ºC) and 2m (26.0ºC) are cooler than the soil temperatures at depths of 3m (26.8ºC) and 4m (27.3ºC) during the hottest months of the year, however at deeper depths the temperatures were almost stable throughout the year. The soil temperatures at the shallower depths were nevertheless not maintained throughout the year but remained below the average daily temperature for a period of 5 to 7 months (shorter time lag, but cooler temperature). During the coolest months, the soil temperature at 1m usually rises to circa 30.3ºC and 30.5ºC (July and August) while the temperature at 3m (28.1ºC and 28.6ºC), and 4m (27.5ºC and 28ºC) remains close to the annual average of 27.7ºC. The temperature of the earth at depths of up to 3m in the study area is between 26.1ºC and 28.9ºC (longer time lag, but higher temperature) annually. At a depth of 1m, the mean quarterly soil temperature starting from December to March is 24.9ºC when the mean maximum ambient temperature is 38.9ºC, while at 2m, 3m and 4m it is 26.0ºC, 26.8ºC, and 27.3ºC respectively. At the depth of 1m, the soil temperature remained below 27.2ºC in the hottest months (November to April) when the daily maximum temperature is at an average of 37.3ºC. The soil temperature at 1m was between 24.4ºC and 25.6ºC between December and March, and it was 26.3ºC in April (5 months below 27ºC). At the depth of 3m, the soil temperature was below 27ºC between January and May at 26.9ºC and 26.7ºC respectively and remained between 27.3°C and 28.9°C for the rest of months. Research has indicated that air supply from PVC based compartments including vents and pipes may have some adverse effects on health of users exposed to it over an extended period (Ohlson & Hardell, 2000; Tickner, Schettler, Guidotti, McCally, & Rossi, 2001).

A survey by Ohlson and Hardell (2000), on 148 cases of testicular cancer and 314 healthy controls collected information on life-time working histories and specific exposures and found that there is six times increase in the risk for seminoma, (a type of testicular cancer), among plastic workers who have been exposed to polyvinyl chloride (PVC).

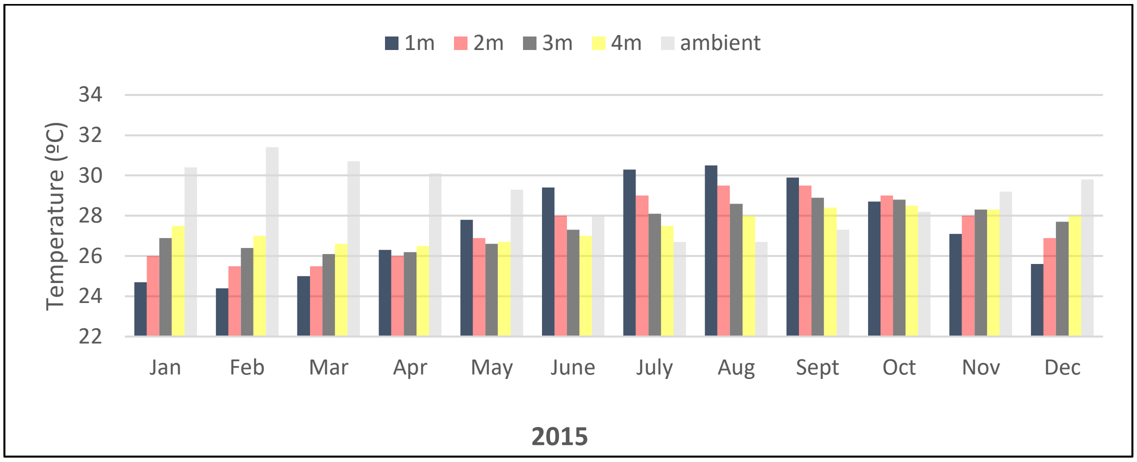


Figure 5. 36 Monthly Soil Temperature Variations at various depths

For ease of fabrication and construction in the test cell (that will not be occupied), 50mm diameter PVC pipes were used. A comparison of the thermal characteristics of other piping materials available is presented in Table 5.4.

Table 5. 4 Thermal conductivity coefficient of various pipe materials (Hijazi, 2018)

Material	Symbol	Thermal Conductivity (W/(m. K)
Polyvinyl chloride	PVC	0.14 - 0.19
Polyethylene (Little density)	LDPE	0.35
Polyethylene (High density)	HDPE	0.43 – 0.52
Polypropylene	PR-R	0.24
Polybutylenes	PB	0.23
Aluminum -Plastic	PAP	0.45

It has been established that cooling effects in PPGPVs is a function of heat exchange between 3 mediums namely the Earth (heat sink), the compartment (pipe) and the fluid (air). The proposed underground cooling system (PPGPV) consists of a 50mm diameter PVC pipe laid at a depth of 1m. The heat exchange pipes are bent in six loops of 1.2m with each connected by elbows to create turbulence at the corners where the air changes direction. Turbulence is known to increase heat transfer (Livingood & Hrycak, 1973). The total length of the PVC pipe used is 9.6m. Prior to this, a shallow pit of 1.4m x 1.4m x 1m was excavated and prepared for the placement of the PVC pipes (Figure 5.36). The pipes are constructed in horizontal and serpentine manner with bends to increase turbulence (Figure 5.37 (a)). The PVC pipes are then carefully laid in the pit and then covered with loose Earth Figure 5.36 (b-d). The air outlet ends of the pipe is coupled to the test cell while the air inlet is coupled to a plenum designed to thermally resist the influences of sun's direct heat on the pipe. The details of the installation and plenum are shown in Figure 5.38. The walls of the plenum are constructed with 2 numbers of 100mm thick solid clay bricks separated by a thickness of 300mm of space filled with mud. The external wall is insulated and finished with a layer of plaster and vitrified ceramic tiles. Two chambers were provided inside the plenum and separated by a reinforced 75mm thick slab with holes to pass vent pipes. The upper chamber is filled with mud after carefully laying the air inlet pipe while the lower chamber remains void for air turbulence and flow.

Figure 5. 37 The PVC pipes held in place before installation (a). 1.4x1.4x1m depth pit to receive the underground pipes and (b). Coupling of 50mm diameter PVC pipe to the experimental cell (c) and in-blower fans connected to PVC inlet pipe from underground pipes before floor finish (d)

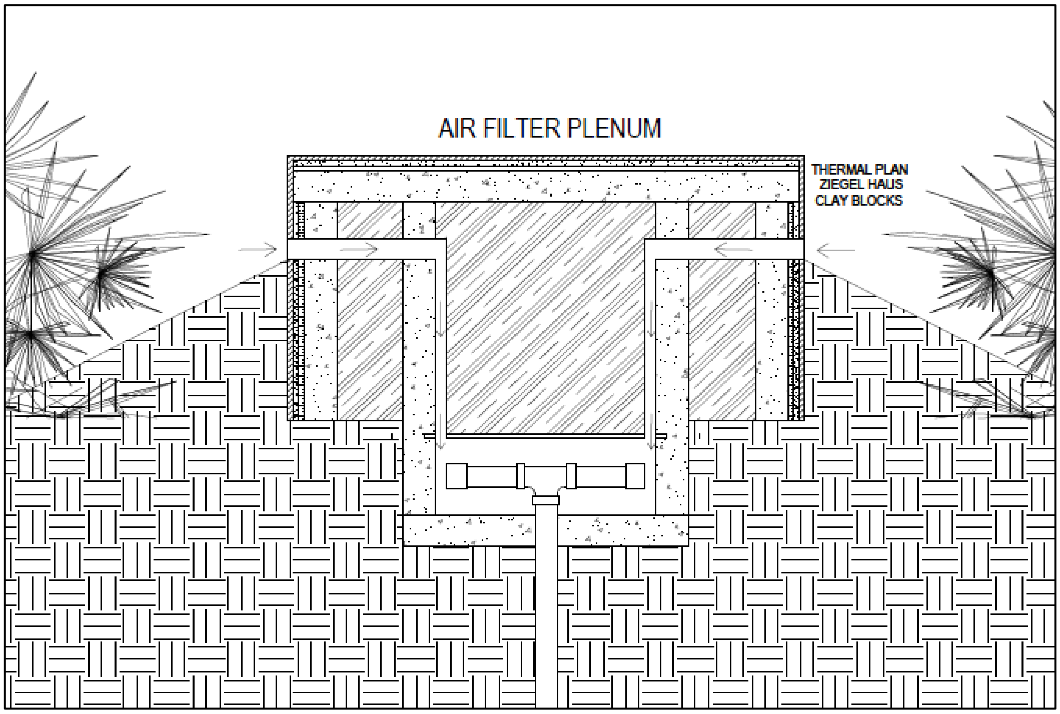


Figure 5. 38 Details showing shading, thermal mass, construction and installation of air pipes in plenum

The plenum is then covered with a 150mm thick concrete slab. Openings were created on the sides of the plenum to admit fresh air into the pipe.

Optionally, the plenum can be watered overnight when the earth temperature has risen due to prolonged daily use/exposure to sun’s radiation during the peak period. Introducing cool night air into this system could also effectively heat flush the earth providing additional chilling capacity for the subsequent day.

Figure 5.39 presents a comparative assessment between the temperature readings in the indoor spaces in CC_1 and PCS_1. It was observed that the application of ground pipes could reduce the air temperature by up to 8°C. The mean temperature difference between the ambient temperature and PCS_1 in the day (from 10:00 hours to 19:00 hours) was 6.4°C, while the mean temperature difference between the ambient temperature and CC_1 in the day (from 10:00 hours to 19:00 hours) was 4.6°C. Application of PPGPV was able to maintain room temperature at 29°C and below till 12:00 hours when the ambient temperature has risen to 36.1°C but remained above comfort range till around midnight. Daily hourly temperature difference of up to 3.3°C was recorded between CC_1 and PCS_1 during peak hours. There was a 9.4% drop in indoor temperature, and a 21.1% drop in the ambient temperature during peak hours because of the application of PPGPV system.

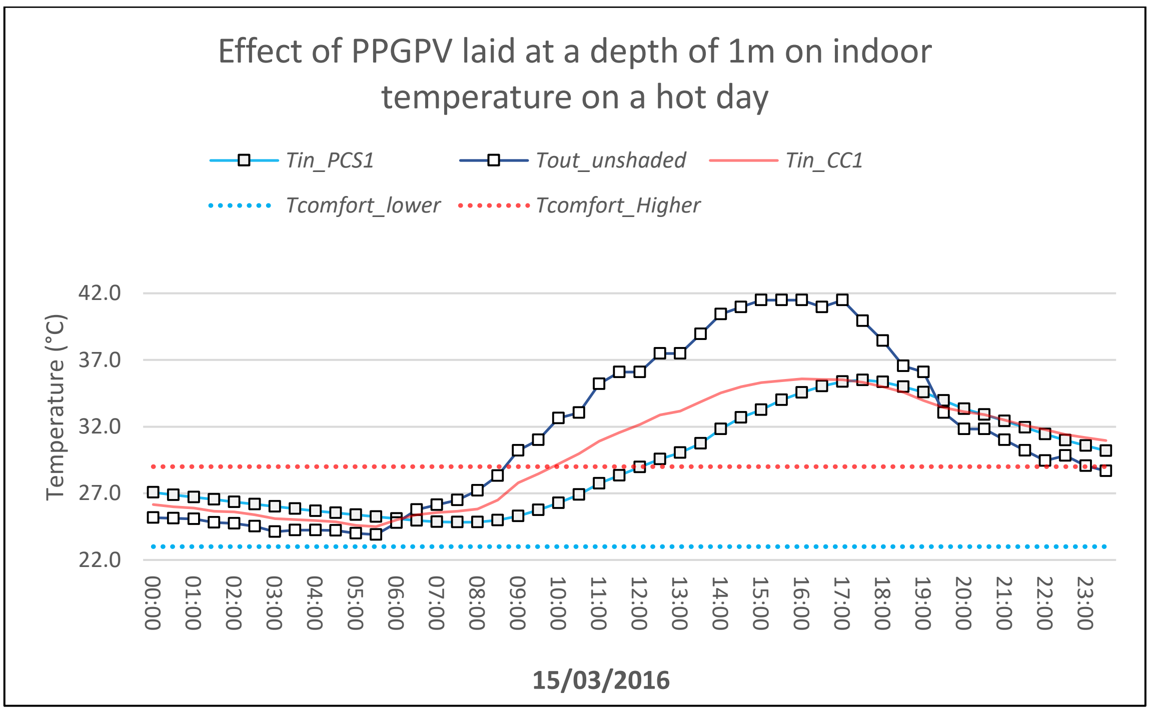


Figure 5. 39 Effect of PPGPV laid at a depth of 1m on indoor temperature on a sunny day

This result is then compared to the readings when shade was applied over the inlet pipe. The aim of this comparison was to confirm the temperature differences at the pipe inlets as a function of shading by covering the pipe air inlet with a thermally designed plenum.

The two air temperatures were plotted alongside each other and the results are presented in figure 5.40.

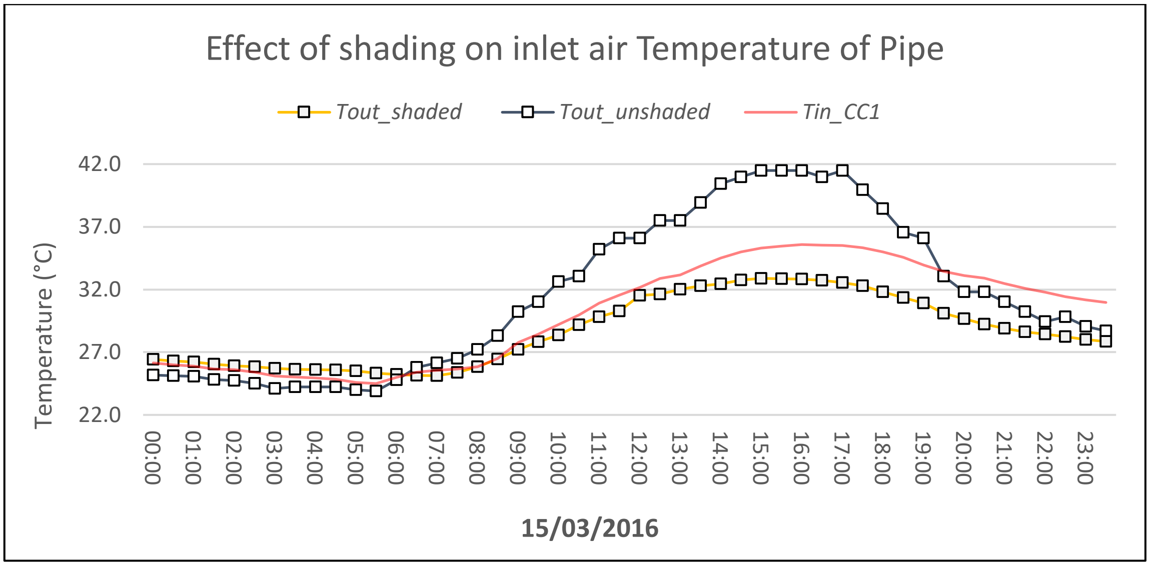


Figure 5. 40 Effects of shading on inlet air temperature of pipe

The air temperature of the shaded pipe was lower than the air temperature of the un-shaded pipe and lower than the indoor air temperature of the un-shaded system CC_1. An hourly temperature difference of up to 8.9°C was achieved by covering the air inlet with a plenum during peaks.

The average temperature difference achieved by shading on air inlet temperature between 10:00 hours and 19:00 hours was 6.6°C. The maximum temperature difference between the temperature of the shaded air inlet and the indoor temperature of CC_1 was 3.7°C around 20:00 hours, and a mean temperature difference of 2°C between 10:00 hours and 18:00 hours. There was a 20.2% reduction in air inlet temperature by the application of a thermally constructed plenum as a shading device for air inlets for the PPGPV.

Having reduced the air inlet temperature, it was now necessary to determine the effects of the reduced air temperature on the indoor temperature of the test cell.

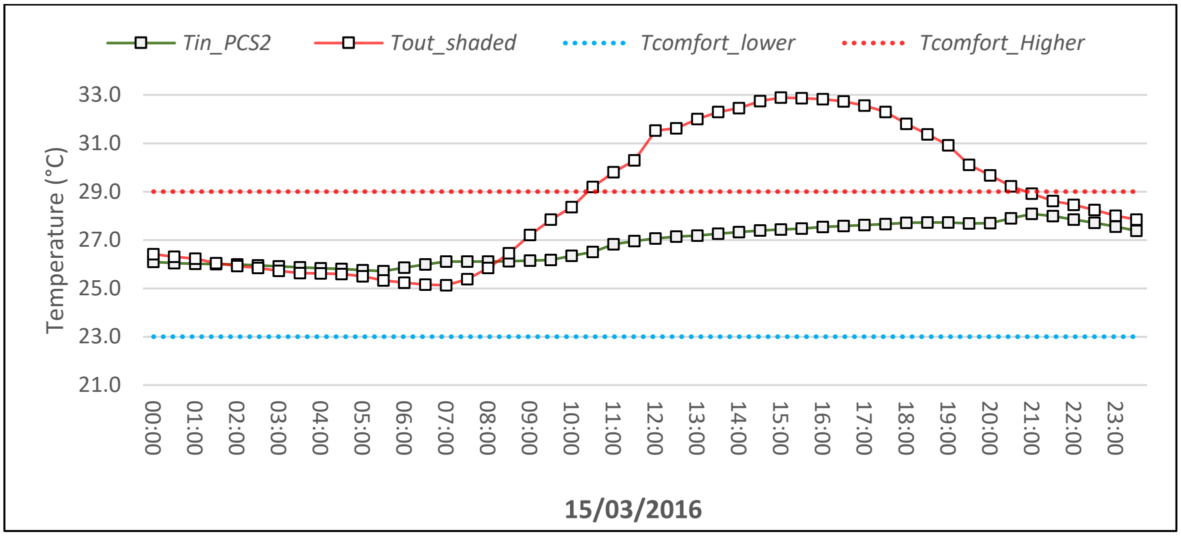


Figure 5. 41 Effects of shading on indoor Temperature

The effects of shading on indoor temperature is presented in Figure 5.41, room temperatures between 26.1°C and 27.7°C were recorded between 10:00 hours and 19:00 hours. The maximum temperature differences between the inlet and the outlet was 5.5°C around 15:00 hours, while the average temperature difference between 10:00 hours and 19:00 hours was 4.3°C. There was a 16.7% further reduction in the inlet temperature, and a 34% reduction of the ambient temperature in the indoor of PCS_2. The application of a shading strategy reduced the indoor temperature recorded in CC_1 by up to 22.4%.

Figure 5.42 presents a comparison of temperature fluctuations in all the scenarios as a function of application of the PPGPV cooling system. The shaded pipe inlet reduced room temperatures by 8°C during peak periods (15:30 hours and 16:30 hours), while the average temperature reduction recorded from 10:00 hours to 19:00 hours was 6.4°C and indoor temperature was maintained at an average of 5.2°C reduction between 19:00 hours to 23:30 hours.

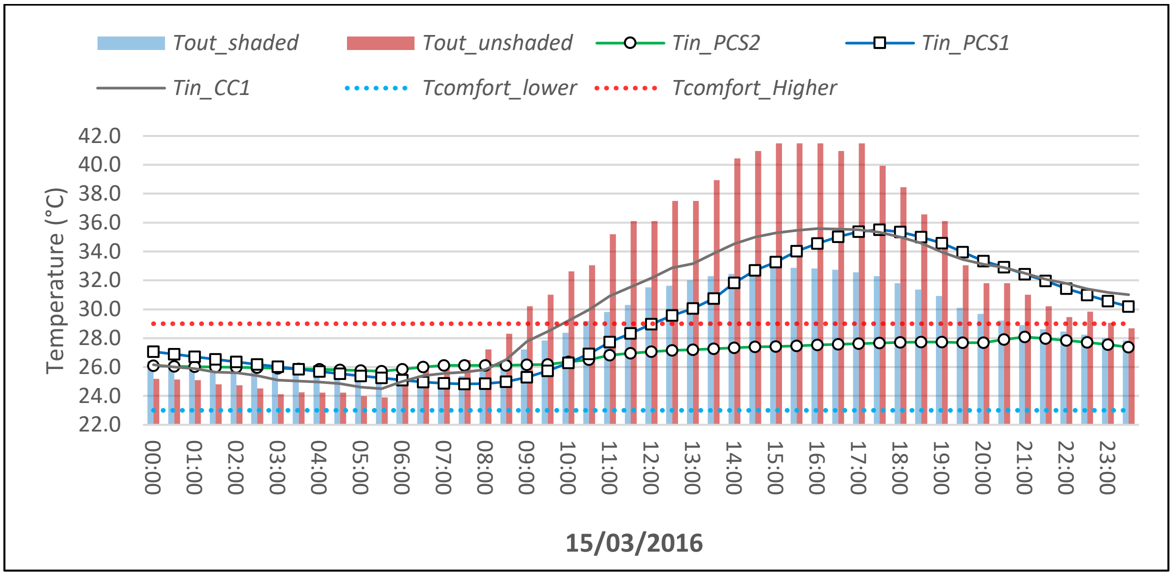


Figure 5. 42 The influence of shaded and bare soil on indoor temperature

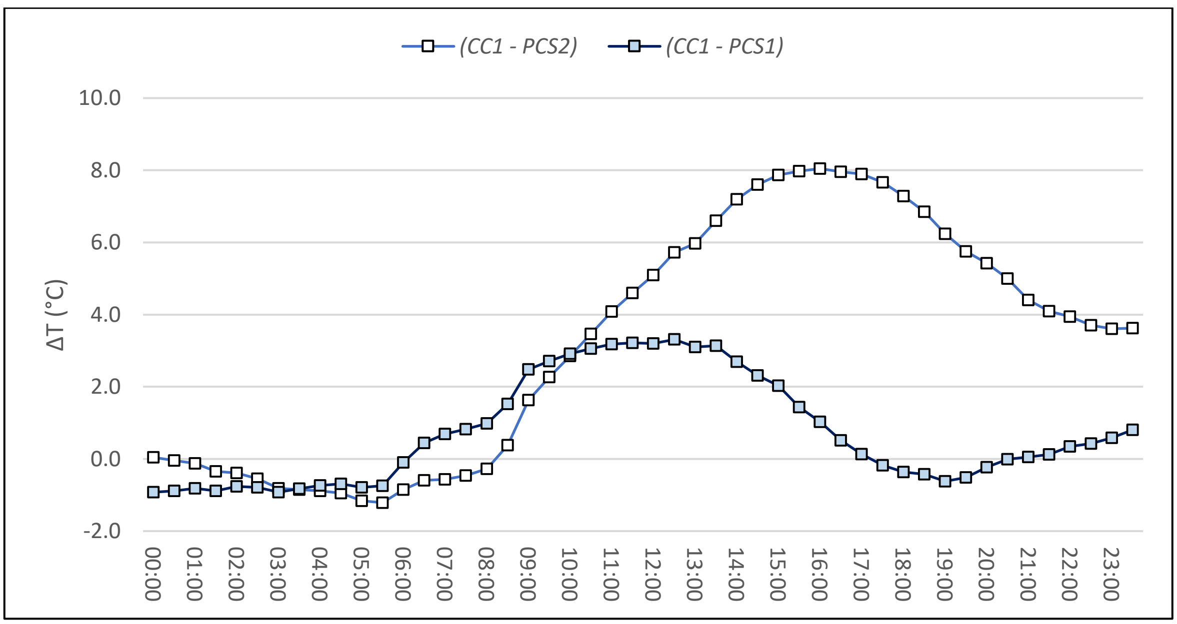


Figure 5. 43 The influence of shaded and bare soil on indoor temperature

Figure 5.43 presents the indoor temperature reductions as a result of the application of a ground pipe in the shaded and un-shaded situations. ΔT was calculated by using the temperature in CC_1 as the reference temperature. It was observed that ΔT was higher when shading was applied over the air inlet to the system. A maximum temperature reduction of 3.3ºC was recorded by 12:30 hours in the un-shaded scenario while temperature reductions in the shaded scenario was 3.5ºC around 10:30 hours and consistently increased to a maximum of 8ºC between 15:30 hours and 16:30 hours, when there was a gradual decline to around 3.6ºC by midnight.

5.6.1 Thermal comfort and Energy/Cooling load reduction due to application of PPGPV

The prototype scale model tests identified low thermal capacity of building fabric as a significant factor in heat regulation and in turn the reason for the relatively high levels of domestic energy demand for cooling. After the modifications there was a significant reduction in indoor temperature, however, the modification alone could not sustain indoor temperatures within the comfort range of 23°C and 29°C throughout the day, and as a result a PPGPV was applied as a cooling measure.

Figures 5.44 presents a psychometric Chart showing the indoor thermal condition in a room space ventilated by a PPGPV system. Relative humidity readings are in the range of 47.3% to 76.4%, while the indoor temperature was circa 28.1°C and 25.7°C respectively. It is observed that temperature was maintained within comfort limits although it tended more towards the upper comfort limit during the nights when the system is shut down. Temperature readings above the upper comfort limit may likely occur with rise in ambient temperature or prolonged use of ground cooling system due to heat gain in the soil. Relative humidity readings were slightly above 75% on the upper scale but within the comfort zone on the lower scale. The application of positive pressure ventilation through PPGPV on a thermally enhanced building fabric sustained indoor temperature within comfort limits most of the time during the day but tended towards the upper limits overnight. The cooling effect of the ground pipe is clearly not sufficient to ensure the internal environment is kept within the target limits.

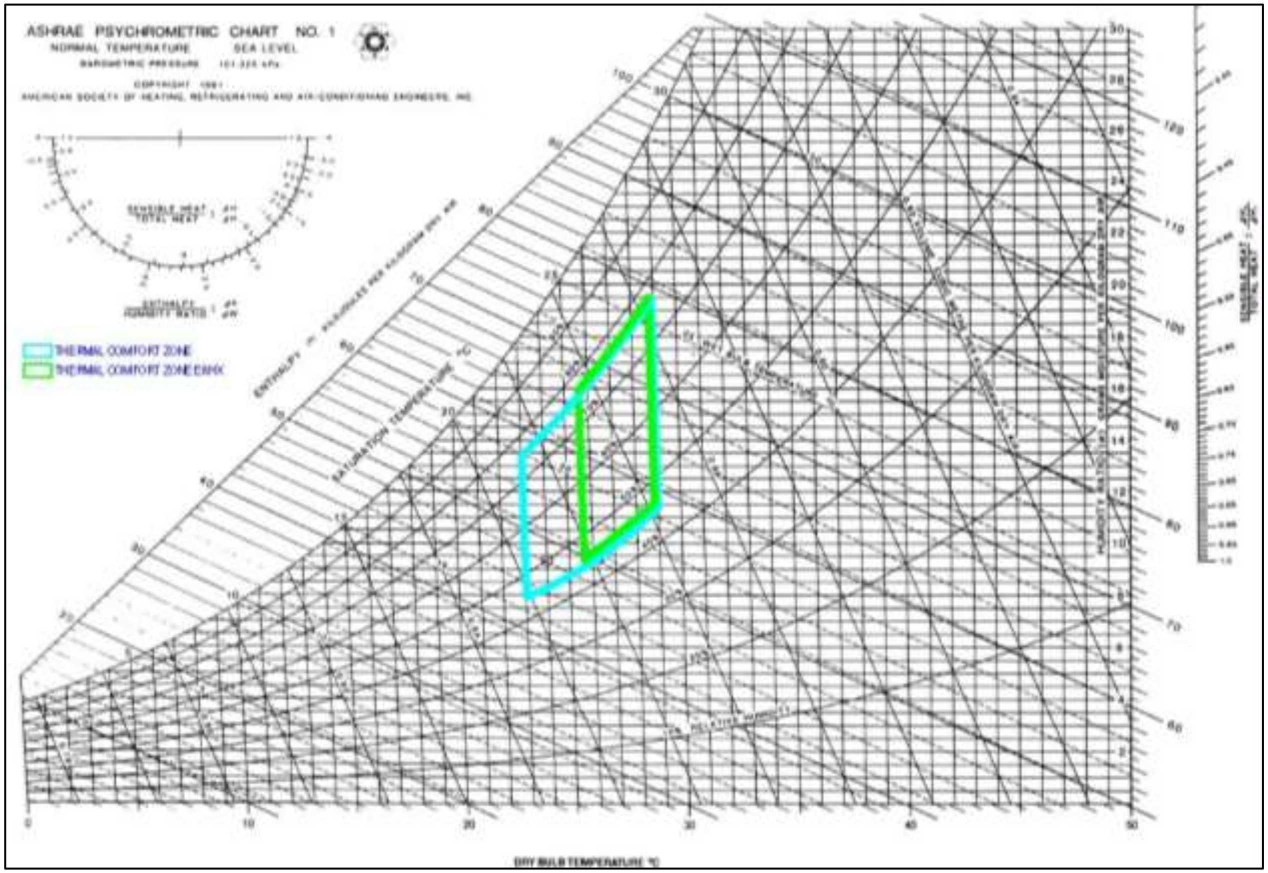


Figure 5. 44 Psychometric chart showing the comfort zone and the effects of PPGPV in combination with a modified building fabric on indoor thermal comfort

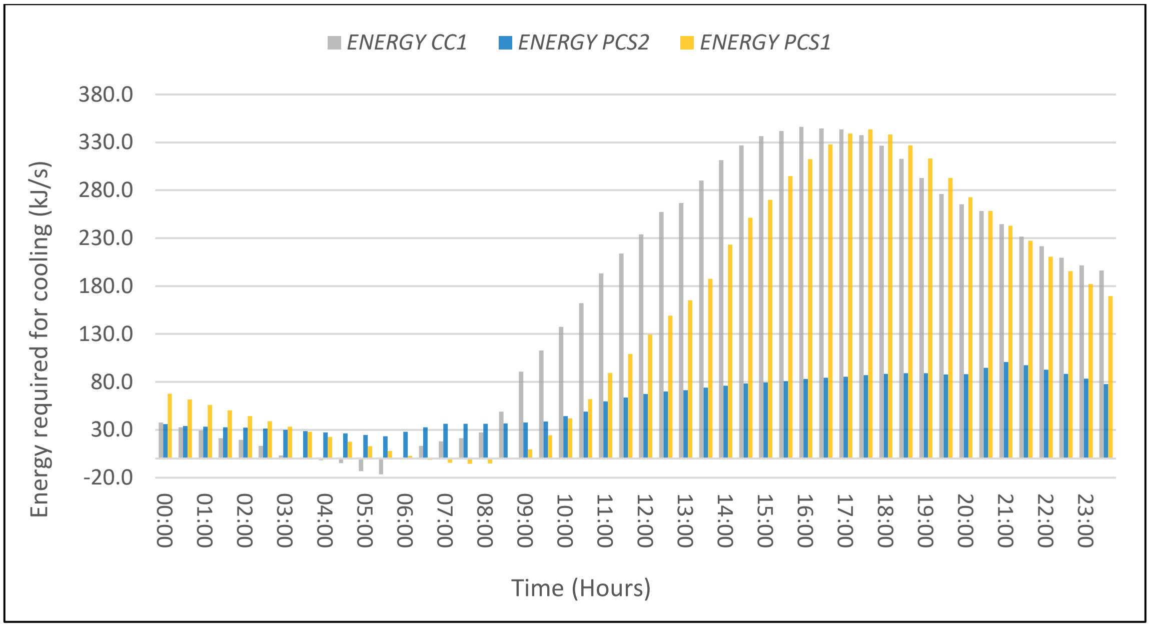


Figure 5. 45 Effects of PPGPV combined with modified building fabric on Cooling Energy demand in a 27m^3 bedroom with thermostat set at 25°C

Figure 5.45 presents the energy required for cooling a room of 27m^3 in a retrofitted building envelope over the base case scenario. It also presents the temperature reductions in the room space. The application of ventilation through buried pipes in combination with a modified building fabric using thermal mass and insulation was able to reduce the indoor temperature of a room by 22.4% over the base case. The reduction in indoor temperature resulted in a drop of the daily energy demand for cooling of the room from 13.2 kWh to 4.8 kWh, which amounts to 63.8% (when a thermostat is set at 25°C) reduction in cooling energy requirement for the space. The energy requirement for cooling is dependent on the thermostat setting at each instance[14]. Positive pressure ventilation through buried pipes

[14]. Thermostats were set at different settings 23°C, 25°C and 26°C respectively. It was found that energy demand for cooling in both the case building and the modified building fabric decreased when thermostat was set at 26°C giving the values of 9.4 kWh and 2.2 kWh respectively but increased when the thermostat

displaced 8.4 kWh of cooling energy at a thermostat setting of 25°C daily and 253.2 kWh each month in the hot months and at this rate, an average of 3038kWh of energy will be saved annually as against 4761kWh predicted use. There was a further reduction in indoor temperature by the application of positive pressure ventilation channelled through underground pipes and indoor comfort conditions were maintained throughout the day admittedly close to the upper limit. It was observed that the coolth accumulated during the day may not be able to charge the thermal mass walls enough to induce effective sensible cooling when the system is turned off. It therefore becomes imperative to apply another passive cooling strategy that will further boost the results achieved through underground positive pressure ventilation.

5.7 Clear night sky (CNS) roof radiant cooling system

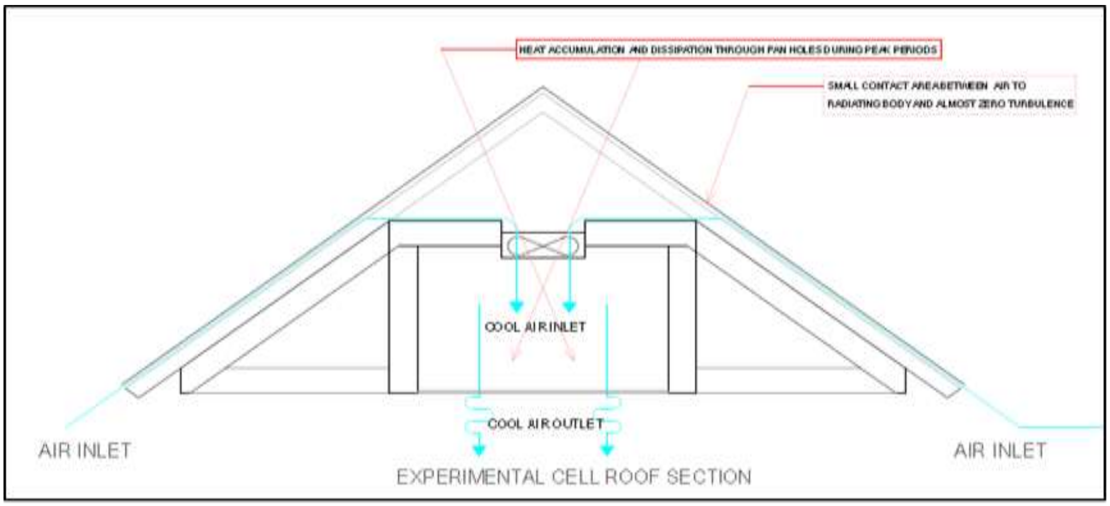
The roof of the experimental cells PCS_1 and PCS_2 were constructed from metal frames and insulated boards producing a U-value of 1.28 W/m^2K. An air circulation cavity was designed to supply and remove air from under the metal roofing sheets. At night, the air loses its heat through convection as its molecules vibrate around the molecules of the roofing sheets under controlled flow rates. In this kind of arrangement, heat accumulation and heat transfer into dwelling spaces in hot afternoons becomes a major concern. The rate of heat transfer from roof to indoor spaces is higher in buildings where ventilation is applied through the roof hence, the roofing system in the proposed passive cooling approach is designed in such a way that during the hot afternoons, heat is flushed from the attic space by either stack effect or via a roof mounted fan - operating on PV generated electricity - installed in the attic. Insulation is used to prevent heat gain through the attic into the main living space. Air is the choice fluid for heat exchange and transfer although it has a

was set at 23°C giving the values of 16.5 kWh and 7.2 kWh respectively. The values of the thermostat setting for room temperature will also determine the percentage of heat energy displaced.

very low thermal conductivity of 0.024 W/mK[15]. The air-based system is easier and significantly more economic to construct when compared with a liquid-based system that will require custom designed copper panels and additional water pumps, valves and frost protection. Cooling systems that use water are more complex in design, maintenance and operational requirements than those that use air. Adaptability to common roofing style was also considered with an air-based system being relatively easy to retro-fit. Figure 5.46 presents the proposed roof design for the radiating system; it shows the air flow directions and the plenum for desiccant storage and air filter pellets. An investigation was carried out in a case study (chapter 4) to determine the sky temperature during the periods with clear skies and it was found that sky temperatures can be as low as -9°C in January and 12.6°C in June. A radiant plate was then used as a roof cover for the experimental cells that was placed on an insulated roof framework that will allow air to flow between the roofing material and an insulated plenum cavity. 0.75mm thick aluminum sheets were used as the roof covers, one left untreated and the other painted with a high emissivity black paint. The temperature of the plates was measured hourly with thermocouples throughout the night starting from 21:00 hours to 8:00 hours. The minimum temperature of the painted plate was 17.3°C between midnight and 6 am, while that of the unpainted plate was 23.4°C over the same time frame. This demonstrated that the thermal properties/emissivity coefficient of the roofing material plays a key role in the systems overall cooling potential. During the night the effective sky temperature dropped below the ambient to a minimum average temperature of -4.8C in January, which is about 24°C lower than the daily average minimum ambient temperature of 20°C. The temperature of the air cavity fell on occasion as low as 16°C. This confirms the viability of the night sky as a cooling mechanism in the study area, however the performance and efficiency of any system will depend on the quality of the thermal interfaces, the ventilation rate (air speed) and the average seasonal cloud cover. Radiometer readings during the hot season (when skies are at their clearest) dropped to -9°C confirming that

15. The thermal conductivity of air varies with temperature. The Figure used above is for temperatures between 0°C and 30°C. Details of the conductivity of air are found in Table 4.1.

the system is well synchronized to deliver increased cooling potential when demand peaks.



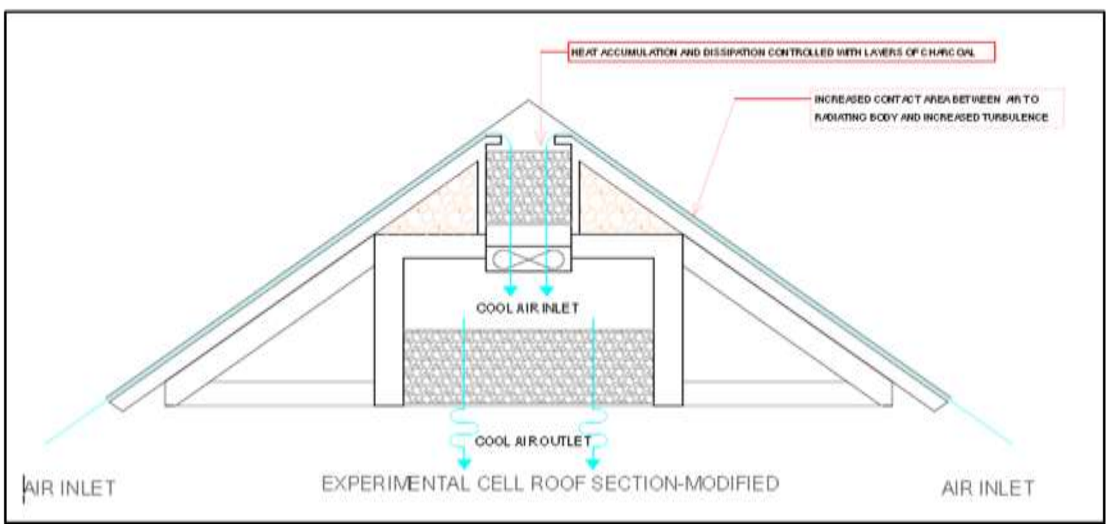


Figure 5. 46 Sections through roof attic as modified for PCS_1 and PCS_2

5.7.1 Testing the system

The roof was set in place and exposed to the sky on the night of 14/03/2016. The setup was powered up at about 20:00 hours and the fans started to draw air into the plenum through the air gap of 10mm provided in the design. The system was left to run throughout the night and was deactivated at 8:00 hours on the morning of 15/03/2016. Figure 5.47 shows the results of the first test. This test was aimed at identifying the effects of clear night sky night radiation on the temperature of air passed under a radiating surface. Air was drawn in at a rate of 1m/s, the minimum air temperature recorded in the air gap was 23.6°C between 5:00 hours and 5:30 hours which was 1.5°C lower than the minimum ambient temperature recorded at night. The average ambient temperature reading for the night was 26.4°C, while the average temperature of the air gap for the night was 25.0°C giving a ΔT of 1.4°C and a 5.3% temperature reduction when air is passed under a radiating surface through a laminar flow pattern. Another setup was arranged where the air flow rate was reduced to 0.3m/s to produce an equivalent of 1 ACH for the volume of the experimental cell, and consequently there was a 1.2°C reduction in the air temperature in the plenum. The results are presented in Figure 5.48. The minimum air temperature attained at the gap was further reduced from 23.6°C to 22.4°C around 5:00 hours, which gives an equivalent of 5.1% decrease. The average air temperature recorded through the night was 23.7°C giving a total of 4.8% reduction of air temperature in the gap and 10.2% reduction of the ambient temperature. The ΔT between the average ambient air and that of the air in the gap was 2.7°C.

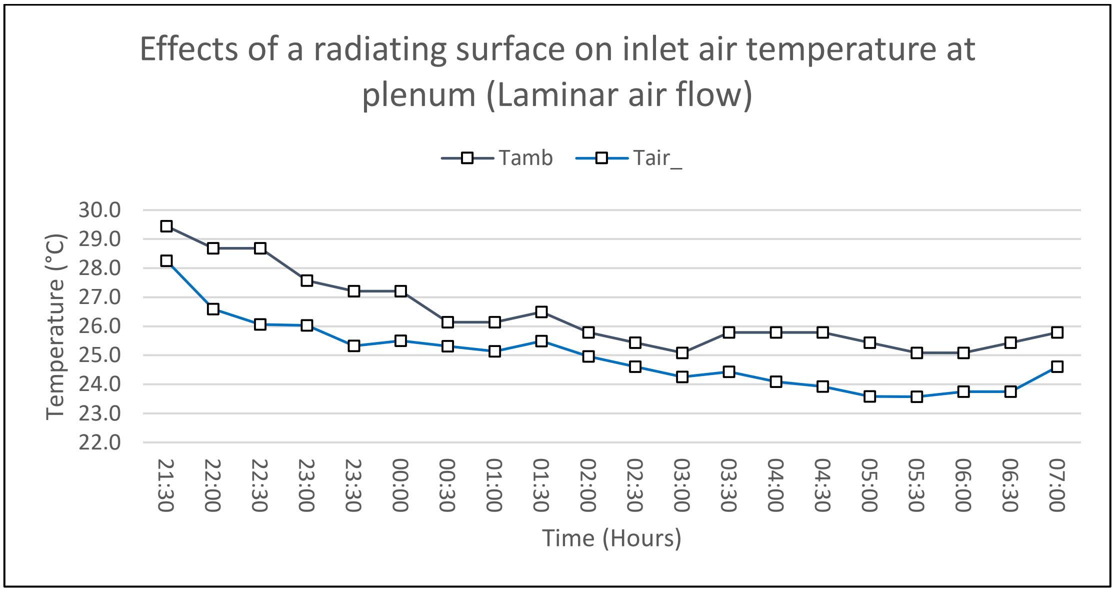


Figure 5. 47 Effects of laminar air flow (1m/s) under a radiating surface on inlet air temperature in the plenum

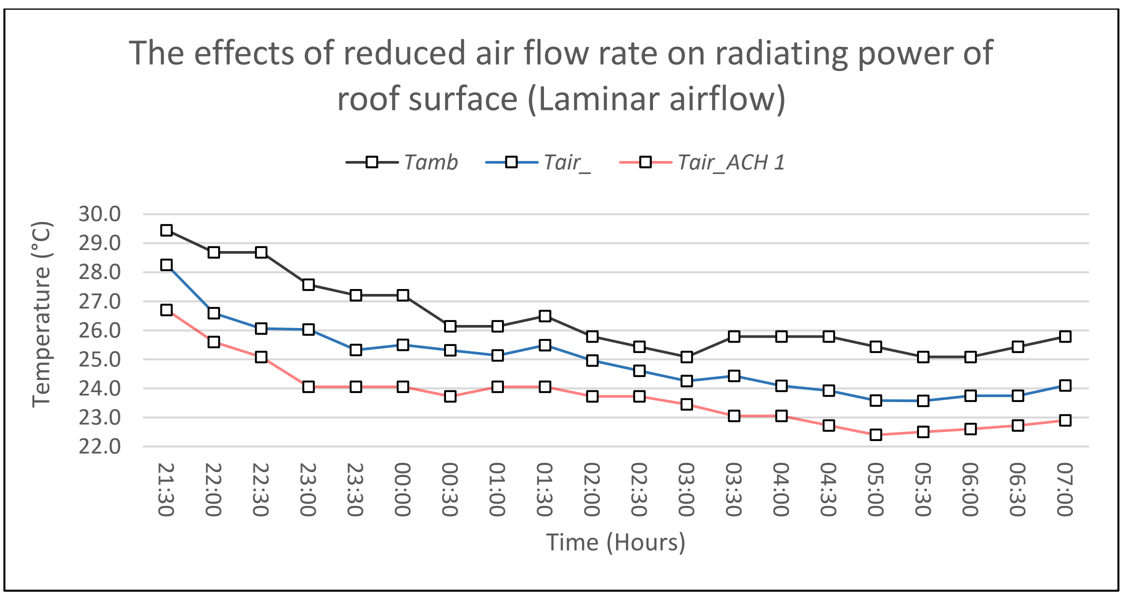


Figure 5. 48 Effects of reduced laminar air flow (0.3m/s) on the temperature of air under a radiating surface

From the results obtained, it was required to increase the interface between the radiating surface and the air molecules. To achieve this, it was necessary to introduce features that would induce turbulent airflow in the air gap as it travels to the plenum. 150 mm x 10 mm x 10 mm studs were arranged in a labyrinth on surface of the plywood and under the roof cover, and then stuffed with fine layer of stainless-steel wires Figure 5.49.

Figure 5. 49 Reconstruction of the roof system to induce turbulent air flow pattern

Air is then passed through the modified roof system at an air flow of 0.3m/s and increased surface area with studs to induce turbulence in the air flow pattern. The results are presented in Figure 5.50. The air inlet temperature was further reduced to 20°C at about 5:00 hours, making it 2.4°C lower than the minimum recorded in the previous set up. The average temperature of air in the plenum throughout the night was 21°C. The ambient temperature was reduced by 20.5%, while the temperature obtained in the previous system was further reduced by 11.4%. The maximum hourly temperature difference between the ambient and the air temperature in the gap was 6.5°C, while the temperature swing of the cool air through the night was 3°C.

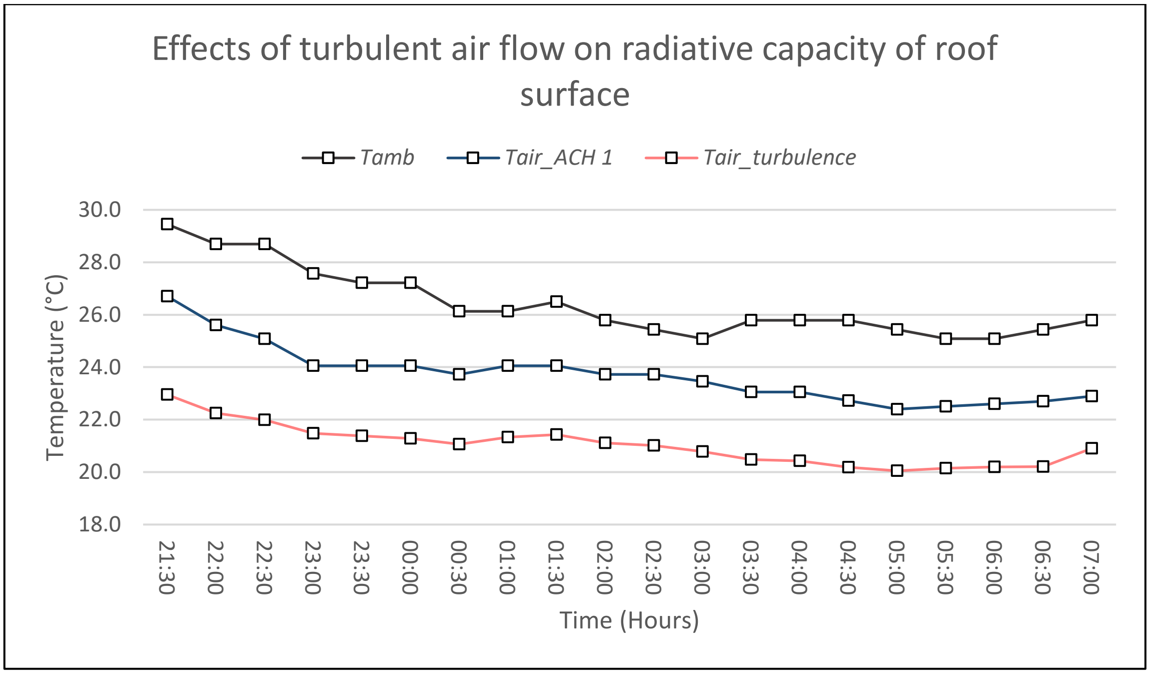


Figure 5. 50 Effects of turbulent air flow regime on the temperature of air passed under a radiating roof surface

Another test was carried out aimed to determine the effects of surface area on the air temperature in the gap. The surface area of the radiating body was increased from 1.82m^2 (1.35x1.35) to 2.84m^2 (2.1x1.35). The same procedure of air movement was then repeated. Figure 5.50 presents the results from the test. Temperature drops were minimal as the lowest recorded air temperature was 19.6°C. The average air temperature throughout the night was 20.6°C giving an average reduction of 0.4C° in the average temperature of air in the previous test.

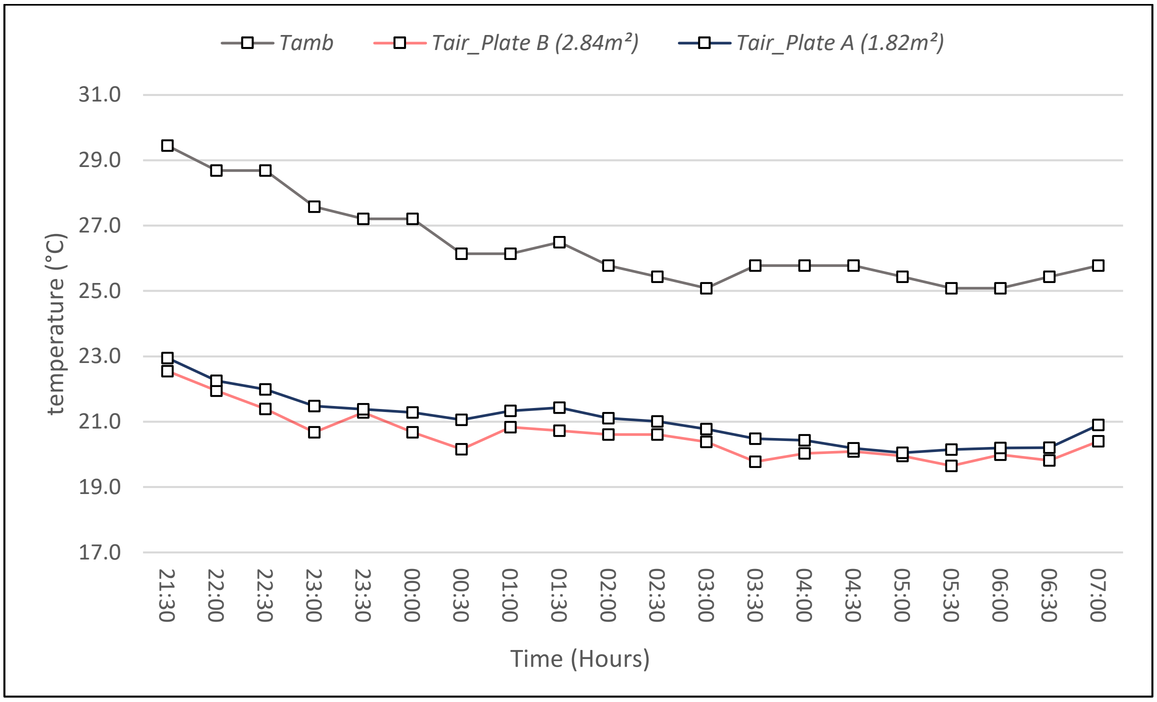


Figure 5. 51 Effects of surface area on the temperature of air passed under a radiating roof surface

Figure 5.51 shows that the modification of the interfaces to increase heat exchange between the radiating surface and the air molecules was able to reduce hourly indoor temperature of the space by up to 7.5°C and maintained an average reduction of 6.5°C indoor temperature reduction throughout the night. The indoor temperature of the Fabric first designed combined with PPGPV between 21:00 hours and 7:00 hours was further reduced by an average of 4.7°C. This technique reduced the average indoor temperature of the PPGPV system at night by 16.6%. Figures 5.52 presents the effects of clear night sky night radiant cooling on indoor temperature of the experimental cells.

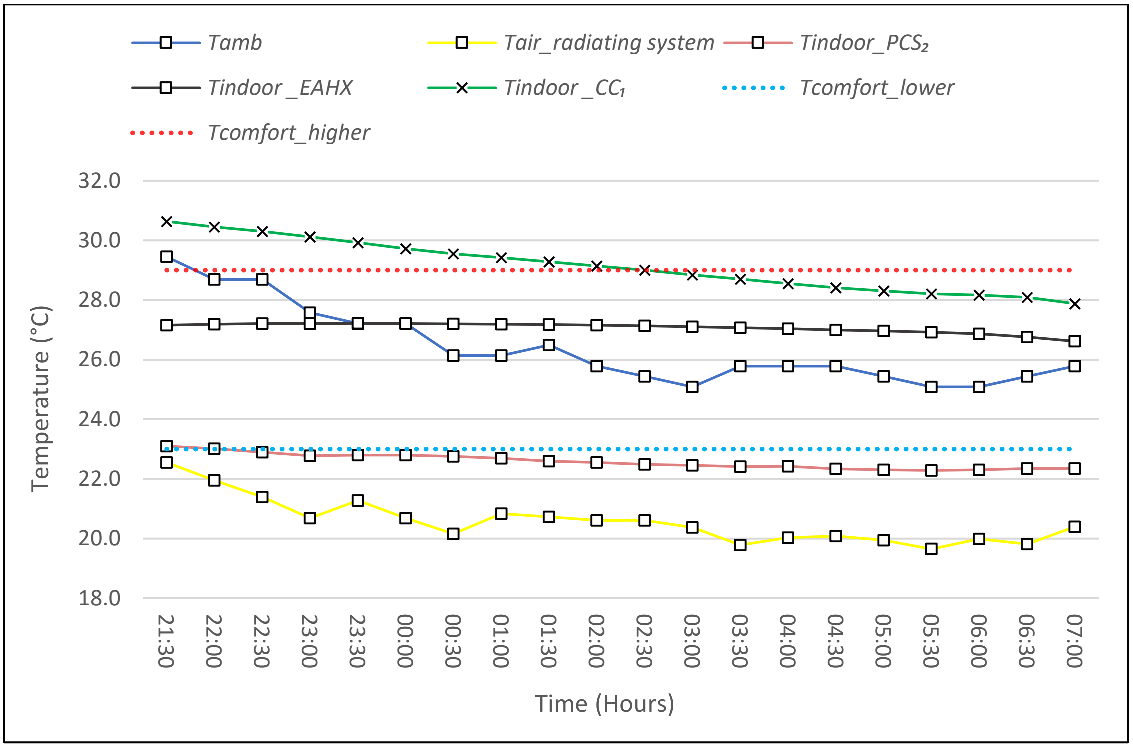


Figure 5. 52 Effects of clear night sky night radiant cooling on indoor temperature of experimental cells

To understand the effects of the length of a radiating surface on the temperature of air in cavity, another test was carried out using a radiating surface of 0.9m x 5m. Data loggers were placed at points 1m, 2m, 3m and 4m respectively, and air was introduced from one end of the radiating plate into the roof cavity. Fig 5.53 and 5.54 present the results showing different air temperatures at different points on the radiating surface. The air temperature was 28°C at 1m, 23.8°C at 2m, 18.8°C at 3m and 18.5°C at 4m on 12/12/2018, while it was 25.8°C, 23.4°C, 20.4°C and 20°C at 1m, 2m, 3m and 4m respectively on 29/12/2018. The average surface temperature of the radiating plate was 23.1°C, 22°C, 18.9°C and 14.7°C at points 1m, 2m, 3m and 4m respectively. These results indicate a reduction in air temperature as length of radiating surface increases. However, it remained relatively constant between 3m and 4m. Surface temperature on the other hand decreased with an increase in the length of the radiating surface which also was relatively constant after a length of 3m.

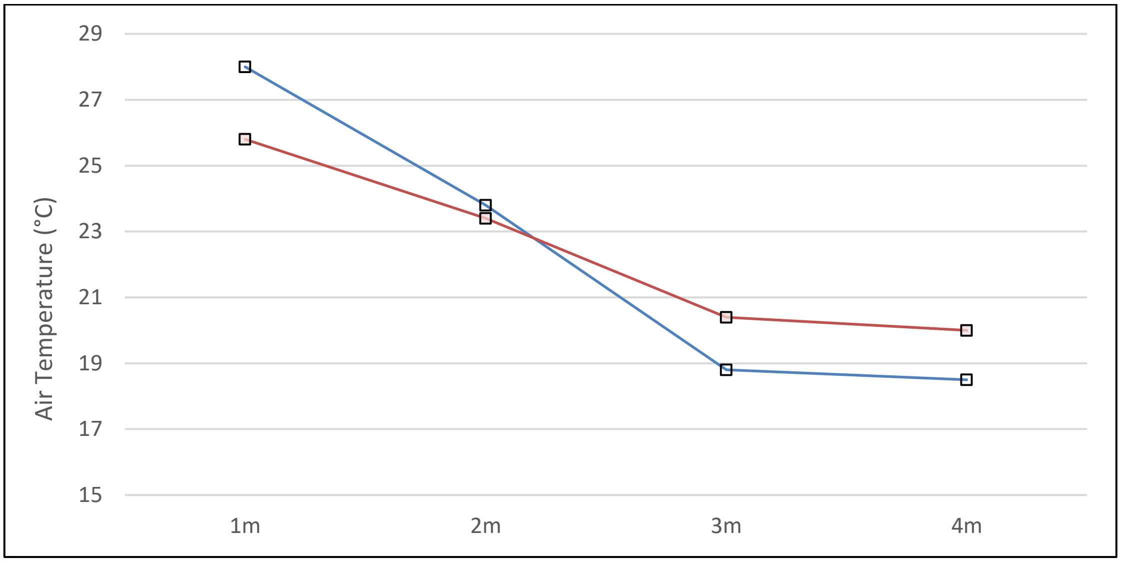


Figure 5. 53 Effects of length of radiating surface on air temperature

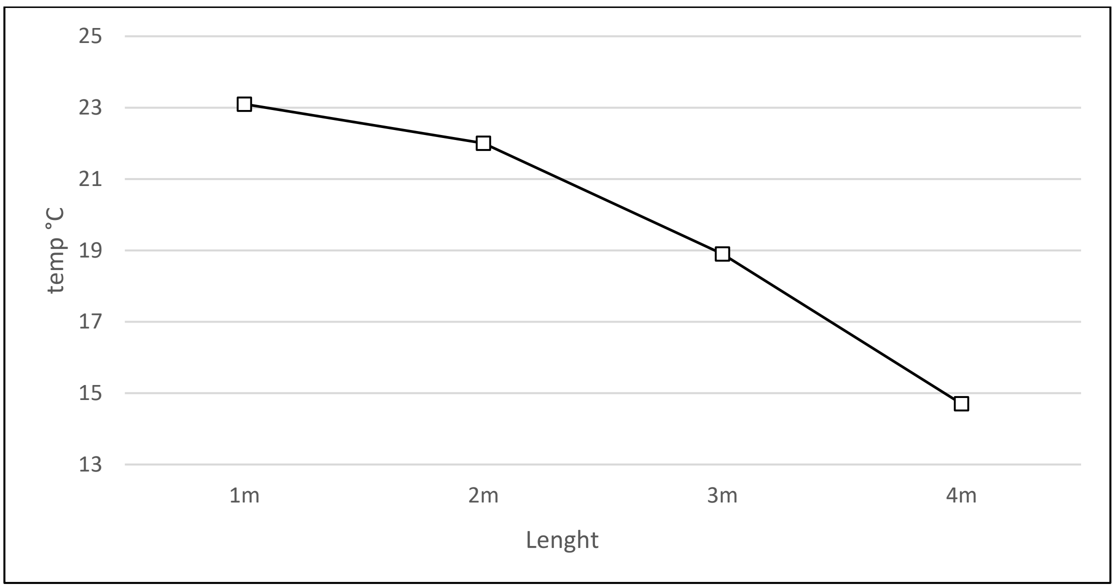


Figure 5. 54 Effects of length of radiating plate on surface temperature

5.7.2 Thermal comfort and Energy/Cooling load reduction due to application of Clear night sky radiant cooling

The building fabric was modified and tested and there was a significant reduction in indoor temperature, however the modification of the building fabric on its own could not sustain indoor temperatures within the comfort range of 23°C and 29°C throughout the day and as a result, PPGPV was applied as a cooling measure to boost the effects of the modified fabric on indoor thermal comfort setting. The application of PPGPV reduced the indoor air temperature and relative humidity substantially. The application of positive pressure ventilation through PPGPV in a thermally enhanced building fabric sustained indoor temperature within comfort limits during the overheated periods of the day but inclined towards the upper limits towards the nights. The cooling achieved by this application may not be enough to provide sensible cooling throughout the night when the building is fully occupied, therefore clear night sky heat flushing was added to produce a combined impact.

Figure 5.55 presents a psychometric chart of the indoor thermal condition in a room space ventilated by the CNS radiating system. The relative humidity was in the range of 50% and RH 73% while the indoor temperature was around 22.3°C to 26.8°C respectively. These temperatures fall within the comfort targets.

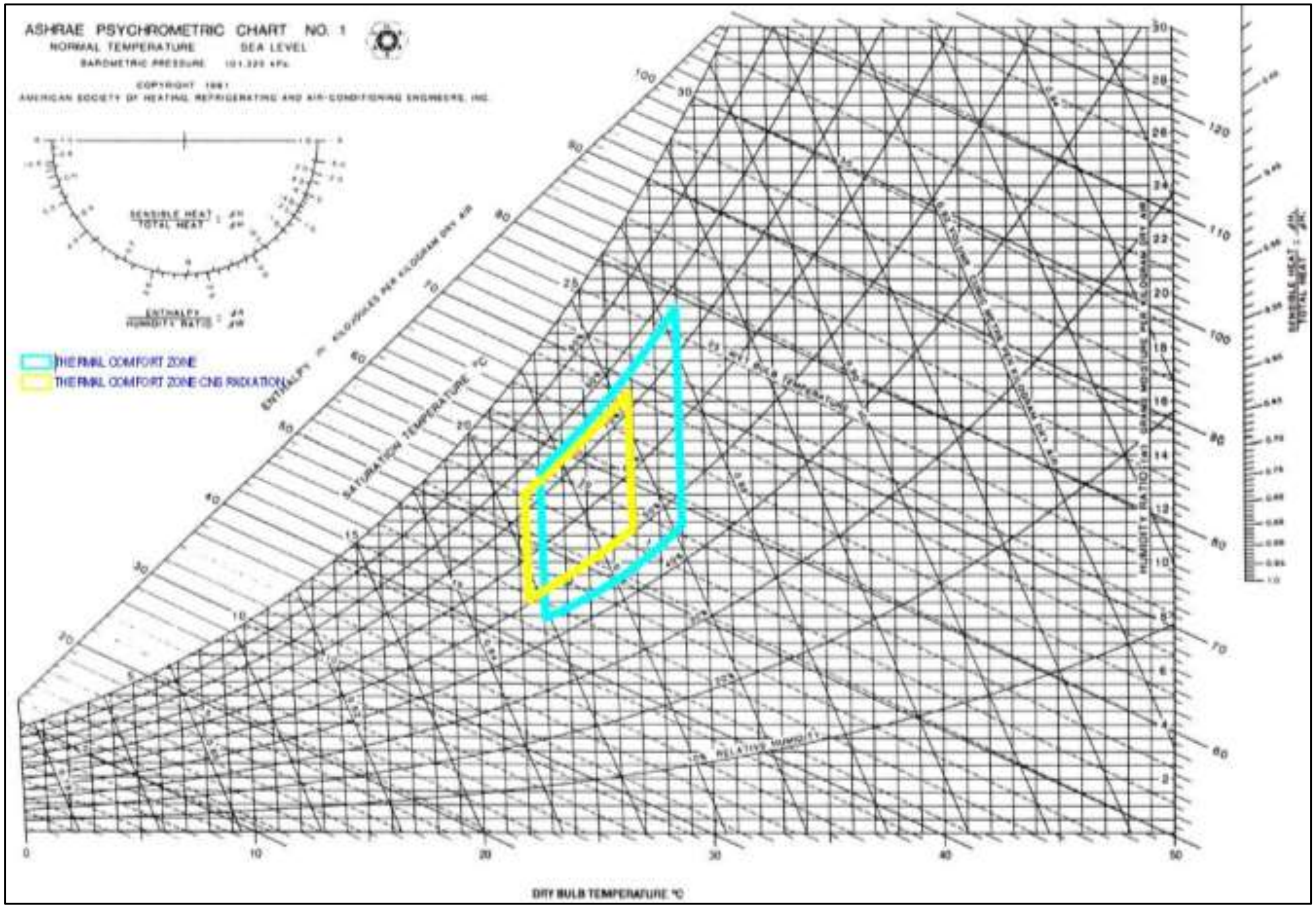


Figure 5. 55 Psychometric chart showing the comfort zone and the effects of clear night sky radiation in combination with a modified building fabric on indoor thermal comfort

Figure 5.56 presents the energy required for cooling a room of $27m^3$ using CNS radiating system in a retrofitted building envelope over the base case scenario. The application of clear night sky radiant cooling in combination with a modified building fabric using thermal mass and insulation was able to reduce the indoor temperature of a room by 22.3% over the base case. The reduction in indoor temperature resulted in a drop of the daily energy demand for cooling of the room from 4.5 kWh to -2.1 kWh, which amounts to 104.7% (when a thermostat is set at 25°C) reduction in cooling energy requirement for the space. The energy requirement for cooling is dependent on the thermostat setting at each instance[16]. The clear night sky radiating system displaced 6.8 kWh of cooling energy at a thermostat setting of 25°C per night and 204kWh was displaced each month. At this rate, an average of 2,448kWh of cooling energy will be displaced annually as compared to the case building.

There was a substantial reduction in indoor temperature by the application of clear night sky radiating system and indoor thermal conditions were maintained throughout the night with residual coolth available to suppress day time solar gains.

[16]. Thermostat settings at 28°C and 29°C can generate cooling energy of 5.4 kWh and 6.5 kWh per night of clear night sky for a bedroom of $27m^3$. The amount of coolth generated and stored will depend on the user preference on required indoor Temperature. Thermostats set at 23°C may not be able to generate storable coolth as the system loses most of its accumulated coolth in the shaft to keep the indoor at such a low temperature.

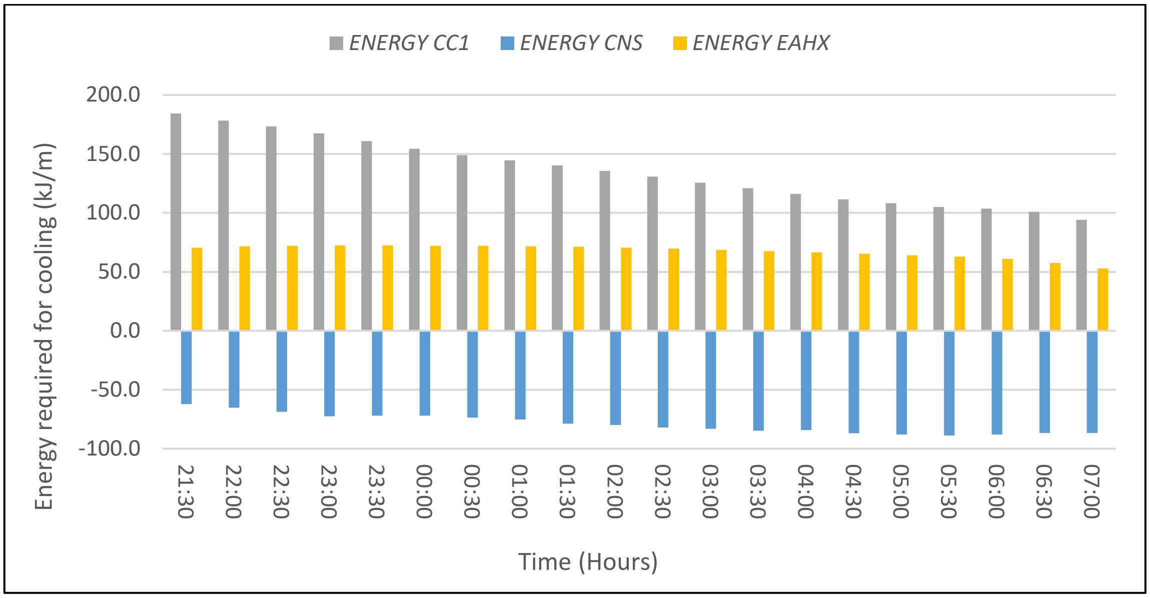


Figure 5. 56 Effects of CNS radiating system combined with modified building fabric on Cooling Energy demand in a 27m^3 bedroom with thermostat set at 25°C

It is observed that the coolth accumulated during the night may sustain the indoor condition of a room up to a certain period the next day before internal heat gains becomes significant. Therefore, combining the PPGPV and the CNS to operate sequentially provide additional synergy. The aim is to reduce indoor room temperature in the night while storing any excess 'coolth' to cool the dwelling as the system is switched to PPGPV. Thermostats placed directly under the roof surface will trigger fans when clear night sky radiation has reduced the temperature to below the indoor air temperature, with the PPGPV being activated by CO_2 sensor. This system can also be deactivated with a thermostat when the indoor temperature is lower than the air temperature at the pipe supply in the plenum and CO2 levels are below 1000ppm.

Figure 5.57 presents a summary of the total effects of all the cooling strategies applied in the experimental set up. The effects are presented in two modes namely a daytime and nighttime mode. Figure 5.58 presents a psychometric chart of the general effect of the applied systems in this study. It also depicts a comparative assessment with ASHRAE standard 55 thermal comfort recommendations for tropical zones and the acceptable thermal comfort boundaries.

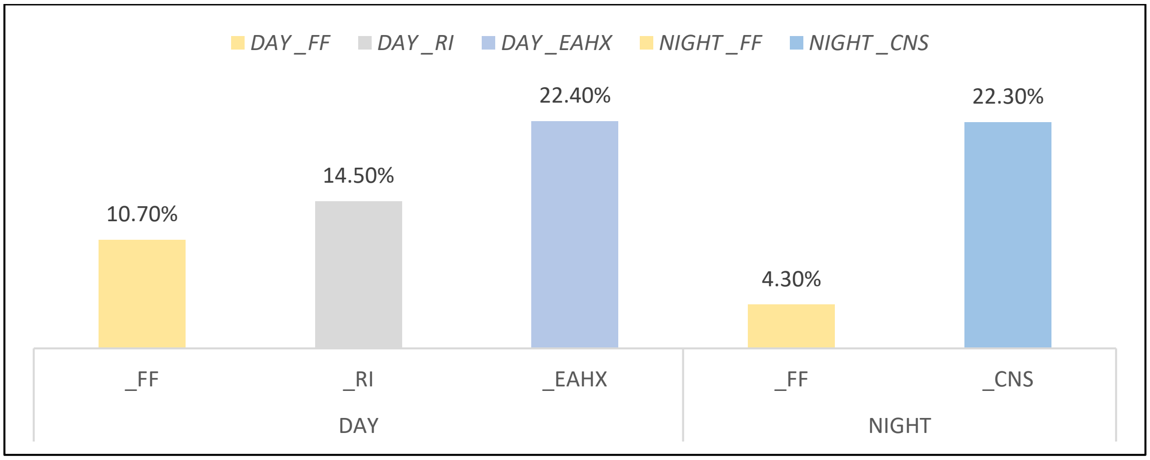


Figure 5. 57 Percentage temperature reduction/heat displacement of different approaches on the indoor temperature of the experimental cells. Fabric first (FF), roof insulation (RI), earth to air heat exchanger (PPGPV), and clear night sky radiating system (CNS)

Fabric first modifications reduced indoor temperature by an average of 10.7% during the day and 4.3% at night, while roof modifications and insulation reduced indoor temperature by an average of 14.4% during the day. Roof insulation did not have a significant effect on the indoor temperature at night. Air supply into buildings using PPGPV reduced indoor temperature by an average of 22.4% in the daytime. The clear night sky radiant cooling system reduced indoor temperature by 22.3% with residual coolth being stored in the insulated thermal mass suppressing daytime temperatures. It is therefore observed from the results presented that the cooling capacities of the applied passive systems namely (PPGPV) and clear night sky (CNS) radiant cooling can be synergized when they work sequentially.

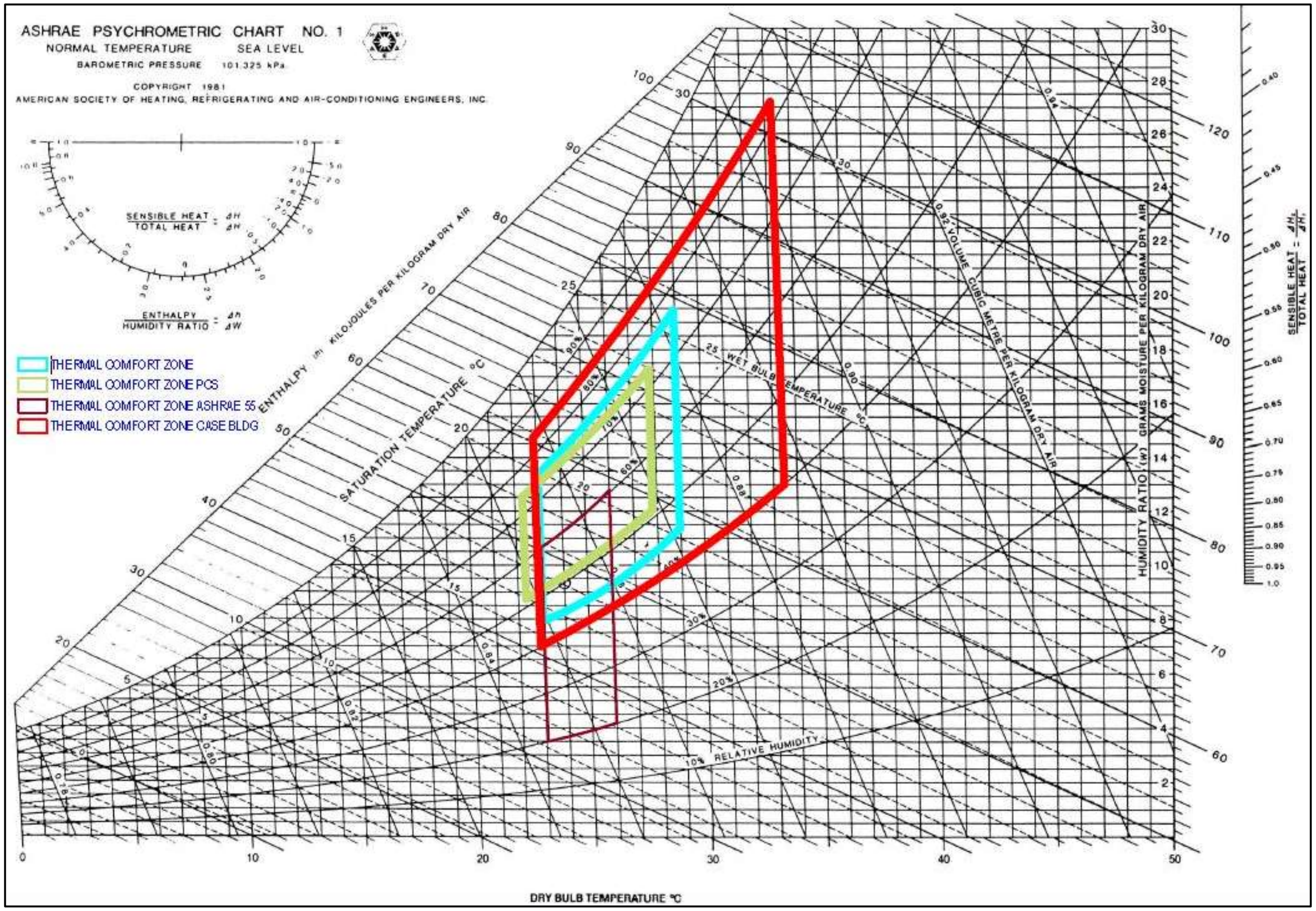


Figure 5. 58 Psychometric chart showing a comparative assessment between the ASHRAE 55 thermal comfort boundaries for tropical zones, comfort boundaries from other research works within the tropics, the case building scenario and the effects of the PCS on indoor thermal comfort

5.8 Chapter Summary

This chapter has reported on the data collected from the parametric testing of scale model prototypes. The developed hybrid system produced results that reduced indoor temperatures by up to 23% with a proportionate reduction in energy demand for cooling. The developed system also demonstrates that indoor air quality can be maintained by controlled airflow to achieve both thermal comfort and maintain indoor air quality without the need to open windows. The power to run these applications can be generated by installing an appropriately sized PV array with battery storage. This effectively produces a zero CO_2 scenario for space cooling if the results from the scale models prove to be an accurate facsimile of real-life conditions that will have to account for the additional casual gains from appliances and the occupants.

Given the limitations of the models, running both systems in sequence appears to be able to maintain internal temperatures within the target comfort parameters and there remains considerable scope for enhancing both systems particularly with the design of the night cooling roof panels where the thermal interfaces have considerable scope for increasing the efficiency of the energy transfer.

6. DISCUSSIONS ON PERFORMANCE AND EFFICIENCY VALIDATION OF THE PROPOSED PASSIVE COOLING SYSTEM

6.1 Introduction

This study has examined the effects of thermal mass and insulation as a first step to heat control in buildings. In addition to this, a collaboration with positive pressure ground pipe ventilation and clear night sky radiant cooling was developed to optimise the operational efficiency of the building in terms of energy output and reduction of peak indoor air temperature as cooling strategies for buildings in south eastern Nigeria. A methodology that involved field study and site measurements was established. To accomplish this, experimental cells were developed following the mode of building design and construction that involved considerations of the thermo-physical properties of the building fabric. A series of modifications were undertaken to achieve 3 different models which were used to investigate the effects of the building envelope in combination with two passive cooling techniques on indoor environment and energy demand for cooling while providing thermal comfort in the indoor environment.

This chapter therefore is a discussion and assessment of the results of the 2 passive cooling techniques applied in a modified building fabric. This includes cost implications, energy saving capacity and the overall thermal comfort achieved by the application of the systems. The assessments will also include the cost of production, running cost and probable payback period of the system as well as a discussion on any shortcomings and potential for improvements.

6.2 Discussions on the effects of the building fabric on indoor heat gain and loss.

The investigation presented data on the effects of diurnal outdoor temperature swings on the indoor temperature of the measured building. It was discovered that there was a very close response to outdoor temperature swings by the indoor environment. There were clear indications that this could be attributed to the uninsulated and lightweight nature of contemporary building practices. As a result, indoor temperature readings of 23°C were recorded in early morning hours with daytime temperatures rising rapidly after 10:00 hours with 33°C being reached by mid-day. A closer assessment linked this ability to the time it takes heat energy to move from the external surface of the building envelope to the internal surface. This study therefore concluded that if the time lag of a building fabric (thermal inertia) is increased, there is likely to be a considerable reduction in indoor temperature when the ambient is at its peak. Extending the time lag of the building fabric will entail an increase in the thermal resistance of the building fabric, ideally the external encapsulation of heavyweight block-work walls with insulation.

The experimentation in the study area also identified low thermal capacity of the building fabric as the main reason behind the high electricity demand for cooling. The study established that walls with U values of $0.39Wm^2K$ can reduce heat gains by an average of 10.7% in the daytime and 4.3% at night, while heat admittance through roofs can be reduced by 14.5% by decreasing the U value of the roof from $2.13Wm^2K$ to $1.28Wm^2K$ when insulation is applied. The DT_{max} value of both walls and roofs increased because of the modifications. The DT_{max} due to an increase in the thermal mass of the wall and an application of external insulation was increased from 1.1°C to 4.9°C, while that in the roof due to additional insulation was increased from 2.5°C to 12.2°C. This is illustrated in Figure 6.1, the DT_{max} of the roof was increased from -59% to -12%, while that of the walls was increased from 5% to 24% due to the modification of the fabric. An increase in DT_{max} of a space indicates a decrease in the variable temperature amplitude of the space and hence an extended time lag in relation to the ambient temperature.

It should be noted that the application of thermal mass in the study on its own could not sustain the comfort requirements as indoor temperature below the upper comfort limit was rarely recorded in the nights when cooling of indoor spaces is mostly required. This was due to the extended time lag; therefore, peak heat periods are experienced during the nights when occupants are sleeping.

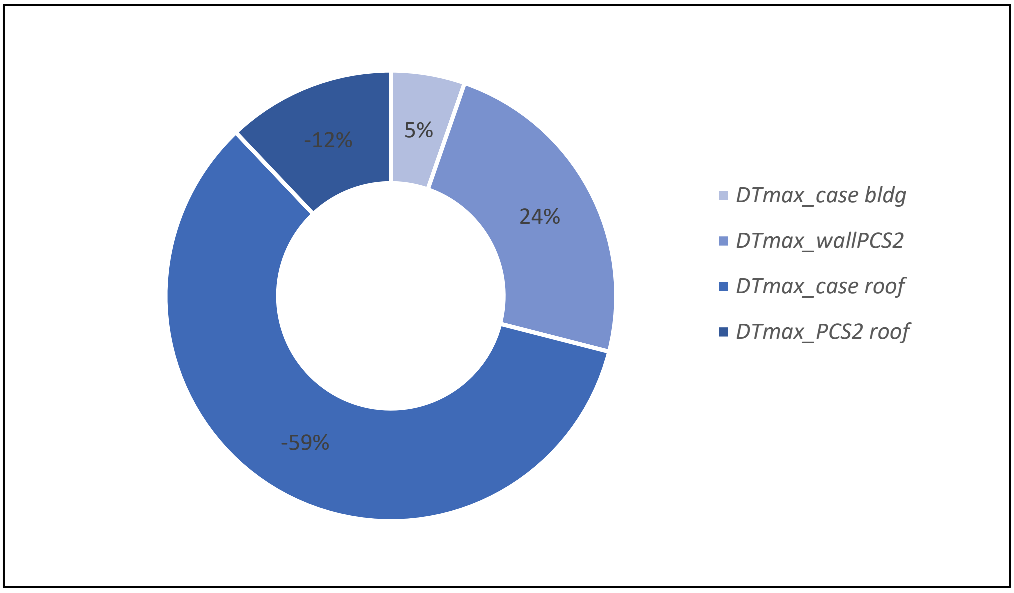


Figure 6. 1 Effects of thermal mass and insulation on the DT_{max} of indoor spaces. Increased percentages in the values of DT_{max} indicates lower temperature amplitudes or an increased in thermal resistance

Another shortcoming of the application of thermal mass and external insulation is elevated levels of internally generated heat since heat dissipation rate is limited in the modified fabric, as more time and energy are required to stabilize the effects of the massing on the target environment. This agrees with the reports of Meir and Roaf (2005) who noted that too much thermal mass may be counter-productive as most cases of overheating within a building environment is attributed to poorly designed building envelope which causes delayed heat transfers from one surface to the opposite side of the component. Therefore, if sufficient cooling is applied as suggested by Keeney and Braun (1997), the indoor room temperature can be maintained within comfort limits, and it agrees that the application of a passive cooling system may reduce heat accumulation thereby reducing cooling loads as suggested by Balaras (1996).

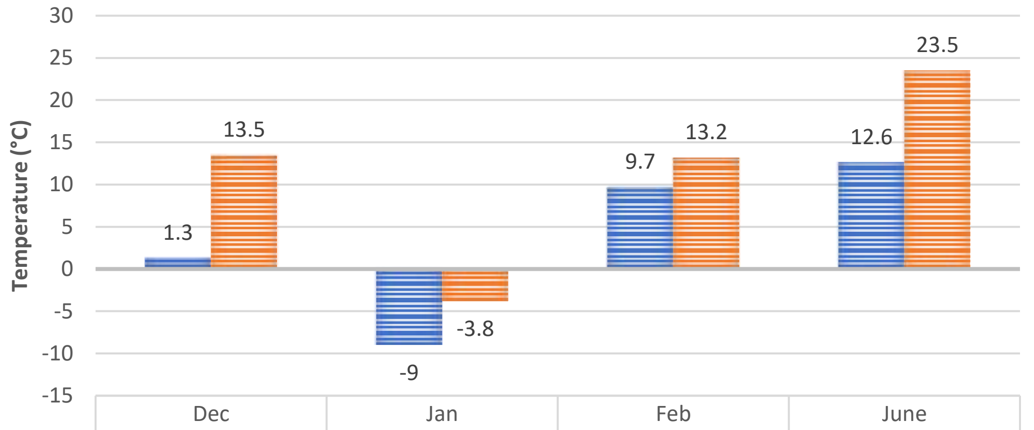
6.3 Discussions on the cooling potentials of the earth and the sky.

Another objective of the present research work was to identify available and viable natural heat sinks within the study area and to investigate the effects they may have on indoor thermal conditions in dwellings. The research required to ascertain the potentials of the identified heat sinks and assess the extent to which these heat sinks may be integrated into a dwelling to ameliorate indoor conditions by reducing heat infiltration and accumulation. The assessment has discovered some important characteristic features of the climate of the study area worth considering in the design and integration of a passive cooling system.

6.3.1 Sky covers and Effective sky Temperature as functions of seasonal climate changes.

The climate of the study area is usually hot, dusty and less humid during the months of November to early May. During this period, maximum daily ambient temperature rises above 38°C, while minimum ambient temperature recorded at nights could be as low as between 22°C and 20°C. Despite the temperature drops at night, occupants of buildings still experience excessive indoor temperatures. It was observed through measurements on site that during the hotter months of the year, diurnal temperature swings of 20°C and above are attainable most of the nights. Diurnal temperature swings of 8°C - 10°C ordinarily are enough to induce a sufficient overnight cooling effect if there is reasonable cool air infiltration, however there is little wind in this region during these months and windows are habitually kept closed due to safety and security concerns.

According to records from WeatherSpark (2016), clear skies occur 47% of the time during the hot months and 13% of the time during the cold months with wind speeds rarely exceeding 7 kph. The research attempted to assess the viability and potentials for indoor cooling particularly when skies are clear. Sky measurements in the study area during the hot periods revealed that effective sky temperatures during the hot season range between -9°C to 8°C. During the cooler months, the effective sky temperature increases, and varies between 12.6°C and 16.6°C as recorded during the nights and early morning hours and 19.8°C to 30.5°C during the afternoons (Figure 6.2). It has to be acknowledged that although sky temperatures appear low during the day, solar gains on any black roof surface will negate any possibility of radiant cooling during these hours.



	Dec	Jan	Feb	June
min	1.3	-9	9.7	12.6
max	13.5	-3.8	13.2	23.5

Figure 6. 2 Maximum and Minimum monthly effective sky temperature in study area recorded between 21:00 hours and 7:30 hours

6.3.1.1 Effects of sky conditions and characteristics on temperature and net radiation of surfaces exposed to the sky.

Further measurements were carried out to assess the potential for black body roof radiation to clear overnight skies. Surface temperature readings varied between 0°C to 18°C in the early morning hours. At these sky temperatures, the radiating surface will deliver between 40W/m^2 and 87W/m^2 of cooling energy per hour between 21:00 hours and 07:30 hours and given a roof surface area 250m^2 this equates to a cooling potential of between 105kWh to 229kWh per night (10.5hrs). The estimated net radiation derived through the calculated sky temperatures was between 38W/m^2 and 77W/m^2, between 21:00 hours and 7:30 hours. These results (surface temperature and radiating power) are similar to those reported by Ezekwe (1986) and Ogueke et al. (2011) in two towns in south eastern Nigeria.

The present study identified that the potential for clear night sky radiant cooling is optimal during the hot season. Previous studies have shown that residents leave their homes to sleep outside in spaces exposed to the coolness of the sky. Relative humidity levels are also lower during this season. The heat experienced in the daytime can be attributed to lesser cloud covers in the sky. Cloud cover will of course affect radiation and in turn heat flushing potentials. By including thermostats that will activate the system when conditions are optimal for heat flushing, the system can react relatively quickly to changing cloud patterns taking advantage of clear skies at short notice to maximise heat flushing and the storage of residual ‘coolth’ within the insulated heavyweight fabric of the building. Figure 6.3 is a comparison of the average cooling capacities of a radiating surface assessed in the present study and previous studies on sky radiation, higher cooling capacities can be obtained depending on the sky condition over the night.

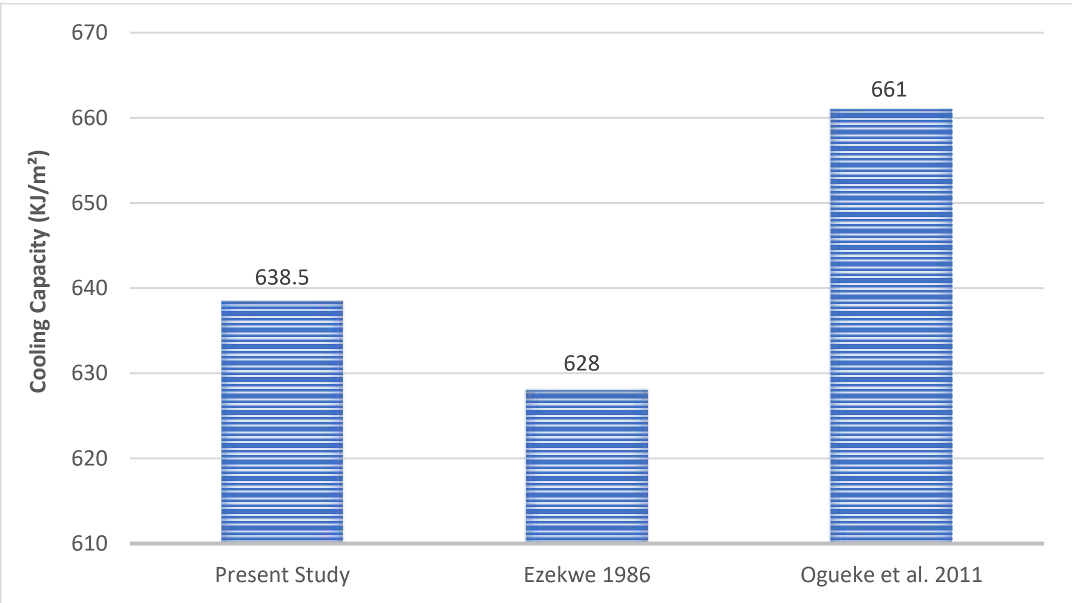


Figure 6. 3 Average cooling Capacities of three studies carried out in different site locations within the south eastern region of Nigeria

6.3.2 Effects of depth and seasonal changes on soil temperature and temperature amplitudes

In order to achieve the second research objective, some assessments were carried out and are presented in section 4.6.1.1. The earth has a limit to its heat exchange capacity that is a function of location, time, depth and conductivity. The study measured soil temperature averages during the hot and the cool months. The study also assessed soil temperatures at different depths starting from 1m to 4m. Figure 6.4 to Figure 6.6 show some observations from the measurements. Temperature readings increased as the depths increased during the hottest months, but the amplitudes reduced thereby stabilising temperature as the depths increased.

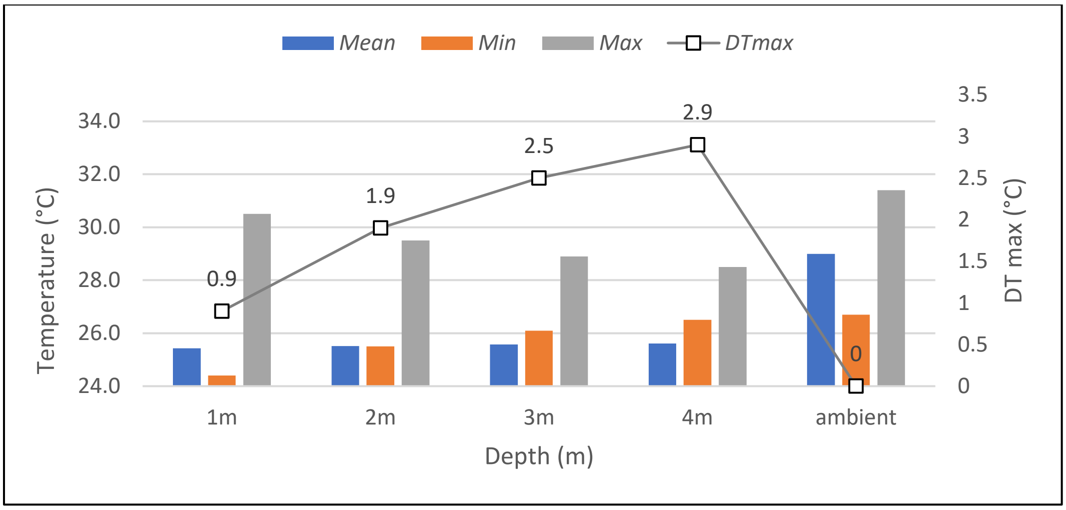


Figure 6. 4 Annual minimum and maximum soil temperatures at different depths.

All the measured annual mean soil temperatures at different depths were confirmed to remain below the following:

- The daily maximum outdoor temperature readings.
- The daily maximum indoor temperature reading
- Upper comfort limit of the study area.
- Annual mean ambient temperature of study area.

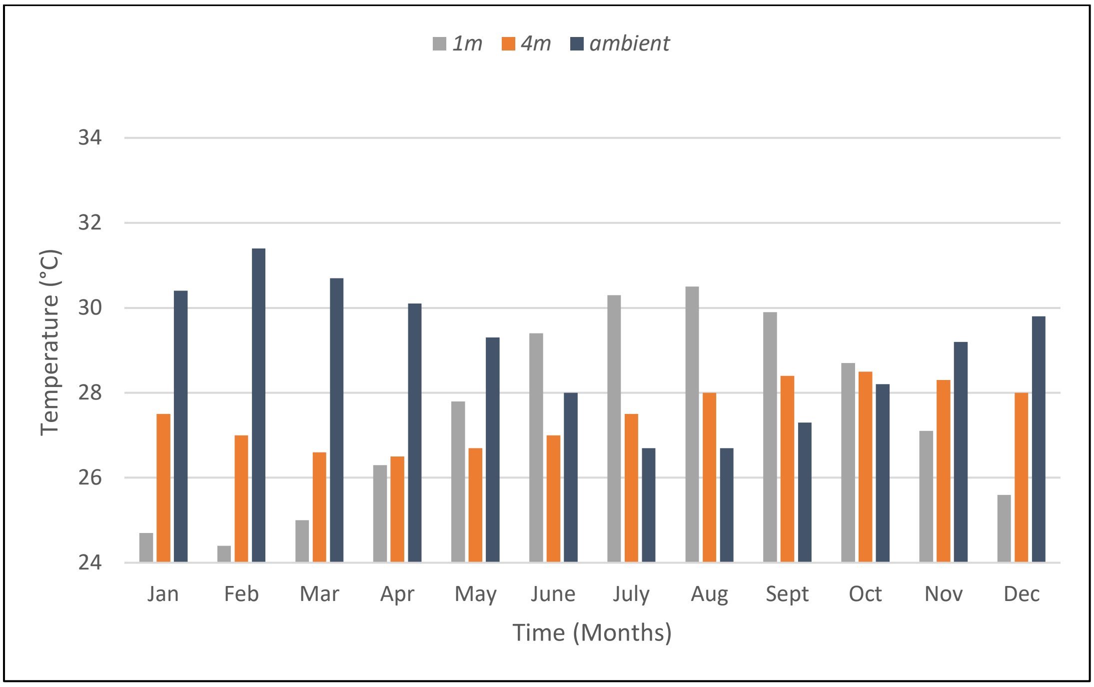


Figure 6. 5 Monthly Soil temperature variances at 1m and 4m

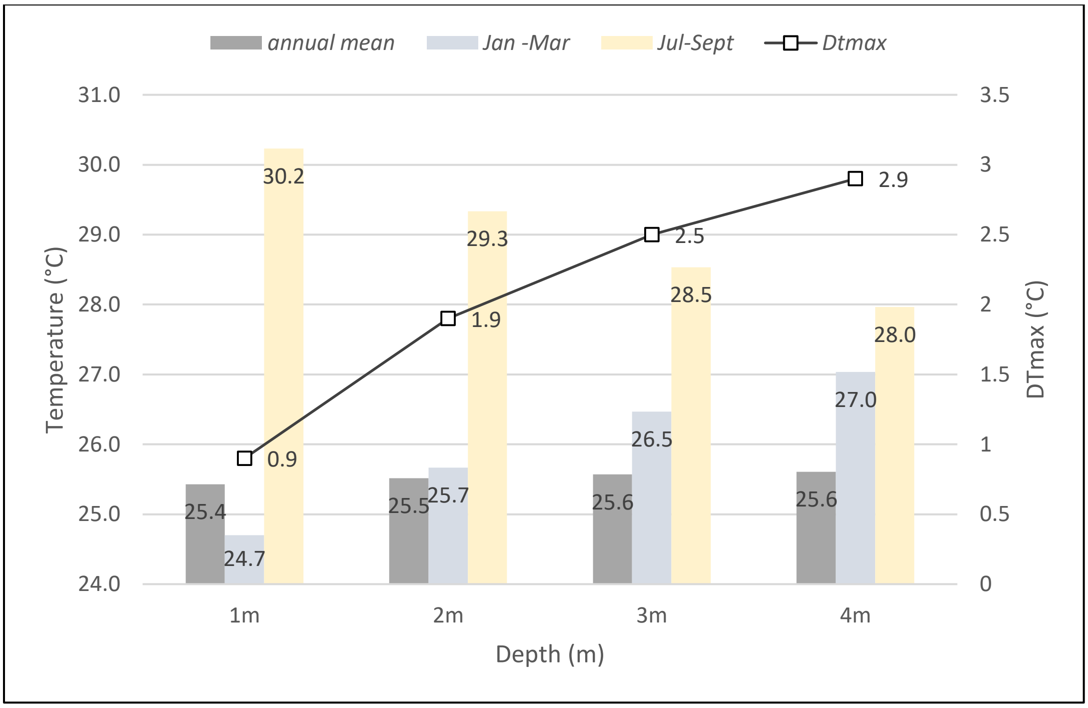


Figure 6. 6 Temperature readings of the soil at different depths showing seasonal amplitudes and mean annual values. Decreased temperature amplitudes result to an increase in DT_{max}

In order to optimise the thermal capacity of the soil, the research further examined the temperature swings in the soil at different depths and it was observed that 1m is an optimal depth for pipe burial during the hot months and 3m was most suitable when the months gets cooler. The reason for this is because the lowest soil temperature was attainable at 1m depth and coincides with the hottest months of the year and it takes an average of 5 months (November to March) for the soil temperature to rise from 24°C to about 30°C. Secondly during the cooler nights in the rainy seasons pipes buried at this depth can serve for indoor air heating.

The research therefore adopted pipes to be buried at 1m and 3m for the hot and cool months respectively. 3m depths were adopted because the daily maximum temperature during the cool months sometimes exceeds 33°C in the day and soil temperature at that depth is below the upper comfort limit and therefore might be useful to stabilize the indoor environments because of the thermal mass and insulated building fabric adopted earlier. The study therefore concludes that it is more profitable in terms of efficiency to bury pipes at different depths to make optimal use of the soil thermal capacity at various depths. Operations of the two separate systems can be harmonized using CO_2 sensors and thermostats.

There was a substantial reduction of about 20% of the ambient air temperature at the point of entry by the application of shading over the pipe. This agrees with the results of Givoni (2007) and (Jacovides et al., 1996). The research also considered the overheating of soils due to continuous usage of the underground pipe especially at shallower levels hence, provisions were made for introduction of water at the levels of the pipe burial. It was ensured that water is not introduced from the surface of the earth therefore introduction of water from the surface will simply transfer the heat to the levels of the buried pipes which will rather be counterproductive as the aim of cooling the soil down may be defeated this way. Secondly, thermal conductivity of the soil can also be improved by water levels; however, the scope of the current research work did not allow time for an experimentation on soil conductivity by the introduction of water into the soil. For further studies, water may be introduced to the soil using buried pipes that protrude above the surface and connected to reservoirs. This is to ensure that sufficient water is introduced while avoiding heat infiltration by surface application.

6.3.2.1 Effects of PPGPV on indoor condition

Air supply by the application of PPGPV system reduced temperatures in enclosed spaces by 22.4% in the daytime. The DT_{max} was increased from 5.9°C to 13.4°C which indicates a more stable indoor temperature particularly when compared with the base case building. There was an average of 84kWh of heat displacement on an average sunny day. The system however could not deliver sufficient heat flushing to cool the internal volume during afternoons and evenings. If for instance the system is reversed at night (say between the hours of 02.00 and 06.00) and cool night air is delivered through the ground pipe, the earth in contact with this will be chilled and this stored 'coolth' would then be available for redistribution into the dwelling after the radiant system is deactivated. As the electricity being supplied is effectively free, there is therefore no carbon penalty and the thermal inertia of the earth at 3m depth can be utilised to further lower the supply air temperature during the day.

The research also tested the dehumidification and purification of supplied air into the system and results showed a 10% reduction in RH levels. This result indicates prospects in the use of local materials such as clay pebbles and charcoal flakes to absorb moisture from the air and hence purify the air introduced into living spaces. These materials are also known to reduce dust and particulate matter however no test was carried out to quantify this effect.

It is however recommended that other research works should focus on the optimisation of heat interfaces in the PPGPV system by looking at variables such as pipe materials, pipe thickness, air flow rates in the pipes, and maximizing turbulent regimes instead of laminar as the air passes through the buried pipes as well as the use of desiccants in the system for dehumidification.

6.4 Assessment of Passive cooling System Performance.

Another objective of the research is to assess the functionality and hence establish the efficiency of the evaluated and adopted passive cooling techniques viable in the study area. This sub section is a discussion on the system performance and will include discussions on thermal comfort performance, energy consumption and output, life cycle impact assessment/environmental issues, cost implications, and will conclude with a performance rating of the proposed system.

6.4.1 Discussions on Thermal Comfort assessment

The building's ability to sustain indoor temperature conditions within the acceptable comfort boundaries including 'healthy' air quality, is a good metric of any system performance.

The daily indoor temperatures were reduced by the application of an upgraded building fabric. The maximum indoor temperature in the modified building scenario was 30.8°C as against 34.8°C recorded in the base case building. There was also a reduction in peak temperatures of 11.5%, while the mean indoor temperature reduction was 10.7%. The average temperature reduction at night was reduced by only 4.7%, which could be attributed to the impact of the thermal mass warming slowly during the day and therefore the thermal inertia takes longer to dissipate this heat build-up until the introduction of cooler night air. Although the 'Fabric First' modifications significantly reduced indoor temperatures, the upper thermal comfort range was exceeded more than 60% of the time (pm hours). Humidity levels also exceeded 75% at night.

The application of a positive pressure ventilation system through buried pipes in the soil at a depth of 1m was able to improve the previous results by supplying cool air that reduced the indoor temperature by 22.4% in the daytime thereby maintaining indoor conditions within the thermal comfort ranges, however, temperature readings rarely fell below 25°C. The minimum recorded indoor temperature was 25.7°C and the maximum was 28.1°C. The decrease in the indoor temperature amplitude is evident in an increase in DT_{max} from 5.9°C to 13.4°C as shown in Figure 6.7. The temperature reductions achieved in this system do not appear to be able to chill the indoor thermal mass however they do provide a good level of ventilation air that is delivered at a temperature below 29ºC maintaining healthy indoor air quality and providing some degree of background heat flushing as the warmer air in the dwelling will be effectively vented through the air outlets at ceiling level.

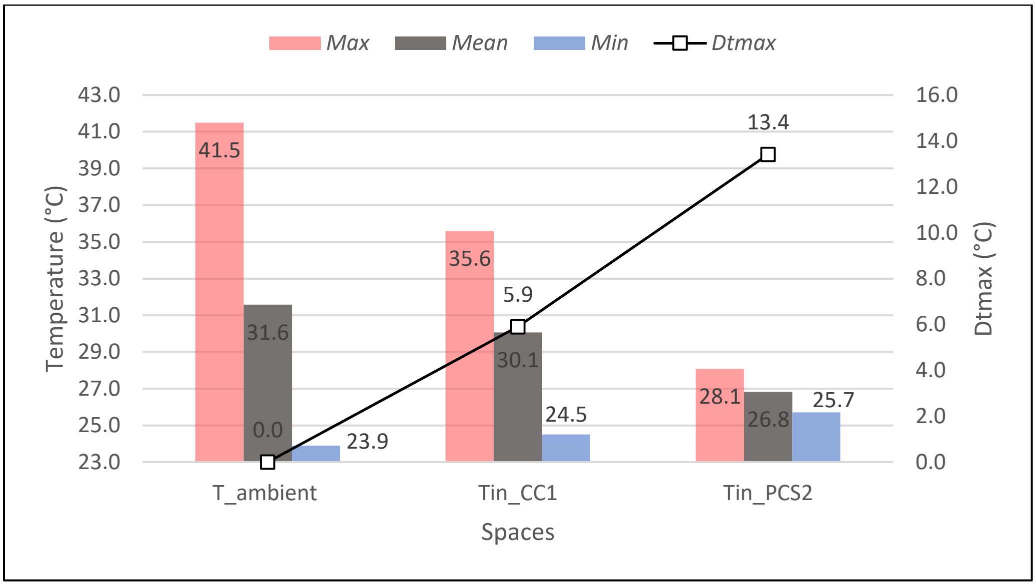


Figure 6. 7 Rise in DT_{max} as a function of Ground pipe positive pressure ventilation into living spaces indicating stabilized temperature swings and reduced indoor maximum temperature. 16 l/s of air was supplied into a room of 27m^3 for 2 occupants at an air speed of 1.2m/s

Going by measured sky temperature and resultant surface temperature of radiating surfaces exposed to the sky, the system has a potential capacity to maintain indoor thermal conditions through the night, if the heat interfaces in the system are optimised. Temperature readings in the CNS were below 23°C for 95% of the running time, suggesting the ability of the system to supply 'coolth' for heat flushing of exposed walls in the shaft which will allow occupants to lose heat by both convection and radiation. It is estimated that optimising the emissivity of the roof and increasing the interfaces for heat exchange could yield lower temperatures than were obtained in the study with what is a relatively crude scale model. The lowest air temperature measured in the plenum of the experimental cells was 19.6°C with an estimated cooling capacity of between 210 kJ/m^2 to 650 kJ/m^2 per night. Temperature readings within the indoor remained within the comfort limit with the upper range at 5.9°C below the upper comfort limit and 0.4°C below the lower comfort limit. The temperatures in the plenum varied between 3.4°C and 0.4°C below the 23°C lower comfort limit. If, however the air input could be channelled through a hypocaust thermally massive wall this would increase the energy transfer and rate of heat flushing while tempering the air being delivered at ground level into the various internal spaces. This technique would therefore minimise the likelihood of the occupants feeling cool draughts at ankle level.

The rate of heat exchange was increased when a more turbulent air flow was achieved by introducing steel wool to the cavity. There is scope to undertake for research in this area to optimise the conflict between heat exchange and increasing the pressure drop across the air cavity that in turn would require a more powerful fan. The level of 'coolth' delivered in the various scale model runs, could maintain indoor temperatures within the target comfort parameters. Presentations of the thermal comfort capacities of the applied techniques can be found in sections 5.3.2, 5.5.1 and 5.6.1 of Chapter 5. Figure 6.8 shows that the CNS performed optimally by sustaining the average indoor temperature steadily within the comfort range of 23°C to 29°C (22.3°C and 23.1°C) The DT_{max} recorded due to the application of the CNS is 6.9°C in the plenum and 6.3°C in the room space, while it is -1.2°C in an unconditioned room space. These readings indicate a substantial drop of the temperature amplitude of the air in the indoor environment. Humidity levels were also reduced by up to 10% due to the application of hygroscopic clay pebbles mixed with activated charcoal flakes which were placed in the plenum provided in the roof attic and were clearly absorbing some moisture. Daytime temperatures in this area would have a tendency to drive this moisture out on a cyclic basis thus allowing the hygroscopic materials to effectively dry out and maintain their ability to re-absorb moisture when the radiant system is re-activated. Thus, both ventilation inputs (ground and radiant) have the ability to reduce the absolute humidity of the incoming air stream, allowing the occupants to lose marginally more heat through evaporative cooling from the skin.

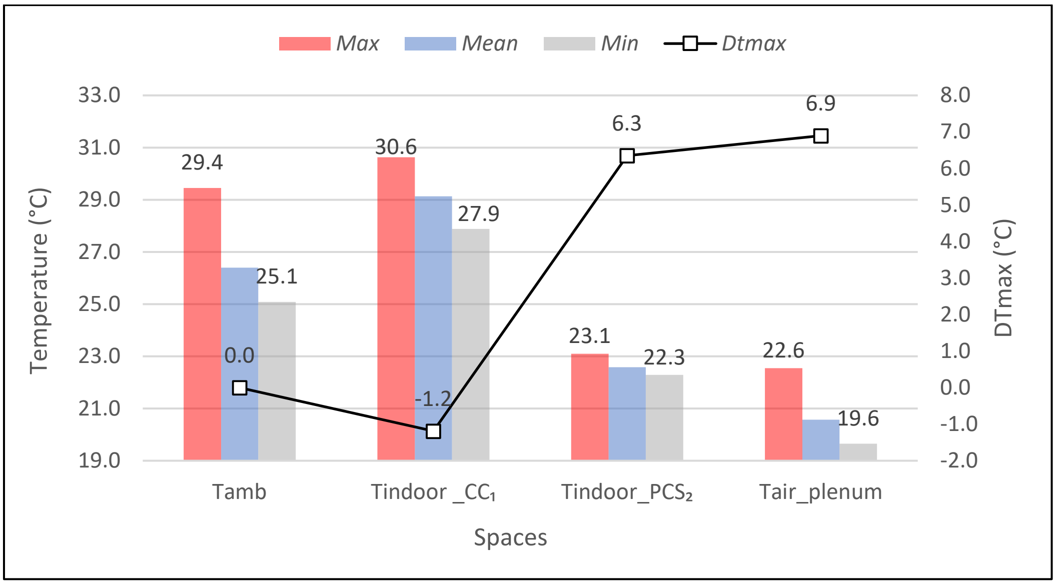


Figure 6. 8 Maximum and minimum indoor temperature due to the application of CNS radiating system

On site the operation of the CNS was manually switched and did not include a thermostat to deactivate the system if the sky became cloudy reducing the emissivity of the roof surface. The system was simply turned on at 21:00 and turned off by 7:30 hours. The system may therefore have on occasion underestimated the cooling potential by introducing warm air during the overnight cycle when the sky may have become overcast. The study therefore may have underestimated the cooling potential of the radiant sky system.

Despite this shortcoming, a temperature reduction of 22% was achieved over a 10.5hrs running cycle, yielding a cooling capacity between 210 kJ/m^2 to 650 kJ/m^2. The study observed that more cooling effects would be achieved if the interfaces for heat transfer are maximised.

The thermal comfort range was sustained when the PPGPV was run during daylight hours and the CNS was activated after dark on the modified building fabric (Figure 6.9.). Both the PPGPV system and the CNS are run at a background level of up to 16l/s for each room in the dwelling (2-person occupancy) at an air speed of 0.9m/s to 1.5m/s to maintain CO_2 concentrations below 1000ppm.

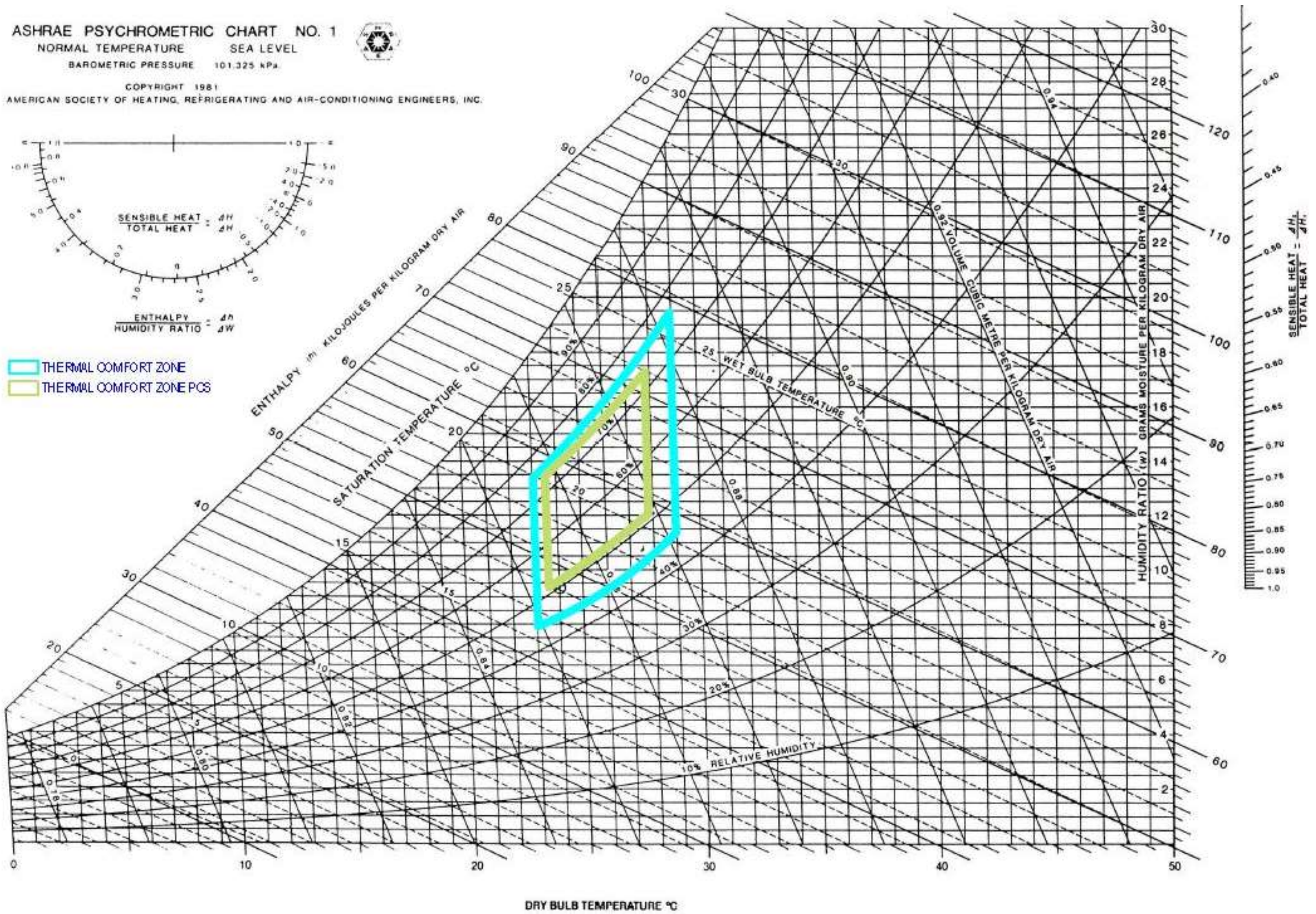


Figure 6. 9 Psychometric chart showing the comfort boundaries from other research works within the tropics, and the effects of the PCS on indoor thermal comfort

6.4.2 Discussions on Energy Performance of the system

The poor thermal capacity of the case building has resulted in high levels of energy consumption for cooling. Improving the fabric of the building envelope reduced energy demand for cooling substantially with the preliminary results from the scale modeling predicting a reduction of cooling loads of 42%, which is equivalent to an average of 147 kWh of cooling energy being displaced each month. This saving will vary by season with the greatest savings achieved during December and January.

Figure 6.10 presents an annual energy use in the applied systems (PPGPV and CNS) in the study area. The results are the mean monthly consumption of each system running separately and both systems running in sequence with a room temperature set at 25°C. There is a remarkable reduction in energy required for cooling of a 27m^3 bedroom space when compared to the base case. The PPGPV recorded a substantial reduction of 63% which is an equivalent displacing an average of 252kWh per month.

The CNS system recorded a reduction of 104% in mean monthly energy demand. However, there was a gross reduction in the energy demand through the year when both systems were combined. The CNS cooling system presented the lowest energy use scenario and produced extra cooling energy provided a greater rate of heat flushing. The total energy savings was highest in the CNS but for thermal comfort and to maximize sensible cooling within living spaces, both systems working in a collaboration was the best combination in terms of efficiency.

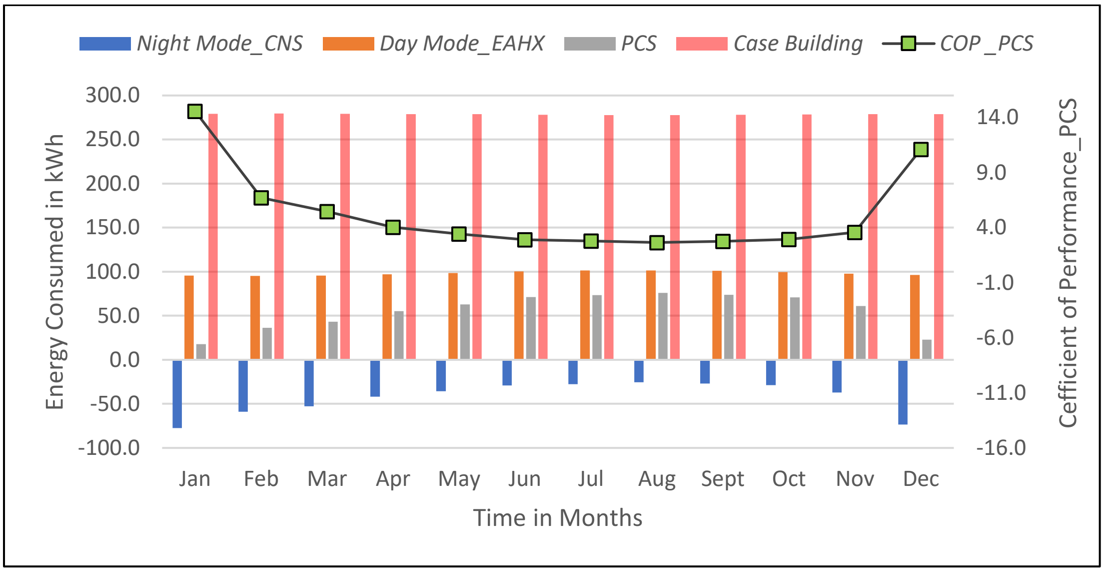


Figure 6. 10 Comparative monthly energy use in the PPGPV, CNS and a synergized PCS with both systems working in tandem (Day and Night Mode)

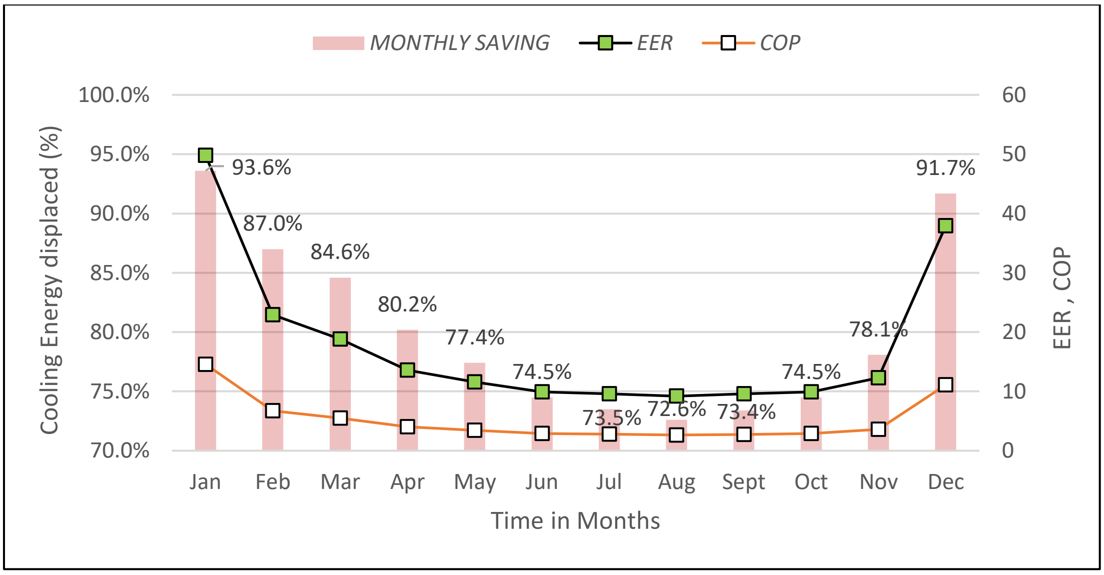


Figure 6. 11 Monthly average performance of the Passive Cooling System

The performance indices are presented in Figure 6.11, the plot shows that the annual average EER of 17.9, (COP = 5.2), with monthly range of EER = 9.2 – 49.8, (COP = 2.7 – 14.6) has the capacity to reduce cooling loads in the Nigerian building sector by 83.5%. The application of the proposed cooling system in Nigerian homes will reduce the energy for cooling by circa 3,343 kWh to 552 kWh (single bedroom) annually. This amounts to an annual energy displacement of 2,791kWh for a bedroom and 11,166 kWh (13,372.4 kWh to 2,206.45 kWh) in a 3-bedroom apartment.

Since 44% of the total energy generated is used by the building sector and 75% of this value is used for cooling, the systems can displace 83.5% of the current cooling demand that will in turn reduce the total energy demand in buildings from 44% to 16.45%.

6.4.3 Discussions on IAQ and CO_2 Emissions

Indoor air quality (IAQ) and CO_2 levels were controlled using the CIBSE Guide B (2001) standards for minimum amount of fresh air requirement in a volume of space, which specifies 8 l/s for a person to contain maximum CO_2 concentrations between 800ppm and 1000ppm at air pressure of between 18 - 30 Pa, however no CO_2 measuring equipment was used in the study as the models could not account for occupant respiration rates. The quality of air introduced was also maintained using layers of clay pebbles mixed with activated charcoal pellets. CO_2 emissions by kWh use of electricity was calculated using an emission factor for India since there are no documented emission factors for Nigeria. Figure 6.12 presents the plot of monthly levels of CO_2 emission as a function of energy usage in the cooling of buildings based on a CO_2 emission factor of 1.3332 kg CO_2/kWh. The results plotted lays emphasis on remarkable reductions in CO_2 emissions because of reduced energy use in the building sector by the application of the proposed PCS, which in turn cuts electric usage. The average monthly CO_2 reductions fell from 1,486 kg to 295 kg, however, as the fans can be run by a modest area of PV array with battery storage for overnight demand, the configuration can be classified as being effectively 'Zero CO_2'.

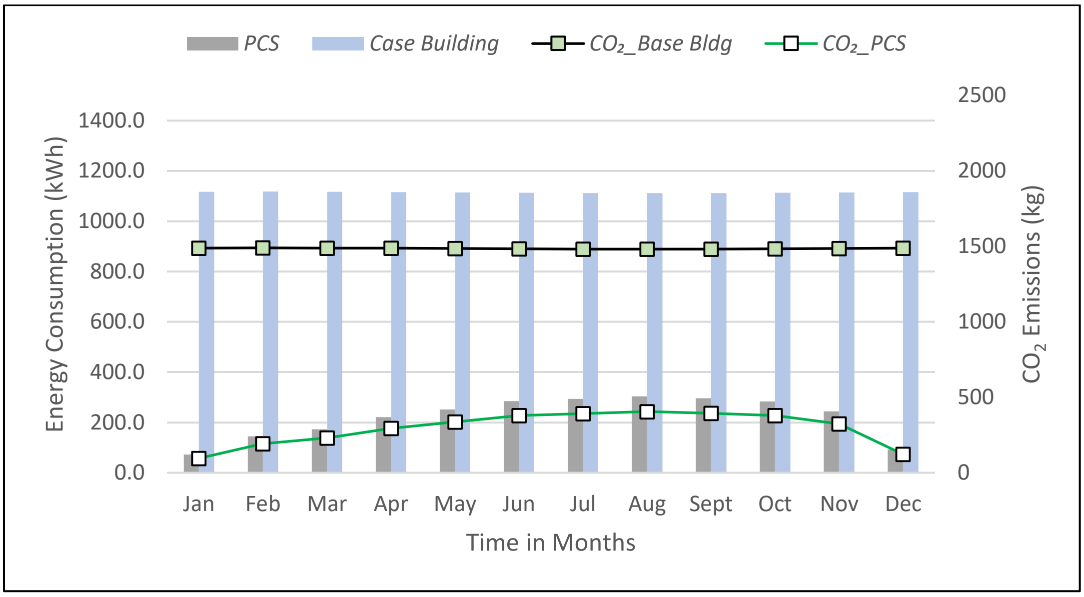


Figure 6. 12 CO_2 emission levels as a function of reduced electricity usage in buildings

6.4.4 Discussions on cost effectiveness and analysis of payback period

The proposed passive cooling system has yielded positive results in terms of indoor thermal comfort, cooling energy reductions and reduced carbon dioxide emission levels. There is however a great need to quantify the cost effectiveness of the proposed passive and hybrid cooling systems. In order to achieve this, the 'capital costs' and 'costs in use' of the passive cooling interventions will be measured and compared alongside that of a conventional AC cooling system. Hence, based on this evaluation, a detailed estimation of 'capital costs', 'costs in use' and a predicted 'payback' periods for the approaches will be presented in this section.

Using the energy consumption tariff of the study area will aid in the calculation of the actual running costs of the applied systems in Ahaba Imenyi. The Nigerian electricity board average tariff for Enugu distribution zone is ₦30.93/kWh of electricity, which is an equivalent of £0.062/kWh. With these figures, the annual consumption costs are presented for a 3-bedroom bungalow with a thermally enhanced Fabric, and then running on PPGPV, CNS, PCS, and the case building running on mechanical ACs.

The annual mean energy consumption for cooling in the study building is circa 13,372.4 kWh. Therefore, using the current domestic electricity consumption tariff, the estimated cooling energy cost becomes ₦413, 608.3:00 (£827.27) yearly. Fabric first design measures reduced the energy cost by 42.2%, amounting to a total cost of ₦239,067.25 (£478.13) being energy consumed each year. In the meantime, a combination of PPGPV and CNS cooling interventions in a synergistic passive/hybrid module (PCS) consumes energy at an estimated cost of ₦68,244:00 (£136.50) yearly due to an average energy saving of 83.5%. At this rate, annual savings of £690.73 (₦345,364:40) could be achieved. Figure 6.13 shows the different levels of energy consumption in the study building when the different cooling interventions are applied, while Table 6.1 presents a calculation of the electricity consumption in the case building running on Mechanical AC and another scenario where it runs on the PCS hybrid formation.

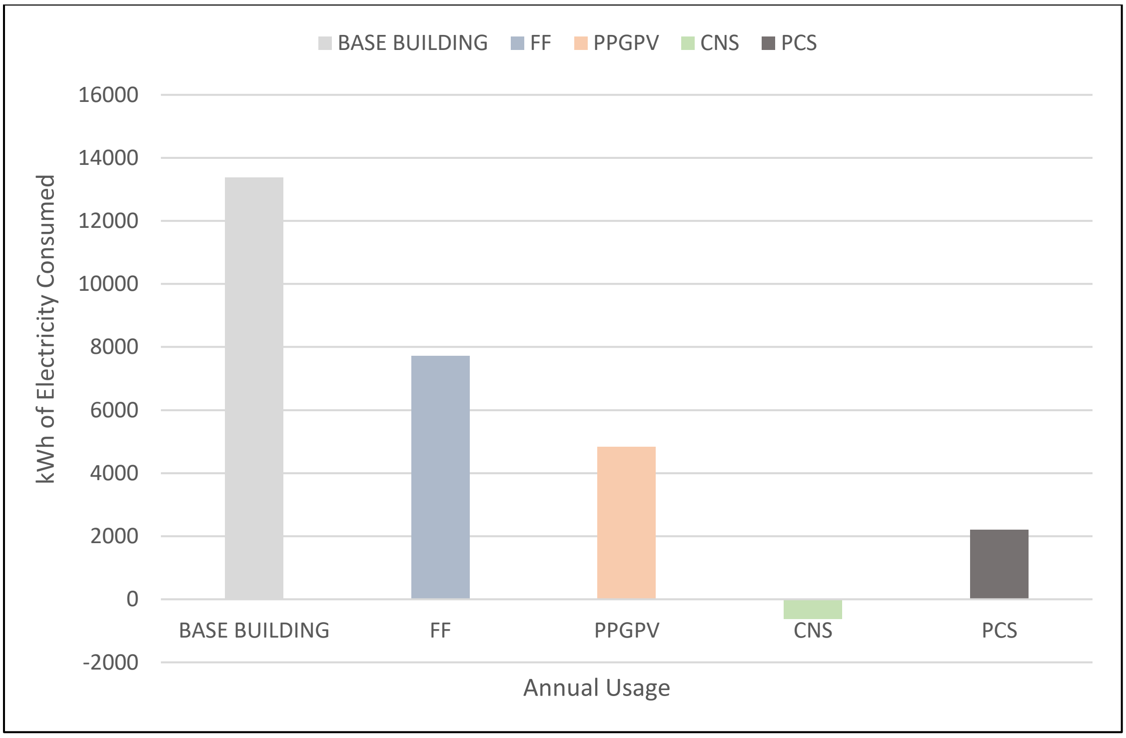


Figure 6. 13 Estimated Average yearly cooling energy cost of various cooling systems

Table 6. 1 Energy Displacement and annual cost implications of the application of Passive cooling system

CASE BUILDING

	Annual Energy Consumption (kWh)	Annual Consumption ₦ (Naira)	Annual Consumption £ (GBP)
Single Bedroom	3342.1	103,371.15	206.74
3-bedroom Aptm	13,372.4	413,608.3	827.27
Tariff	1KWh	30.93	0.06

PASSIVE COOLING SYSTEM APPLICATION ANNUAL CONSUMPTION

	Annual Energy Consumption (kWh)	Annual Consumption ₦ (Naira)	Annual Consumption £ (GBP)
Single Bedroom	551.45	17,056.3	34.11
3-bedroom Aptm	2,206.45	68,179.3	136.36
Tariff	1KWh	30.93	0.06

PASSIVE COOLING SYSTEM APPLICATION ANNUAL SAVINGS

	Annual Energy Displaced (kWh)	Annual Savings ₦ (Naira)	Annual Savings £ (GBP)
Single Bedroom	2,790.7	83,314.8	166.63
3-bedroom Aptm	11,166	345,364.4	690.73
Tariff	1KWh	30.93	0.06

A combination of the proposed fabric first design approach with the PPGPV and CNS radiant cooling will entail adding the cost of fabric first design to the initial cost of the passive cooling approaches. To determine the capital cost of the materials, the Nigerian building material market prices are used. Table 6.2 presents the estimated cost (£/m^2) of the proposed fabric first design components for walls, floors, insulation and insulation of windows. The capital cost of retrofitting the building fabric is quantified and the estimated at approximately ₦1,636,400:00 (£3,272:80) including cost of installations. The cost for the fabrication of the passive cooling systems including installation of different components, PV panels, and other operational costs is approximately ₦1,100,000 (£2,200:00). The total cost of production of the system and the upgrades to the building fabric are estimated at N2,736,400 (£5472:80).

Table 6. 2 Estimated cost for the application of proposed Fabric First modifications

Fabric first component	Thickness(m)	Area(m^2)	Rate (£/m^2)	Amount (£)
Polyurethane foam (PUR)	0.05	450	4	1,800:00
Extruded Polystyrene Boards (XPS)	0.05	260	5	1,300:00
Window Glazing (insulated glass)		28.8	6	172.80
TOTAL COST				**3,272.80**

A rational estimation was made for the major components of PPGPV and the CNS radiant cooling systems comprising of pipes, low energy fans photovoltaic panels and batteries, including costs of installations and maintenance with regards to the Nigerian market. Apart from the estimated capital cost of the proposed systems, the calculations also cover the operation costs for the study building with full mechanical cooling system operation. The amount of energy generated by PV panels is also factored into the energy calculation. Table 6.3 presents a comparison of the cost implications of installation, maintenance and operation of a conventional AC system, the PPGPV system, and the CNS systems respectively in a 3-bedroom bungalow, while Table 6.4 is a comparison of total costs by system type. There are discrepancies in the cost requirements in the different applied systems with the conventional AC system requiring more energy and consequently more costs to operate. The cost of installation and maintenance of the PPGPV was higher than the CNS which may be attributed to the wide-ranging level of pipe works with implicating excavation and drilling costs for the ground pipe installation. Nonetheless, the CNS appears to be the most cost-effective approach amongst the systems applied in terms of capital cost, maintenance and operational budgets.

Table 6. 3 A Detail of cost estimation of various cooling systems

System Type	Components	Capital Cost (£)		Maintenance Cost (£/Year)	Energy Use (£year)
		Element	Installation		
Case Building AC	5 x window air conditioner units (1200BTU/3000W)	1,150	400	250	*827*
PPGPV	Ground Polyethylene HDPE pipes 90m (200mm diameter)	650	300	75	*299.5*
	6 x Inline fans (mixed) 115/65W (138 l/s)	120	40	25	
CNS	6 x Inline fans (mixed) 115/65W (138 l/s)	120	40	25	*39*
	High Emissivity paint	365	120	30	
Photovoltaic Cells	2 x PVC panels (160W/12V Battery	200	50	40	*n/a*

Table 6. 4 Comparison of total costs by system type

Total Cost (£)	**AC**	**PPGPV**	**CNS**	**PCS**
Capital Cost	1,550	1,110	645	1,755.00
Capital Cost + Maintenance	1,800	1,210	700	1,910.00
Capital Cost + Fabric First	5,072.80	4,382.80	3,917.80	5,182.80
Energy Use	**827**	**299.5**	**39**	**136.00**

Unlike in the PPGPV and CNS systems which have longer life spans and requires less maintenance due to the fact that most of the major components such as pipes are already buried in the ground or embedded as part of the building, the conventional mechanical

ACs have a shorter life span and attracts higher maintenance costs which may include regular servicing such as refill of refrigerant, cleaning, fixing of compressor problems and leakages.

Although the hybrid system applied appears to offer significant savings in capital and maintenance costs over conventional AC system. There may also be constructional and operational limitations as well. For a PPGPV pipes to be laid, large area of excavation is required in order to lay the pipes either horizontally or vertically which might also take a longer period to achieve depending on the size of the system. This may be a difficult task for already existing buildings, and it becomes more efficient to consider ground pipe ventilation during design stages and construction process as applying the system in already existing buildings may entail higher upfront costs hence, a longer payback period.

There is potential for condensation on the radiating surfaces in the CNS system which may result to mould growth and water damage if not well controlled. This may be a limiting factor for the radiant cooling system in a warm humid environment. To avoid condensation, surface temperatures should never be equal or below the dew point temperature in the space conditioned. Some known standards suggest minimal range for relative humidity in spaces as between 60% and 70%. Consequently, air temperatures at 24ºC would mean dew points of 15ºC to 18ºC. Secondly, decreasing the surface temperature to values below the dew point for short periods may reduce or totally eliminate condensation.

Low energy dehumidifiers can as well be of great importance in limiting high humidity levels in conditioned buildings. This will in turn raise the cooling capacity of the systems. The application of this system in an already completed building in Nigeria may be more capital intensive than when it is applied during design and or construction stages.

Fabric first applications reduced the energy consumption by 42.2% from 13,372kwh to 7,729.3kwh. The capital cost and operational cost of the fabric first approach can be recouped in a period of 6 years.

Although the integrated PCS is marginally more expensive to set up than the CNS, this hybrid system can offset 11,166 kWh of electricity which amounts to ₦345,364:40 (£690:73) cost offset annually. At this rate, the estimated cost of this system can be recovered in approximately 8 years Figure 6.14.

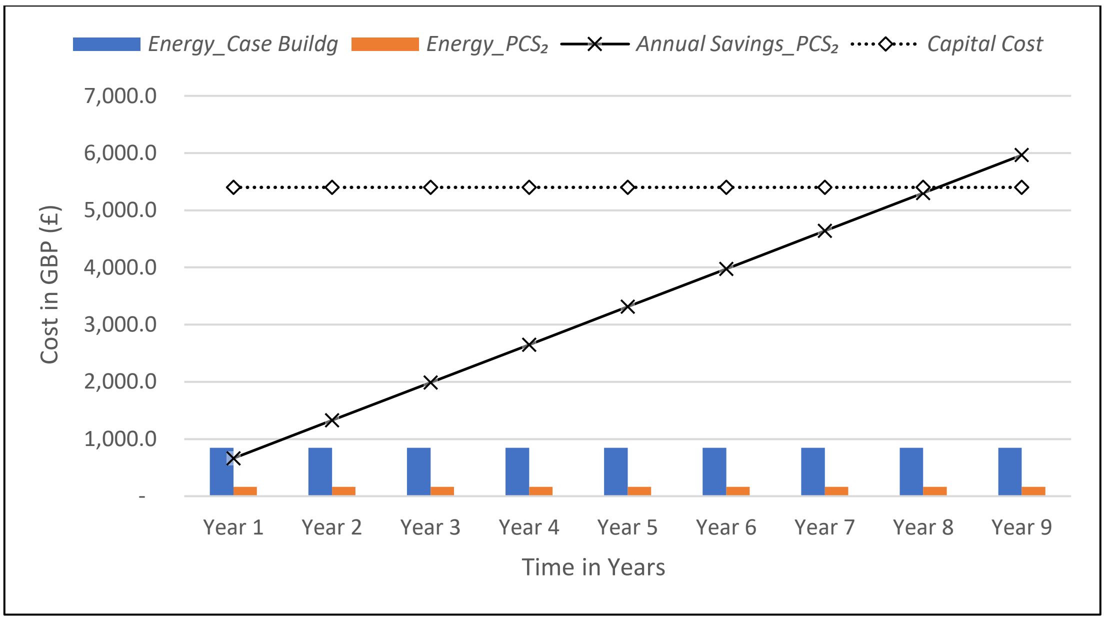


Figure 6. 14 Estimation of Payback period for the combined PPGPV and CNS cooling systems applied in a modified building fabric

6.5 Chapter Summary

The analysis of results obtained from the investigation on the application of PCS has demonstrated a substantial reduction in indoor temperature and hence a reduction in the energy demand for cooling in residential buildings in south eastern Nigeria. There is a clear agreement between the research intention and the performance of the applied passive cooling systems on a thermally enhanced building fabric.

The system has a capacity to displace 11,166 kWh of cooling energy annually in a 3-bedroom apartment within Ahaba Imenyi in South Eastern Nigeria. The annual estimated average energy demand for cooling in the base case building was 13,372 kWh, while that in the applied PCS is 2,206.45 kWh. The indoor thermal environment was maintained within the thermal comfort boundaries of ASHRAE 55 standard for mechanical and naturally ventilated environments as modified by researchers within Nigeria and other tropical regions. CO_2 levels were maintained below 1,000ppm by applying the appropriate air volumes of 8 l/s per person as recommended by CIBSE B. The modification of the building fabric reduced cooling energy by 42.2%, while PPGPV and CNS reduced cooling energy by 63.8% and 104.7% respectively, when the required room temperature is set at 25°C. A combination of PPGPV and CNS working in tandem as PCS appeared as the most effective system and resulted in 83.5% reduction in electricity consumption, which amounts to CO_2 emission reductions from 1,486 kg to 295 kg annually. This amounts to circa 1.191 kg of CO_2 displaced from demand for cooling energy in buildings.

The PCS was more expensive to construct than the PPGPV and CNS cooling systems, as it is the total capital cost for both. From the cost analysis undertaken comparing capital with savings in running costs, it was determined that this configuration has a payback period of circa 8 years. The performance and efficiency of the passive cooling system has the potential to be improved if the thermal interfaces are optimised with air flow rates.

7. CONCLUSIONS AND RECOMMENDATIONS

7.1 Introduction

This last chapter is a summary of the research from the reviews, field investigation, experimentation and analysis. The primary aim of the research is to investigate the potentials of a passive cooling system to displace a reasonable amount of cooling energy and at the same time provide comfortable and healthy indoor environment in residential buildings in south eastern Nigeria. The research has previously come up with a hypothesis that suggests that transformations in the design, construction and operational protocols of building envelopes can allow the building to interact intelligently with natural heat sinks for passive cooling, resulting in a significant off-setting of mechanical air conditioning while achieving year-round thermal comfort and 'healthy' indoor air quality, for occupants in low income households in Nigeria.

Eight questions were established in the research with each of the question addressing and contributing to the achievement of the research objectives. Presented in this chapter are the key findings of the study and its contribution to the body of knowledge. Recommendations and guidelines towards perfections in this field are also provided for different sectors which includes government, stakeholders and future researchers. These subjects are treated in the sections below.

7.2 Key Findings

The present research work has attempted to provide a passive cooling system to displace a reasonable amount of cooling energy in a typical residential building in south eastern Nigeria.

An overview and general background of the research was presented which emphasised on issues which contribute to the excessive energy consumption in the building sector, and consequently leads to increased CO_2 emission levels. Factors which contribute to discomfort in residential buildings were also highlighted. With a research hypothesis formed, aims and objectives of the study, and the research questions were established. It highlighted on the likely contribution of the study and some foreseen limitations of the research. A research methodology was also adopted. The site location and the climate features of the selected study area was explored. The Macro climate conditions and the physical characteristics of the study area was emphasized together with seasonal changes, which explained why buildings react in certain ways to seasonal climate changes and hence, the effects on the indoor living environment.

The building fabric and materials, including construction techniques were studied, and the study linked external heat gains to the light nature of building fabrics with high U values and lack of insulation in the roofs and the ceiling layers. Many research works have emphasized that improving the building envelope, will improve the heat transfer within the spaces. This study therefore resolved that if the time lag of a building fabric is extended, perhaps there might be considerable reduction in indoor temperature when the ambient is at its peak. Extending the time lag of the building fabric will involve an increase in the thermal resistance of the building fabric which may introduce some challenges if there are no clear methods to take care of internally generated heat. The reviews in the literature also identified natural heat sinks as potential source of heat control if their effects are well incorporated into building designs.

The following research objectives were achieved through the findings in the review of literature.

- To identify other passive cooling strategies other than cross ventilation which could be applied effectively in building in South Eastern Nigeria.

- To investigate the effects of heat moderation as a function of the thermo-physical features of building Fabrics on indoor temperature and on energy demand for cooling.
- To investigate some simple but viable passive cooling strategies that are readily available which can be incorporated in a single or combined system running independently or concurrently.

Further to this, an investigation was carried out in a location in south eastern Nigeria, which assessed the housing typologies and analysed the thermophysical properties of existing building in the area. The experimentation in the study area identified low thermal capacity of building fabric as the main reason behind the high domestic cooling energy demand and consumption which arises from excessive use of mechanical cooling appliances because of elevated indoor temperatures. The research also identified some factors such as: air and noise pollution, security/privacy, and protection from insects and dust as some major reasons that force house users to disregard the use of windows which is the commonest means of natural ventilation in buildings in South Eastern Nigeria and consequently one of the reasons the use of mechanical Air Cooling devices is rampant in the region. Some state-of-the-art application of passive cooling approaches were explored and it was found that the seasonal changes in the South Eastern Nigeria can in fact offer some passive/hybrid cooling potentials which has never been employed in conditioning buildings. Among some interventions which were identified are, a possible combination of radiant cooling due to surfaces exposed to the clear sky to improve the diurnal temperature swing which is low in the study area and possibly use of low energy means to induce/move the cool air from the system into the building. To be able to do this, the sky was identified as a heat sink that could provide the necessary coolth to drive the innovation. The research also identified the earth as another potential heat sink readily available in the study area to drive underground pipe ventilation, and went further to assess the heat capacities of these heat sinks and how they may be integrated into a functional building fabric to ameliorate indoor conditions by reducing heat infiltration and accumulation within living spaces.

7.2.1 Ground Source Earth cooling and Ventilation Potentials

The earth has a limit to its heat exchange capacity which is a function of location, time and depth. Temperature of the soil increased as the depths increased during the hottest months, but the amplitudes reduced thereby stabilizing temperature as the depths increased. Measured soil temperatures at 3m and 4m always remained below the daily maximum temperature readings, the daily maximum indoor temperature reading and the upper comfort limit of the study area. 1m is an optimal depth for pipe burial as lowest soil temperature was attainable during the hot months and 3m was most suitable when the months gets cooler, and it takes an average of 5 months (November to March) for the soil temperature to rise from 24°C to about 30°C at 1m depth. The study therefore concludes that it is more profitable in terms of efficiency to bury pipes at different depths to make optimal use of the soil thermal capacity at various depths.

The following research objectives were achieved through the findings.

- To identify and investigate the potentials of available and viable natural heat sinks and their effects on indoor temperature in a warm humid climate.
- To investigate the potentials and effects of passive cooling techniques on a building fabric enhanced by a combination of insulation and thermal inertia and time lag on indoor temperature to ameliorate temperature peaks.

7.2.2 U values of Building Fabric

The study established that walls with U values of $0.39Wm^2K$ can reduce heat gains by an average of 10.7% in the daytime and 4.3% at night, while heat admittance through building roofs can be reduced by 14.5% by decreasing the U value of the roof from

$2.13Wm^2K$ to $1.28Wm^2K$ when insulation is applied. The application of thermal mass and insulation on its own could not sustain the thermal comfort requirements. Another shortfall of the application of thermal mass and external insulation is likely elevated levels of internally generated heat since heat dissipation rate is limited in the modified fabric, which will in turn require more time and energy to stabilize the effects of the massing on the target environment.

7.2.3 Positive Pressure Ground Pipe Ventilation

Supplying air through buried pipes (positive pressure ground pipe ventilation) at certain depths into indoor spaces reduced temperatures in enclosed spaces by 22.4% in the daytime. There was an average of about 84.6 kWh of heat displacement on an average sunny day. The system however could not deliver enough coolth for cooling of the thermal walls for night use. The research acknowledged that this could be mainly because of the soil temperature and some factors that could improve coolth delivered by the system which will include adjustments of some parameters that affects the heat interfaces in the system.

7.2.4 Clear Night Sky Radiant Cooling

CNS radiating system performed optimally by sustaining the average indoor temperature steadily within the comfort range of 23°C and 29°C at 22.3°C and 23.1°C respectively, with temperatures usually below 23°C. Temperature reductions of 22.3% was achieved over a 10.5hrs running time of the system at night, yielding a cooling capacity between 210 kJ/m^2 to 650 kJ/m^2. The study observed that more cooling effects would be achieved if the interfaces for heat transfer is maximized. Laminar regime of air movement did not create enough heat exchange between the air molecules and the radiating surface.

The thermal comfort range was sustained when the PPGPV and CNS radiating system work in tandem on a modified building fabric. The temperature and humidity levels were sustained in the applied system according to thermal comfort ranges for naturally ventilated buildings which was determined by previous research work in warm humid regions including Nigeria. The following research objectives were achieved through the findings in this chapter.

- To investigate the applicability of the identified approaches and techniques in a warm humid climate.

The poor thermal capacity of the case building is the reason for high energy consumption for cooling in the study area. Improving the fabric of the building envelope reduced energy demand for cooling substantially with a 42.2% annual reduction in air-conditioning cooling loads in a bedroom set at 25°C which is an equivalent of 147.3 kWh of cooling energy displaced monthly. The PPGPV recorded a substantial reduction of 63.8% (daytime) which is an equivalent displacement of 252 kWh of cooling energy monthly, while the CNS system recorded a reduction of 104.7% (nights) in mean monthly energy demand. The monthly energy consumption was reduced from 4.5 kWh for the base case to -2.1 kWh for the CNS scenario. The CNS cooling system presented the lowest energy use scenario and produced extra cooling energy that could charge the thermally enhanced building fabric. The total energy savings was highest in the CNS but for thermal comfort and to maximize sensible cooling within living spaces, both systems working in a collaboration was the best combination in terms of efficiency. The performance indices of the PCS show that with an annual average EER of 17.9, (COP = 5.2), the cooling system has the capacity to reduce cooling loads in the Nigerian building sector by 83.5%. The application of the proposed cooling system will reduce the energy for cooling by 11,166 kWh (13,372.4 kWh to 2,206.45 kWh) in a 3-bedroom apartment with the sitting room and the dining rooms half the value of cooling energy expended in the bedrooms.

Since 44% of the total energy generated is used by the building sector, and 75% of this value is used for cooling, and the proposed passive cooling system can displace 83.5% of cooling energy in buildings, it will in turn reduce the total energy demand in the building sector from 44% to 16.45%.

7.2.5 Payback

From the cost analysis carried out, it is found that the capital cost of construction and operations of the PCS can totally be recovered in a period of 8 years. The following research objectives were achieved through the findings in this chapter.

- To establish the efficiency of the applied systems running independently or as a combined system running in synergy.
- To identify the most effective amongst them in terms of cost and performance.

7.3 A summary of Research Questions

Giving to the research key findings, the present study has reasonably answered the main questions raised and has also demonstrated that the hypothesis emphasized in the research is achievable. The summary of the questions is presented below.

Question 1: *Why do most buildings in the study area depend solely on mechanical air conditioning when the doors and or the windows are closed?*

The answers to this question are provided in chapters 1 and 3 of this report where it was observed that most cases of elevated indoor temperature are chiefly due to closure of doors and windows hence blocking the only practicable means of natural cross ventilation. When this happens, the only option left for circulation of air is the use of Air conditioners as ceiling and table fans ends up recirculating used air high in CO_2 concentrations.

Question 2: *What are the effects of the thermo-physical properties of the building fabric on indoor temperature and energy demand for cooling due to heat loss, heat gain, heat storage and heat dissipation?*

The answers to this question are provided in chapter 3 and 4 of this report. The study identified the low thermal capacity of building fabric as the key factor behind elevated room temperatures especially when windows are closed and the resultant high domestic cooling energy demand and consumption which arises from excessive use of mechanical cooling appliances while trying to keep indoor spaces cool.

Question 3: *Can the building fabric be modified to reduce external heat gains and hence reduce the cost of cooling when the windows are not in use?*

The answer to this question is provided in chapter 5 of the thesis when the building fabric was upgraded by increasing the thermal mass and applying an insulation layer at the external wall. This also included insulation of the roof and the ceiling layers. Based on the results obtained after testing the modified building, it was found that there was 10.7% temperature reduction through walls and 14.5% temperature reduction by insulation of roofs and ceilings. These temperature reductions amounted to a total of 25.2% heat energy displaced by modification of the building fabric.

Question 4: *Given to the fact that warm humid environment in South Eastern Nigeria has less air movement, what other means of passive cooling strategies apart from cross ventilation could be applied in buildings?*

The answers to this question are provided in chapters 3, 4 and 5 where it was shown that there are other potential means of inducing optimal air movement into the building by using low energy fans and other low energy air moving devices that are powered by PV panels and could be applied in a synergistic formation with the proposed passive cooling strategies.

Question 5: *What are the potentials of the identified natural heat sinks for indoor passive air conditioning in a warm humid climate and to what extent can they be applied?*

The answer to this research question is provided in chapter 3 and chapter 4. The earth has a good thermal capacity to receive and retain heat energy. The temperature of the earth at 3m to 4m remains below the indoor upper comfort limit by an average of 1°C and at shallower levels of 1m to 2m, it remains slightly above the lower comfort limits by an average of 1°C during the hottest months of the year. The former has amplitudes of about 1°C which makes the temperature at that depth almost constant throughout the year, while the later has swings of about 6.1°C and a period of 5 to 6 months between the minimum and the maximum temperatures. On the other hand, the effective sky temperature in the study area ranges between 10°C to 32°C below the lower comfort limit of 25ºC when there is cloudless sky and hardly exceeds 26°C during the nights of cloudiest skies.

Question 6: *What are the potentials of a synergy between ground pipe ventilation system and clear night sky radiant cooling on delivering cooler air and expelling warm air via enhanced stack effect when applied to a modified building fabric?*

The answers to this research question are provided in Chapter 5 which studied the cooling ability and characteristics of the soil temperature and the effective sky temperature within the study area. The study found that the earth is usually cooler than the indoor temperature when the ambient is at its peak. This effect is usually reversed at nights when the ambient falls below the soil temperature. However, during the night period, the effective sky temperature drops depending on cloud conditions. The study also found that by passing air through buried pipes to exchange heat with the soil in the day and passing air under radiating roofing sheets at night and channelling both into living spaces, the indoor temperature of such spaces was reduced and as well doused the effects of internally generated heat while ventilating and eliminating CO_2 concentrations within such living spaces. The application of positive pressure ventilation through PPGPV on a thermally enhanced building fabric sustained indoor temperature within comfort limits during the day but tended towards the upper limits during the nights. However, the coolth achieved by this application was not enough to effectively charge the building fabric for sensible cooling at night when the building will be fully occupied. And on the other hand, there was substantial reduction in indoor temperature by the application of clear night sky radiating system, and indoor thermal conditions were maintained throughout the night and remained below the lower comfort limit most of the time. The CNS radiating system in the experimental cell showed abilities to generate about 2 kWh of cooling energy per night.

Question 7: *What are the viable passive cooling strategies that are readily available which can be incorporated in a single or combined system running independently or concurrently?*

The answer to this question was provided in chapter 3 by the review of ground pipe ventilation system which works with the heat sink "earth", and the clear night sky radiant cooling system which works with the heat sink "sky". Among other passive cooling techniques identified are night cooling, which in this case the study has to mimic natural night cooling by improving the diurnal temperature range when cool air is passed through surfaces radiating to the sky is passed into the building at night. The study also identified potentials in sensible cooling and the capacity of the building fabric to act as heat resistors from outside while acting as a coolth retainer from the inside. Fabric first design measures were therefore identified as the chief approach to any other passive cooling method.

Question 8: *Can the identified approaches and techniques perform in a warm humid climate?*

The answers to this question are also provided in chapter 5 where a field test of the constructed models was carried out in Ahaba Imenyi which is a town in warm humid south eastern Nigeria. The building modification reduced the indoor temperature but remained above the upper comfort about 90% of the time during the day. The positive pressure ground cooling system reduced indoor temperatures by 22.4% in the daytime, while the

Clear night sky radiating system reduced indoor temperature by 22.3% in the night, when both systems worked in isolation. The positive pressure ground pipe ventilation maintained indoor temperature within the comfort limit but remained towards the upper limit. The CNS was able to sustain indoor temperature below 26°C and most times was below the lower comfort limit which indicates potentials for storable coolth in the thick walls of the structure.

Question 9: *To what extent can these approaches, either individually or in combination, present a cost-effective solution that will displace air conditioning and its associated carbon emissions?*

The answers to the above question was provided in Chapter 6, when the different approaches were individually analysed in a 27m^3 bedroom and were all found to exhibit levels of reductions in indoor temperature and heat energy. The fabric modification showed a displacement of 42.2% of heat energy, however this reduction did not have significant effect on the indoor thermal comfort conditions as the upper comfort limit was exceeded more than 65% of the time. The positive pressure ground pipe ventilation displaced 63.8% of heat energy which amounted to an equivalent of 252 kWh of heat energy displaced monthly. The CNS displaced 104.7% which amounted to 6.8 kWh of cooling energy at a thermostat setting of 25°C per night and 142 kWh displaced each month while generating circa 63.6 kWh of cooling energy monthly. For an average 3-bedroom apartment, the PPGPV and CNS running in tandem was able to displace 83.5% of cooling energy requirement which was an equivalent reduction from 13,372.4 kWh to 2,206.45 kWh annually, therefore an annual displacement of 11,166 kWh of cooling loads. The PCS also reduced CO_2 emissions due to reduced electricity consumption from 1,486 kg to 295 kg when compared to a regular 3-bedroom apartment in the warm humid south eastern Nigeria.

Question 8: *Which of the approaches is the most effective in terms of cost and performance?*

The cost effectiveness of the different approaches was analysed and the answer to the above question is provided in Chapter 6 where it was discovered that the different approaches on their own reduced energy consumption considerably and hence each had a positive effect on the cost reduction in energy used by different degrees. The hybrid cooling system which comprised the PPGPV and the CNS working in tandem was found to be the most effective system. The payback period was calculated to be in the region of 8 years discounting possible financial bounties being generated by the carbon savings.

7.4 Performance gaps

The analysis of results obtained from the investigation on the application of PCS has demonstrated potentials for substantial reduction in indoor temperature and hence a reduction in the energy demand for cooling in residential buildings in south eastern Nigeria. There is a clear agreement between the research intention and the performance of the applied passive cooling systems on a thermally enhanced building fabric. However, the application of the PCS to reduce indoor temperature and energy for cooling in buildings in a climate such as warm humid south eastern Nigeria may present some challenges.

Situations such as in instances where there is limited space on site will consequently result in constructional and operational restrictions. For a PPGPV pipes to be laid, large area of excavation is required in order to lay the pipes either horizontally or vertically which might also take a longer period to achieve depending on the size of the system. This may be a difficult task for tight sites with already existing buildings, and at such, it becomes more efficient to consider ground pipe ventilation during design stages and construction process as applying the system in already existing buildings may entail higher upfront costs hence, a longer payback period.

In most cases, a reduction in temperature will subsequently increase chances of condensation on the radiating surfaces in the CNS system which may result to mould growth and water damage if not well controlled. This may be a limiting factor for the radiant cooling system in an environment such as warm humid one. To avoid condensation, surface temperatures should never be equal or below the dew point temperature in the space conditioned, and on radiating surfaces. Some known standards suggest minimal range for relative humidity in spaces as between 60% and 70%. Therefore, air temperatures at 24ºC would mean dew points of 15ºC to 18ºC. Secondly, decreasing the surface temperature to values below the dew point for short periods may drastically reduce or totally eliminate condensation.

Low energy functional dehumidifiers can as well be of great importance in limiting high humidity levels in conditioned buildings. This will in turn raise the cooling capacity of the passive/hybrid system. The capital and operational costs of these low energy humidifiers which are PV powered are so insignificant in the overall capital and operational cost of the cooling systems and will not have any effect on the payback period.

Another dehumidification strategy is the application of porous activated charcoal briquettes. Activated charcoal takes in moisture and odour into sizeable trays or bags which can occasionally (usually 2 to 3 months) be placed in the sun to dry out the accumulated moisture and can be reused as many times as possible. Application of charcoal briquettes is a simply dehumidification tool/ method that has been in use since 3750 BC but in the past few years, it has gained popularity and also attracted attention among many control strategies for indoor moisture and removal of Volatile Organic Compounds (VOC). Charcoal briquettes do not make use of energy but have been proven to efficiently remove and control possible indoor moisture in the conditioned rooms and in turn improves thermal comfort and enhance energy saving.

Thirdly, due to the low wind speeds, low energy active devices would be constantly required to induce air movement for an optimal operation of the cooling system. In most cases, these fans can be a source of noise especially at nights. The capital and operational costs of these fans are factored into the capital cost of construction of the system.

The use of lightweight building materials especially for construction of walls, roofs and ceilings are common practices in Nigeria where production of building materials is not regulated. It may however be a challenging task to educate people on the need to try other innovative approaches in buildings especially such as insulated heavy-weight construction; an approach that is currently alien. Some other shortcomings or barriers are the socio-cultural acceptance, land restrictions in the circumstance of the PPGPV and cloud cover at certain times of year that will reduce the efficacy of the CNS. The main heat exchange fluid in this research work is air and the specific heat capacity of air decreases as temperature decreases. Sky temperatures as low as -9°C and surface temperature of a radiating surface of 0°C were recorded in the study area indicating a greater level of cooling potential than was actually achieved using the scale model. The interfaces created in this research could be improved to optimise heat exchange between the internal surface boundary and the air.

The application of this system in an already completed building in Nigeria may be more capital intensive than when it is applied during design and or construction stages.

7.5 Recommendations

The passive cooling techniques and approaches applied in this research are by no means exhaustive however, the results obtained aligned with the research hypothesis and therefore the following recommendations and guidelines towards the perfection of this field are provided for different sectors which includes the Nigerian government, stakeholders and students for future research work.

1. Make energy efficiency of buildings in Nigeria a criterion by cconsidering local climate, resources and design procedures that will allow for a high reproduction potential and working closely with the local stake holders to provide a data base and sound technology for energy efficient designs to those involved in planning and construction of buildings. Material and equipment providers should also familiarise with the development of product related key data which will stand as guide in the design of energy efficient buildings and for ease of implementation and testing procedures in accordance with the new requirements.
2. Create awareness on the need to maximize energy efficiency in buildings by the utilization of cheaper renewable energy generators such PVCs to reduce fossil fuel consumption which will in turn reduce CO_2 emissions.
3. Create policies that will require periodic review of energy performance status of buildings to ensure compliance with energy saving standards/requirements.
4. Create strict policies that will change the orientation in the building sector by developing energy building code and the introduction of design catalogues for affordable energy efficient buildings, which will be targeted at meeting the minimum energy requirements for building permits/approval.
5. Create awareness through publication of updated manuals for building occupants on the disadvantages of energy waste in buildings by constantly educating them on the need to fully exploit the potentials of climate adaptive designs as the most cost-effective efficiency measure/option and to also consider the availability of energy efficient products. Pilot projects can be set up for a typical residential building with the aim to demonstrate the potentials of energy efficient design by building testable prototypes on site in order to allow for a reasonable and unique comparison in terms of design procedures, cost, affordability and energy savings as scales.

6. Create awareness on the negative consequences/environmental impacts of uncontrolled energy consumption especially within buildings by encouraging the use of appropriate building materials and design methods/approaches that will enhance passive conditioning of indoor spaces.

7. Expanding the field of investigation to cover the production of materials or design approaches that would maximise the cooling potentials of the earth and the sky for indoor conditioning in Nigeria building sector, by focusing on innovations and researches which would produce an optimal heat interface between the heat sinks and the heat conveying fluids.

8. Future research should also focus on the application of the passive cooling systems in public buildings such as train stations and airports including office buildings.

9. Simulation models are used to represent a real-world system in a virtual environment therefore granting ease of adjustments in the performance of a system under different operating conditions. They can also predict the thermal behaviour, cost analysis, calculation of energy requirements and can as well help in high accuracy and faster decision making as it concerns possible devices to be used in a building space prior to their construction. It can also simulate the costs of energy in existent buildings in their current conditions making it easy to establish the best thermal retrofitting options/measures to implement in the buildings under analysis. There is need therefore to employ professional simulation software tools such as ESP-r (Energy Simulation Software tool), IES-VE (Integrated Environmental Solutions - Virtual Environment), TRNSYS, EnergyPlus, and IDA ICE (Indoor Climate Energy) in future research work in Nigeria to virtually model and test such passive/hybrid innovations in order to avert the accompanying complexity and strain that comes with physically demonstrating and monitoring such hybrid system in larger/complex buildings.

10. Research on production of building materials from local sources which might in part or completely replicate the qualities of materials previously used in vernacular buildings in Nigeria.
11. Further studies should include the effects of internal heat gains on the overall performance of the passive cooling system. Hence subsequent research work may test the efficiency of the system in an operational building environment with full occupant capacity and activities.
12. Economic studies should be encouraged to appraise the cost effectiveness of the application of the passive cooling system in Nigerian buildings as such financial estimations may likely attract the actual implementation of the techniques applied in the system.
13. Future research should explore the potentials for storage of coolth from clear night sky radiant cooling using specially designed thermal massing to serve as thermal batteries underneath building structure, which could also be extended to charging the surrounding earth in the underground pipe cooling system with the aim of achieving an optimally charged heat sink for maximum thermal interface during peak periods.
14. The climatic conditions of the various zones of Nigeria have different diurnal temperature range. This study was limited to the climatic conditions of the South Eastern Nigeria. Hence, further research is essential to explore the potential of similar passive/hybrid cooling interventions in other climatic regions of Nigeria.

References

Adebamowo, M. (2007). Thermal Comfort in Urban Residential Buildings in Lagos Metropolis. *Unpublished PhD Thesis. Lagos State University, Ojo, Nigeria*.

Agas, G., Matsaggos, T., Santamouris, M., & Argyriou, A. (1991). On the use of the atmospheric heat sinks for heat dissipation. *Energy and buildings, 17*(4), 321-329.

Agbola, T. (1990). Affordability and Cost-recovery in Shelter Projects: The Case of Nigeria. *Third World Planning Review, 12*(1), 59.

Agyenim, F., Hewitt, N., Eames, P., & Smyth, M. (2010). A review of materials, heat transfer and phase change problem formulation for latent heat thermal energy storage systems (LHTESS). *Renewable and sustainable energy reviews, 14*(2), 615-628.

Ajibola, K. (2001). Design for comfort in Nigeria—a bioclimatic approach. *Renewable energy, 23*(1), 57-76.

Ajoge, H. O., Yende-Zuma, N., Jatau, E. D., Ibrahim, S., Olonitola, S. O., & Shittu, O. S. (2013). Community-based intervention is necessary for the control of HIV in North-Central Nigeria. *International Journal of Infectious Diseases, 17*(4), e234-e239.

Akadiri, P. O., Chinyio, E. A., & Olomolaiye, P. O. (2012). Design of a sustainable building: A conceptual framework for implementing sustainability in the building sector. *Buildings, 2*(2), 126-152.

Akande, O. K., & Adebamowo, M. A. (2010). *Indoor thermal comfort for residential buildings in hot-dry climate of Nigeria.* Paper presented at the Proceedings of Conference: Adapting to Change: New Thinking on Comfort, Cumberland Lodge, Windsor, UK.

Al-Ajmi, F., Loveday, D., & Hanby, V. I. (2006). The cooling potential of earth–air heat exchangers for domestic buildings in a desert climate. *Building and Environment, 41*(3), 235-244.

Al-Nimr, M., Kodah, Z., & Nassar, B. (1998). A theoretical and experimental investigation of a radiative cooling system. *Solar energy, 63*(6), 367-373.

Allard, F., Ghiaus, C., Santamouris, M., & Wouters, P. (2006). *Natural ventilation in the urban environment*: Earthscan. London.

Alp, A. V. (1991). Vernacular climate control in desert architecture. *Energy and buildings, 16*(3), 809-815.

Altamirano-Medina, H., Davies, M., Ridley, I., Mumovic, D., & Oreszczyn, T. (2006). Moisture Performance Criteria for UK Dwellings.

Anderson, B. (2006). Thermal properties of building structures. *CIBSE Guide A: Environmental Design. 7th Edition, Norwich: The Chartered Institution of Building Services Engineers*, 3-1.

Ångström, A. K. (1915). *A study of the radiation of the atmosphere: based upon observations of the nocturnal radiation during expeditions to Algeria and to California* (Vol. 65): Smithsonian Institution.

Anna Jagger. (2008). Polyethylene: discovered by accident 75 years ago. Retrieved from https://www.icis.com/resources/news/2008/05/12/9122447/polyethylene-discovered-by-accident-75-years-ago/

Anon. (1984). Dynamic insulation: the next step? *Building Services, 6*, 41.

Anselm, A. J. (2012). *Earth Shelters; A Review of Energy Conservation Properties in Earth Sheltered Housing*: INTECH Open Access Publisher.

Anyagafu, S. V. (2014). Nigeria records over 10,000 deaths through 'generator' fumes

Vanguard Newspaper. Retrieved from http://www.vanguardngr.com/2014/08/nigeria-records-10000-deaths-generator-fumes/

Areemit, N., & Sakamoto, Y. (2005). *Feasibility study of the passive solar room dehumidifying system using the sorption property of a wooden attic space through field measurement.* Paper presented at the International Conference Passive and Low Energy Cooling for Built Environment, May, Santorini, Greece.

Armenta-Déu, C., Donaire, T., & Hernando, J. (2003). Thermal analysis of a prototype to determine radiative cooling thermal balance. *Renewable energy, 28*(7), 1105-1120.

Arup, & Genre, D. (2016). *Building Energy Efficiency Guideline for Nigeria*. Retrieved from Shehu Yar'adua Way, Mabushi Abuja, Nigeria.: https://energypedia.info/images/c/c7/Building_Energy_Efficiency_Guideline_for_Nigeria_2016.pdf

ASHRAE. (1974). *ASHRAE Handbook of Fundamentals*: Mar Lin Book Company.

Ashwood, A., & Bharathan, D. (2011). Hybrid cooling systems for low-temperature geothermal power production.

Athienitis, A. K., & Santamouris, M. (2013). *Thermal analysis and design of passive solar buildings*: Routledge.

Attic Heat Harvester. (n.d). Attic Heat Harvester Edinburgh UK Performance Data. Retrieved from http://www.atticheatharvester.com/attic-heat-harvester-edinburgh-uk-performance.html

Aubinet, M. (1994). Longwave sky radiation parametrizations. *Solar energy, 53*(2), 147-154.

Auliciems, A. (1981). Towards a psycho-physiological model of thermal perception. *International Journal of Biometeorology, 25*(2), 109-122.

Awotona, A. (1990). Nigerian government participation in housing: 1970–1980. *Habitat International, 14*(1), 17-40.

Badiora, A. I., Oluwadare, D. B., & Dada, O. T. (2014). Nature of residential burglary and prevention by design approaches in a nigerian traditional urban center. *Journal of Applied Security Research, 9*(4), 418-436.

Balaras, C. (1996). The role of thermal mass on the cooling load of buildings. An overview of computational methods. *Energy and buildings, 24*(1), 1-10.

Balaras, C., Droutsa, K., Argiriou, A., & Asimakopoulos, D. (2000). Potential for energy conservation in apartment buildings. *Energy and buildings, 31*(2), 143-154.

Balcomb, J. D. (1983). *Heat storage and distribution inside passive-solar buildings*. Retrieved from

Bascom, R., Bromberg, P. A., Costa, D. L., Devlin, R., Dockery, D. W., Frampton, M. W., . . . Utell, M. (1996). Health effects of outdoor air pollution. *American journal of respiratory and critical care medicine, 153*(2), 477-498.

Bascom, R., Kesavanathan, J., & Swift, D. L. (1996). Indoor Air Pollution: Understanding the Mechanisms of the Effects. *Indoor Air and Human Health*, 151.

Benjamin, S., Reynolds, J., & McGuinness, W. (1992). Mechanical and electrical equipment for buildings: John Wiley & Sons, 8th edition, ISBN 0-471-52502-2.

Berdahl, P., & Fromberg, R. (1982). The thermal radiance of clear skies. *Solar energy, 29*(4), 299-314.

Berdahl, P., & Martin, M. (1984). Emissivity of clear skies. *Solar energy, 32*(5), 663-664.

Berdahl, P., Martin, M., & Sakkal, F. (1983). Thermal performance of radiative cooling panels. *International journal of heat and mass transfer, 26*(6), 871-880.

Bird, R. E., & Hulstrom, R. L. (1981). *Simplified clear sky model for direct and diffuse insolation on horizontal surfaces*. Retrieved from

Bisoniya, T. S., Kumar, A., & Baredar, P. (2013). Experimental and analytical studies of earth–air heat exchanger (EAHE) systems in India: a review. *Renewable and sustainable energy reviews, 19*, 238-246.

Bliss, R. W. (1961). Atmospheric radiation near the surface of the ground: a summary for engineers. *Solar energy, 5*(3), 103-120.

Blondeau, P., Spérandio, M., & Allard, F. (1997). Night ventilation for building cooling in summer. *Solar energy, 61*(5), 327-335.

Blunden, J. (2013). 2013 State of the Climate: Carbon dioxide tops 400 ppm Retrieved from https://www.climate.gov/news-features/understanding-climate/2013-state-climate-carbon-dioxide-tops-400-ppm

Bob Berwyn. (2016). Far From Turning a Corner, Global CO2 Emissions Still Accelerating.   Retrieved from https://insideclimatenews.org/news/19052016/global-co2-emissions-still-accelerating-noaa-greenhouse-gas-index

Bojić, M., Papadakis, G., & Kyritsis, S. (1999). Energy from a two-pipe, earth-to-air heat exchanger. *Energy, 24*(6), 519-523.

Bojic, M., Trifunovic, N., Papadakis, G., & Kyritsis, S. (1997). Numerical simulation, technical and economic evaluation of air-to-earth heat exchanger coupled to a building. *Energy, 22*(12), 1151-1158.

Bokel, J. (2007). The Effect of Window Position and Window Size of the Energy Demand for Heating. *Cooling, and Electrical Lighting*.

British Standard, B. (2002). 5250: 2002 (2002),"Code of practice for control of condensation in buildings". *British Standard BS, 5368*.

Brown, W. G., & Solvason, K. (1962). Natural convection through rectangular openings in partitions—1: Vertical partitions. *International journal of heat and mass transfer, 5*(9), 859IN1863-862868.

Brunt, D. (1932). Notes on radiation in the atmosphere. I. *Quarterly Journal of the Royal Meteorological Society, 58*(247), 389-420.

CAHF. (2018). Housing Finance In Africa: A review of Africa's housing finance markets. *Centre for Affordable Housing Finance in Africa*.

Cammarata, G., & Marletta, L. (1990). Ventilazione e benessere ambientale negli edifice in regime estivo. *Condizionamento dell'aria Riscaldamento Refrigerazione, 34*(3), 467-473.

Catalanotti, S., Cuomo, V., Piro, G., Ruggi, D., Silvestrini, V., & Troise, G. (1975). The radiative cooling of selective surfaces. *Solar energy, 17*(2), 83-89.

Cavelius, R., Isaksson, C., Perednis, E., & Read, G. E. (2005). Passive cooling technologies. *Austrian Energy Agency*, 125.

Centeno, M. (1982). New formulae for the equivalent night sky emissivity. *Solar energy, 28*(6), 489-498.

Chua, K., Chou, S., & Yang, W. (2010). Advances in heat pump systems: A review. *Applied Energy, 87*(12), 3611-3624.

CIBSE, G. A. (2006). Environmental design. *The Chartered Institution of Building Services Engineers, London*.

Claridge, D., & Bhattacharyya, S. (1991). The measured energy impact of air leakage on frame wall systems. *Final Report, DOE, USA. Google Scholar*.

Clark, C., & Blanpied, M. (2013). *RADIATTVE AND ALTERNATIVE DEHUMIDIFICATION STRATEGIES FUR HUMID CLIMATES.* Paper presented at the Passive and Low Energy Alternatives I: The First International PLEA Conference, Bermuda, September 13-15, 1982.

Clark, G. (1981). Passive/hybrid comfort cooling by thermal radiation. *Passive Cooling: American Section of the International Solar Energy Society, Miami Beach*.

Clark, G., & Blanpied, M. (1979). *The effect of IR transparent windscreens on net nocturnal cooling from horizontal surfaces.* Paper presented at the Proceedings of the 4th National Passive Solar Conference, Kansas City, MO.

Clark, J. A. (1978). Environmental systems performance: Bull. Comput. Aided Archit. Des. No. 23 (Feb. 1977) pp 27–38. *Computer-Aided Design, 10*(3), 208.

Coch, H. (1998). —Bioclimatism in vernacular architecture. *Renewable and sustainable energy reviews, 2*(1), 67-87.

Cook, J. (1989). *Passive cooling*. Retrieved from

Cooper, P., Christie, E., & Dunkle, R. (1981). A method of measuring sky temperature. *Solar energy, 26*(2), 153-159.

Creswell, J. W., & Creswell, J. D. (2017). *Research design: Qualitative, quantitative, and mixed methods approaches*: Sage publications.

Cross, N. (1999). Design research: A disciplined conversation. *Design issues, 15*(2), 5-10.

Damilola, A. (2018). Types of Houses in Nigeria. Retrieved from https://www.propertypro.ng/blog/types-of-houses-in-nigeria/

Day, C., & Roaf, S. (2007). *Ecohouse: a design guide*: Routledge.

De Dear, R. J., Brager, G. S., Reardon, J., & Nicol, F. (1998). Developing an adaptive model of thermal comfort and preference/discussion. *ASHRAE Transactions, 104*, 145.

De Paepe, M., & Janssens, A. (2003). Thermo-hydraulic design of earth-air heat exchangers. *Energy and buildings, 35*(4), 389-397.

Dedear, R., & Auliciems, A. (1985). Validation of the predicted mean vote model of thermal comfort in six Australian field studies. *ASHRAE Transactions, 91*(2B), 452-468.

Designing Buildings Wiki. (2018). Geothermal pile foundations *Designing Buildings Wiki*.

Diaz, C. (1994). *Climate-responsive design for non-domestic buildings in warm climates: optimisation of thermal mass for indoor cooling.* Open University.

Dobson, R. (2005). Thermal modelling of a night sky radiation cooling system. *Journal of Energy in Southern Africa, 16*(2), 20-31.

Egbedi, H. (2017, 13 Feb 2017). Welcome to Onitsha: the city with the world's worst air. *The Guardian*. Retrieved from https://www.theguardian.com/cities/2017/feb/13/polluted-onitsha-nigeria-perpetual-dust-city-world-worst-air

Eicker, U., & Dalibard, A. (2011). Photovoltaic–thermal collectors for night radiative cooling of buildings. *Solar energy, 85*(7), 1322-1335.

Elleh, N. (1997). *African architecture: evolution and transformation*: McGraw-Hill Professional Publishing.

Elsarrag, E., Al-Horr, Y., & Imbabi, M. S.-E. (2012). *Improving building fabric energy efficiency in hot-humid climates using dynamic insulation.* Paper presented at the Building Simulation.

Eludoyin, O., Adelekan, I., Webster, R., & Eludoyin, A. (2014). Air temperature, relative humidity, climate regionalization and thermal comfort of Nigeria. *International Journal of Climatology, 34*(6), 2000-2018.

Engineeringtoolbox. Air Properties Retrieved from http://www.engineeringtoolbox.com/air-properties-d_156.html

Engineers, C. I. o. B. S. (2001). *Reference Data: CIBSE Guide C*: Butterworth-Heinemann.

Eriksson, T., & Granqvist, C. (1982). Radiative cooling computed for model atmospheres. *Applied optics, 21*(23), 4381-4388.

Etiosa, U., Mathew, A., Agharese, E., Ogbemudia, O., Osazee, P., & Ose, G. (2009). Energy efficiency survey in Nigeria: a guide for developing policy and legislation. *International, Rivers*, 1-37.

Evans, J. M. (2003). Evaluating comfort with varying temperatures: a graphic design tool. *Energy and buildings, 35*(1), 87-93.

Ezekwe, C. (1986). Nocturnal radiation measurements in Nigeria. *Solar energy, 37*(1), 1-6.

Ezekwe, C. (1990). Performance of a heat pipe assisted night sky radiative cooler. *Energy Conversion and Management, 30*(4), 403-408.

Ezinwanne Udechukwu, C. (2008). Obstacles to individual home ownership in Nigeria. *International Journal of Housing Markets and Analysis, 1*(2), 182-194.

Fang, L., Clausen, G., & Fanger, P. O. (1998). Impact of temperature and humidity on perception of indoor air quality during immediate and longer whole-body exposures. *Indoor Air, 8*(4), 276-284.

Fanger, P. (1970). Thermal comfort. Analysis and applications in environmental engineering. *Thermal comfort. Analysis and applications in environmental engineering.*

Fanger, P. O., Melikov, A. K., Hanzawa, H., & Ring, J. (1988). Air turbulence and sensation of draught. *Energy and buildings, 12*(1), 21-39.

Fathy, H. (1986). Natural energy and vernacular architecture.

Fawkes, S., Howarth, N., Krarti, M., & Padmanabhan, P. (2016). *Investing for Energy Productivity in the GCC–Financing the Transition*. Retrieved from

FederalMinistryOfEnvironment-Nigeria. (2014). *Nigeria's Second National Communication (Under the United Nations Framework Convention on Climate Change).* Retrieved from Abuja, Nigeria: http://unfccc.int/resource/docs/natc/nganc2.pdf

Florides, G., & Kalogirou, S. (2007). Ground heat exchangers—A review of systems, models and applications. *Renewable energy, 32*(15), 2461-2478.

Fraser , D. W., Tsai , T. R., Orenstein , W., Parkin , W. E., Beecham , H. J., Sharrar , R. G., . . . Team*, t. F. I. (1977). Legionnaires' Disease. *New England Journal of Medicine, 297*(22), 1189-1197. doi:10.1056/nejm197712012972201

Frenken, K. (2005). *Irrigation in Africa in figures: AQUASTAT Survey, 2005* (Vol. 29): Food & Agriculture Org.

Fuentes, M. K. (1987). *A simplified thermal model for flat-plate photovoltaic arrays*. Retrieved from

Gado, T., & Mohamed, M. More Accurate Computer Simulation for Intelligent Buildings: Exporting 3D Building Models to Detailed Thermal Simulation Software. *Intelligent Buildings International, University of Dundee, Scotland, UK*.

Gagge, A. P., Fobelets, A., & Berglund, L. (1986). A standard predictive index of human response to the thermal environment. *ASHRAE Trans.;(United States), 92*(CONF-8606125-).

Gallo, C. (1998). —The utilization of microclimate elements. *Renewable and sustainable energy reviews, 2*(1), 89-114.

Gan, G. (1998). A parametric study of Trombe walls for passive cooling of buildings. *Energy and buildings, 27*(1), 37-43.

Garg, H. (1982). Treatise on solar energy, Fundamentals of Solar Energy, Vol. 1: Chichester: Wiley.

Geissler, S., Österreicher, D., & Macharm, E. (2018). Transition towards energy efficiency: developing the Nigerian building energy efficiency code. *Sustainability, 10*(8), 2620.

Ghisi, E., & Tinker, J. A. (2005). An ideal window area concept for energy efficient integration of daylight and artificial light in buildings. *Building and Environment, 40*(1), 51-61.

Givoni, B. (1969). Man, climate and architecture. *Elsevier;()*.

Givoni, B. (1976). Man, Climate and Architecture (2nd edn.) Applied Science: London.

Givoni, B. (1983). Review of passive heating and cooling research *Passive and Low Energy Architecture* (pp. 339-352): Elsevier.

Givoni, B. (1991). Performance and applicability of passive and low-energy cooling systems. *Energy and buildings, 17*(3), 177-199.

Givoni, B. (1992). Comfort, climate analysis and building design guidelines. *Energy and buildings*, *18*(1), 11-23.

Givoni, B. (1994). *Passive low energy cooling of buildings*: John Wiley & Sons.

Givoni, B. (1998a). *Climate considerations in building and urban design*: John Wiley & Sons.

Givoni, B. (1998b). Effectiveness of mass and night ventilation in lowering the indoor daytime temperatures. Part I: 1993 experimental periods. *Energy and buildings, 28*(1), 25-32.

Givoni, B. (2007). Cooled soil as a cooling source for buildings. *Solar energy, 81*(3), 316-328.

Givoni, B., & Katz, L. (1985). Earth temperatures and underground buildings. *Energy and buildings, 8*(1), 15-25.

Goforth, M. A., Gilchrist, G. W., & Sirianni, J. D. (2002). *Cloud effects on thermal downwelling sky radiance.* Paper presented at the AeroSense 2002.

Golaka, A., & Exell, R. (2007). An investigation into the use of a wind shield to reduce the convective heat flux to a nocturnal radiative cooling surface. *Renewable energy*, *32*(4), 593-608.

Gold, K. (2014). *Post-harvest handling of seed collections*: Millennium Seed Bank Partnership.

Greenwood, B. (1999). Meningococcal meningitis in Africa. *Transactions of the Royal Society of Tropical Medicine and Hygiene, 93*(4), 341-353.

Greenwood, B. (2006). 100 years of epidemic meningitis in West Africa–has anything changed? *Tropical medicine & international health, 11*(6), 773-780.

Group, W. B. (2015). *The Little Green Data*: World Bank Publications.

Group, W. B. (2016). *The Little Green Data*: World Bank Publications.

Group, W. B. (2017). *The Little Green Data*: World Bank Publications.

Guide B, C. (2001). B2: Ventilation and air conditioning. *CIBSE, London*.

Gupta, C. (1993). Solar passive buildings for developing countries. *Sadhana, 18*(1), 77-104.

Hait, J. (1983). *Passive Annual Heat Storage: Improving the Design of Earth Shelters*: Rocky Mountain Research Center.

Hall, M. R., Casey, S. P., Loveday, D. L., & Gillott, M. (2013). Analysis of UK domestic building retrofit scenarios based on the E. ON Retrofit Research House using energetic hygrothermics simulation–Energy efficiency, indoor air quality, occupant comfort, and mould growth potential. *Building and Environment, 70*, 48-59.

Hamberg, I., Svensson, J. S. E., Eriksson, T. S., Granqvist, C.-G., Arrenius, P., & Norin, F. (1987). Radiative cooling and frost formation on surfaces with different thermal emittance: theoretical analysis and practical experience. *Applied optics, 26*(11), 2131-2136.

Hawes, D., Banu, D., & Feldman, D. (1990). Latent heat storage in concrete. II. *Solar energy materials, 21*(1), 61-80.

Hay, H. R. (1978). *A passive heating and cooling system from concept to commercialization.* Paper presented at the Proceedings of the annual meeting of the International Section of the Solar Energy Society.

Hensen, J. L. M. (1991). *On the thermal interaction of building structure and heating and ventilating system*: Technische Universiteitt Eindhoven.

Hijazi, J. F. J. (2018). *Towards Displacing Domestic Air Conditioning in KSA: An Assessment of Hybrid Cooling Strategies Integrated with 'Fabric First' Passive Design Measures.* University of Strathclyde, Glasgow., University of Strathclyde, Glasgow.

Hines, A. L. (1993). *Indoor air: Quality and control*: PTR Prentice Hall.

Hollick, J. (2013). Solar Cooling with NightSolar. Retrieved from http://solarwall.com/posts/solar-cooling-with-nightsolarr-218.php

Hollmuller, P., & Lachal, B. (2001). Cooling and preheating with buried pipe systems: monitoring, simulation and economic aspects. *Energy and buildings, 33*(5), 509-518.

Hottel, H., & Egbert, R. (1942). Radiant heat transmission from water vapor. *Trans. Amer. Inst. Chem. Eng, 38*, 531-568.

Houghten, F., Blackshaw, J., Pugh, E., & McDermott, P. (1932). Heat transmission as influenced by heat capacity and solar radiation. *ASHVE Transactions*, *38*(1), 232-284.

Howieson, S. (2005). *Housing and asthma*: Taylor & Francis.

Howieson, S., Sharpe, T., & Farren, P. (2014). Building tight–ventilating right? How are new air tightness standards affecting indoor air quality in dwellings? *Building Services Engineering Research and Technology, 35*(5), 475-487.

Huang, W., & Lam, H. (1997). Using genetic algorithms to optimize controller parameters for HVAC systems. *Energy and buildings, 26*(3), 277-282.

Humphreys, M. (1981). The dependence of comfortable temperatures upon indoor and outdoor climates. *Studies in Environmental Science, 10*, 229-250.

Husman, T. (1996). Health effects of indoor-air microorganisms. *Scandinavian journal of work, environment & health*, 5-13.

Hussaini, I. U., & Abdul Majid, N. H. (2015). Energy development in Nigeria and the need for strategic energy efficiency practice scheme for the residential building sector. *Management of Environmental Quality: An International Journal, 26*(1), 21-36.

Hyde, R. (2008). *Bioclimatic housing: innovative designs for warm climates*: Earthscan.

Hyde, R., & Pedrini, A. (2002). *An Energy Conservation Architectural Design Tool for Warm Climate (LTV): The tool development and testing.* Paper presented at the Expert „s Conference on Tropical Daylight and Building, Singapura.

Ikejiofor, U. (1999). The God that Failed: A Critique of Public Housingin Nigeria, 1975–1995. *Habitat International, 23*(2), 177-188.

Iloeje, O. (1985). Design construction and test run of a solar powered solid absorption refrigerator. *Solar energy, 35*(5), 447-455.

Investopedia. (2018). Descriptive Statistics *Investopedia*.

Isaacson, R. H. (2014). Temperature and humidity air treatment system: Google Patents.

ISO, E. (1996). 6946. *Building components and building elements Thermal resistance and thermal transmittance Calculation Method, Standards Norway, Oslo, Norway*.

Jacovides, C., Mihalakakou, G., Santamouris, M., & Lewis, J. (1996). On the ground temperature profile for passive cooling applications in buildings. *Solar energy, 57*(3), 167-175.

Jafarian, S., Jaafarian, S., Haseli, P., & Taheri, M. (2010). Performance analysis of a passive cooling system using underground channel (Naghb). *Energy and buildings, 42*(5), 559-562.

Jakob, M., & Madlener, R. (2004). Riding down the experience curve for energy-efficient building envelopes: the Swiss case for 1970–2020. *International Journal of Energy Technology and Policy, 2*(1-2), 153-178.

Karakatsanis, C., Bahadori, M. N., & Vickery, B. (1986). Evaluation of pressure coefficients and estimation of air flow rates in buildings employing wind towers. *Solar energy, 37*(5), 363-374.

Karsten Ley, Gaines, J., & Ghatikar, A. (2014). *The Nigerian Energy Sector - an Overview with a Special Emphasis on Renewable Energy, Energy Efficiency and Rural Electrification*. Retrieved from https://www.giz.de/en/downloads/giz2014-en-nigerian-energy-sector.pdf

Kasten, F., & Czeplak, G. (1980). Solar and terrestrial radiation dependent on the amount and type of cloud. *Solar energy, 24*(2), 177-189.

Kawuwa, A., Sani, A., Mustapha, S., & Ishaku, D. (2015). Development of strategies for sustainable energy efficient building codes in Nigeria. *International Journal of Scientific and Research Publications, 5*(4), 1-7.

Keeney, K. R., & Braun, J. E. (1997). Application of building precooling to reduce peak cooling requirements. *ASHRAE Transactions, 103*(1), 463-469.

Khan, N., Su, Y., & Riffat, S. B. (2008). A review on wind driven ventilation techniques. *Energy and buildings, 40*(8), 1586-1604.

Khedari, J., Waewsak, J., Thepa, S., & Hirunlabh, J. (2000). Field investigation of night radiation cooling under tropical climate. *Renewable energy, 20*(2), 183-193.

Knoema. (2012). Nigeria Distribution of Regular Households 2006. Retrieved 2017 http://nigeria.opendataforafrica.org/ivpwkze/nigeria-distribution-of-regular-households-2006

Knoema. (2015). Nigeria - Population - Population density. Retrieved from https://knoema.com/atlas/Nigeria/topics/Demographics/Population/Population-density

Kontoleon, K., & Bikas, D. (2002). Modeling the influence of glazed openings percentage and type of glazing on the thermal zone behavior. *Energy and buildings, 34*(4), 389-399.

Koranteng, C., Mahdavi, A., Orehounig, K., & Pröglhöf, C. (2009). *Thermal performance of office buildings in Ghana.* Paper presented at the Proceedings of the 11th International IBPSA Conference.

Kreider, J. F., & Rabl, A. (1994). Heating and cooling of buildings: design for efficiency McGraw-Hill. *New York*.

Kubota, M., Hamabe, T., Nakazono, Y., Fukuda, M., & Doi, K. (2000). Development of a lightweight brake disc rotor: a design approach for achieving an optimum thermal, vibration and weight balance. *JSAE review*, *21*(3), 349-355.

Kubota, T., Chyee, D. T. H., & Ahmad, S. (2009). The effects of night ventilation technique on indoor thermal environment for residential buildings in hot-humid climate of Malaysia. *Energy and buildings*, *41*(8), 829-839.

Kubota, T., & Ossen, D. R. (2009). Spatial characteristics of urban heat island in Johor Bahru City, Malaysia. *Proceedings of the 3rd South East Asian Technical Universities Consortium (SEATUC'09), Johor Bahru, Malaysia*, 39-44.

Kusuda, T. (1969). *Thermal response factors for multi-layer structures of various heat conduction systems.* Paper presented at the ASHRAE journal.

Kusuda, T. (1975). *The effect of ground cover on earth temperature.* Paper presented at the Proc. Conf. on Alternatives in Energy Conservation, the Use of Earth-Covered Buildings, Forth Worth, Texas.

Kusuda, T., & Achenbach, P. R. (1965). *Earth temperature and thermal diffusivity at selected stations in the United States*. Retrieved from

Kwag, B. C., & Krarti, M. (2017). Development of design guidelines for thermo-active foundations. *Indoor and Built Environment*, 1420326X17690018.

Lawal, A., Akinbami, J., & Akinpade, J. (2012). Assessing effectiveness of utilization of passive design parameters on active energy consumption in public buildings in warm-humid climate. *Journal of Civil Engineering and Construction Technology, 3*(4), 140-147.

Lechner, N. (1991). *Heating, Cooling, Lighting: Design Methods for Artitects*: Wiley.

Lee, K. H., & Strand, R. K. (2008). The cooling and heating potential of an earth tube system in buildings. *Energy and buildings, 40*(4), 486-494.

Liedl, P. (2011). *Interaction Climate–Human–Building: Planning tools for office buildings in different climate zones in the context of room climate and energy with a detailed climate analysis.* Dissertation at TUM.

Lienhard, I., Lienhard, V., & John, H. (2006). A heat transfer textbook: Published by phlogiston press, Cambridge, Massachusetts. USA. pp714.

Lienhard, J. H. (2013). *A heat transfer textbook*: Courier Corporation.

Liman, K., & Allard, F. (1995). Ventilation-Thermal Mass Subtask-Final Report. *La Rochele, France, University of La Rochelle*.

Liping, W., & Hien, W. N. (2007). The impacts of ventilation strategies and facade on indoor thermal environment for naturally ventilated residential buildings in Singapore. *Building and Environment, 42*(12), 4006-4015.

Livingood, J. N., & Hrycak, P. (1973). Impingement heat transfer from turbulent air jets to flat plates: a literature survey.

Lowe, R., & Johnston, D. (1997). A Field Trial of Mechanical Ventilation with Heat recovery in Local Authority, Low Rise Housing, Final report. *Centre for the Built Environment, Faculty of Health and Environment, Leeds Metropolitan University UK*.

Malik, S. (2011, 22/05/2011). Power problems: Generators add to air and noise pollution. *The Express Tribune*. Retrieved from https://tribune.com.pk/story/173568/power-problems-generators-add-to-air-and-noise-pollution/

Masterson, K. D. (1977). Selective surfaces for solar-thermal conversion. *Journal of Solid State Chemistry, 22*(1), 41-49.

Maurer, J. (1887). *The nocturnal radiation and their size in absolute mass.* Paper presented at the Proceedings of the Royal Prussian Academy of Sciences,German Academy of Sciences, Berlin. .

McIntyre, D. (1980). *Indoor climate*: Elsevier.

McLeod, R. S., Hopfe, C. J., & Kwan, A. (2013). An investigation into future performance and overheating risks in Passivhaus dwellings. *Building and Environment, 70*, 189-209.

Meir, I. A., & Roaf, S. C. (2005). *The future of the vernacular: Towards new methodologies for the understanding and optimization of the performance of vernacular buildings*: Taylor & Francis, London and New York.

Mihalakakou, G. (2003). On the heating potential of a single buried pipe using deterministic and intelligent techniques. *Renewable energy, 28*(6), 917-927.

Mihalakakou, G., Lewis, J., & Santamouris, M. (1996). On the heating potential of buried pipes techniques—application in Ireland. *Energy and buildings, 24*(1), 19-25.

Mihalakakou, G., Santamouris, M., & Asimakopoulos, D. (1994). Modelling the thermal performance of earth-to-air heat exchangers. *Solar energy, 53*(3), 301-305.

Mihalakakou, G., Santamouris, M., Asimakopoulos, D., & Papanikolaou, N. (1994). Impact of ground cover on the efficiencies of earth-to-air heat exchangers. *Applied Energy, 48*(1), 19-32.

Mihalakakou, G., Santamouris, M., Asimakopoulos, D., & Tselepidaki, I. (1995). Parametric prediction of the buried pipes cooling potential for passive cooling applications. *Solar energy, 55*(3), 163-173.

Mijinyawa, Y., Adesogan, S. O., & Ogunkoya, O. G. (2007). A survey of roof failures in Oyo State of Nigeria. *Journal of Building Appraisal, 3*(1), 52-58.

Mike Luciuk. (2009). *NIGHT RADIATIVE COOLING*. Retrieved from http://www.asterism.org/tutorials/tut37%20Radiative%20Cooling.pdf

Mills, A. (1995). Heat and Mass Transfer, Irwin. *Inc., Chicago*.

Mohammed, A. N. (2010). *The Impact of HVAC System Operation and Selection on Energy Efficiency in Office Buildings in Hot Climates.* King Fahd University of Petroleum and Minerals.

Mohammed, I., Nasidi, A., Alkali, A., Garbati, M., Ajayi-Obe, E., Audu, K. A., . . . Abdullahi, S. (2000). A severe epidemic of meningococcal meningitis in Nigeria, 1996. *Transactions of the Royal Society of Tropical Medicine and Hygiene, 94*(3), 265-270.

Moore, P. S. (1992). Meningococcal meningitis in sub-Saharan Africa: a model for the epidemic process. *Clinical infectious diseases, 14*(2), 515-525.

Muncey, R. (1979). *Heat transfer calculations for buildings*: Elsevier Science & Technology.

Nayak, J., & Prajapati, J. (2006). Handbook on energy conscious buildings. *Prepared under the interactive R & D project*(3/4), 03.

Nduka, D., & Ogunsanmi, O. E. (2015). Stakeholders perception of factors determining the adoptability of green building practices in construction projects in Nigeria. *Journal of Environment and Earth Science, 5*(2), 188-196.

Nielsen, P. V. (2007). Analysis and design of room air distribution systems. *HVAC&R Research, 13*(6), 987-997.

Nunes, R. A. X., Costa, V. C., Sade, W., Araújo, F. R., & Silva, G. M. (2018). Selective Surfaces of Black Chromium for Use in Solar Absorbers. *Materials Research, 21*(1).

Nwaigwe, K., Okoronkwo, C., Ogueke, N. V., & Anyanwu, E. (2010). Review of nocturnal cooling systems. *International Journal of Energy for a Clean Environment, 11*(1-4).

Odogwu, G. (2016). Nigerian Institute of Architects going green. *Punch*. Retrieved from https://punchng.com/nigerian-institute-architects-going-green/

Ogbonna, A., & Harris, D. (2008). Thermal comfort in sub-Saharan Africa: field study report in Jos-Nigeria. *Applied Energy, 85*(1), 1-11.

Ogu, V. I. (1996). *Housing and environmental services in Benin City, Nigeria.* University of Cambridge.

Ogu, V. I. (1999). Housing enablement in a developing world city: the case study of Benin City, Nigeria. *Habitat International, 23*(2), 231-248.

Ogu, V. I., & Ogbuozobe, J. E. (2001). Housing policy in Nigeria: towards enablement of private housing development. *Habitat International, 25*(4), 473-492.

Ogueke, N., Onwuachu, C., & Anyanwu, E. (2011). *Experimental Study of Long-Wave Night Sky Radiation in Owerri; Nigeria for Passive Cooling Application.* Paper presented at the World Renewable Energy Congress-Sweden; 8-13 May; 2011; Linköping; Sweden.

Ogunshakin, L., & Olayiwola, L. (1992). The collapse of official housing policy in Nigeria. *Habitat International, 16*(1), 41-53.

Ogunsote, O. O., Prucnal-Ogunsote, B., & Adegbie, M. (2010). *Optimizing Passive Cooling Systems in Residential Buildings: A Case Study of Akure, Nigeria.* Paper presented at the Proceedings of the International Conference on Man, Technological Advancement and Sustainable Environment held at the Federal University of Technology, Akure.

Ohlson, C.-G., & Hardell, L. (2000). Testicular cancer and occupational exposures with a focus on xenoestrogens in polyvinyl chloride plastics. *Chemosphere, 40*(9), 1277-1282.

Ojosu, J. O., Chandra, M., Oguntuase, O., Agarwal, K. N., Komolafe, L. K., & Chandra, I. (1988). Climatological and Solar Data for Nigeria: For the Design of Thermal Comfort in Buildings. *Nigerian Building and Road Research Institute.*

Okafor C. (2016). Energy Efficiency Models Can Save Nigeria 57.5% of Energy. Retrieved from https://www.thisdaylive.com/index.php/2016/10/04/energy-efficiency-models-can-save-nigeria-57-5-of-energy/

Okoronkwo, C., Nwigwe, K., Ogueke, N., Anyanwu, E., Onyejekwe, D., & Ugwuoke, P. (2014). An experimental investigation of the passive cooling of a building using nighttime radiant cooling. *International journal of green energy, 11*(10), 1072-1083.

Olesen, B. W. (2002). Radiant floor heating in theory and practice. *ASHRAE journal, 44*(7), 19.

Olesen, B. W., & Parsons, K. (2002). Introduction to thermal comfort standards and to the proposed new version of EN ISO 7730. *Energy and buildings, 34*(6), 537-548.

Olgyay, V. (2015). *Design with climate: bioclimatic approach to architectural regionalism*: Princeton University Press.

Organization, W. H. (2018). Household air pollution and health. Retrieved from http://www.who.int/news-room/fact-sheets/detail/household-air-pollution-and-health

Orme, M., Liddament, M. W., & Wilson, A. (1994). *An analysis and data summary of the AIVC's numerical database*: Oscar Faber.

Ouedraogo, B., Levermore, G., & Parkinson, J. (2012). Future energy demand for public buildings in the context of climate change for Burkina Faso. *Building and Environment, 49*, 270-282.

Ozgener, O., Ozgener, L., & Tester, J. W. (2013). A practical approach to predict soil temperature variations for geothermal (ground) heat exchangers applications. *International journal of heat and mass transfer, 62*, 473-480.

Parent, D., Stricker, S., & Fugler, D. (1996). *Ventilation in houses with distributed heating systems.* Paper presented at the DOCUMENT-AIR INFILTRATION CENTRE AIC PROC.

Parker, D. S. (2005). Theoretical evaluation of the NightCool nocturnal radiation cooling concept. *Submitted to: US Department of Energy. FSEC-CR-1502-05*.

Parker, D. S., Sherwin, J. R., Hermelink, A. H., & Center, F. S. E. (2008). NightCool: A Nocturnal Radiation Cooling Concept. *2008 ACEEE Summer Study on Energy Efficiency in Buildings*, 209-222.

Peel, M. C., Finlayson, B. L., & McMahon, T. A. (2007). Updated world map of the Köppen-Geiger climate classification. *Hydrology and earth system sciences discussions, 4*(2), 439-473.

Pfafferott, J. (2003). Evaluation of earth-to-air heat exchangers with a standardised method to calculate energy efficiency. *Energy and buildings, 35*(10), 971-983.

Pfafferott, J. (2004). Enhancing the design and operation of passive cooling concepts. *Fraunhofer IRB-Verlag, Stuttgart*.

Popiel, C. O., Wojtkowiak, J., & Biernacka, B. (2001). Measurements of temperature distribution in ground. *Experimental Thermal and Fluid Science, 25*(5), 301-309.

Roaf, S., & Hancock, M. (1992). Energy efficient building.

Robert, B., Olesen, B., & Kim, K. (2010). History of radiant heating and cooling systems, Part 2. *ASHRAE J, 52*, 40-47.

Rosenlund, H. (2000). Climatic design of buildings using passive techniques. *Building Issues, Vol 10*.

Saitoh, T., & Ono, T. (1984). Simulative analysis for long-term underground cool storage incorporating sky radiation cooling. *Journal of solar energy engineering, 106*(4), 493-496.

Santamouris, M., & Asimakopoulos, D. (1996). *Passive cooling of buildings*: Earthscan.

Santamouris, M., & Kolokotsa, D. (2013). Passive cooling dissipation techniques for buildings and other structures: The state of the art. *Energy and buildings, 57*, 74-94.

Santamouris, M., Mihalakakou, G., & Asimakopoulos, D. (1997). On the coupling of thermostatically controlled buildings with ground and night ventilation passive dissipation techniques. *Solar energy, 60*(3-4), 191-197.

Sanusi, A. N. Z. (2012). Low energy ground cooling system for buildings in hot and humid Malaysia.

Sassi, P. (2006). *Strategies for sustainable architecture*: Taylor & Francis.

Sawa, B., & Buhari, B. (2011). Temperature variability and outbreak of meningitis and measles in Zaria, northern Nigeria. *Research Journal of Applied Sciences, Engineering and Technology, 3*(5), 399-402.

Sehli, A., Hasni, A., & Tamali, M. (2012). The potential of earth-air heat exchangers for low energy cooling of buildings in South Algeria. *Energy Procedia, 18*, 496-506.

Sherman, M. H., & Chan, W. R. (2006). Building air tightness: research and practice. *Building Ventilation: the state of the Art*, 137-162.

Sima, J., Sikula, O., Kosutova, K., & Plasek, J. (2014). Theoretical evaluation of night sky cooling in the Czech Republic. *Energy Procedia, 48*, 645-653.

Simonetti, M., Fracastoro, G., & Perino, M. (2008). CFD transient analysis of night cooling strategy applied to school building. *Department of Energetic, Turin Politechnic, Italy*.

Singh, M. K., Mahapatra, S., & Atreya, S. (2009). Bioclimatism and vernacular architecture of north-east India. *Building and Environment, 44*(5), 878-888.

Sodha, M. S., Bansal, N. K., Bansal, P. K., Kumar, A., & Malik, M. A. S. (1986). *Solar passive building*: Pergamon Press,Elmsford, NY; None.

Sreshthaputra, A. (2003). *Building design and operation for improving thermal comfort in naturally ventilated buildings in a hot-humid climate.* Texas A&M University.

Stamatiou, G. (1991). An investigation into the insitu" U" values of wall construction.

Standard, A. (2004). Standard 55-2004. *Thermal environmental conditions for human occupancy,* 9-11.

Standard, I. (1994). 7730. *Moderate thermal environments–Determination of the PMV and PPD indices and specification of the conditions for thermal comfort*.

Stephenson, D. G., & Mitalas, G. (1967). Cooling load calculations by thermal response factor method. *ASHRAE Trans.;(United States), 73*.

Swami, M., Fairey, P., & Kerestecioglu, A. (1990). *An analytical assessment of the desiccant enhanced radiative cooling concept'.* Paper presented at the Proceedings of the 12th Annual ASME Solar Energy Conference, Miami, Florida, USA.

Swinbank, W. C. (1963). Long-wave radiation from clear skies. *Quarterly Journal of the Royal Meteorological Society, 89*(381), 339-348. doi:10.1002/qj.49708938105

Swinbank, W. C. (1963). Long-wave radiation from clear skies. *Quarterly Journal of the Royal Meteorological Society, 89*(381), 339-348.

Szokolay, S. V. (2014). *Introduction to architectural science: the basis of sustainable design*: Routledge.

Taylor, B. J., Webster, R., & Imbabi, M. S. (1998). The building envelope as an air filter. *Building and Environment, 34*(3), 353-361.

Taylor, T., Counsell, J., & Gill, S. (2013). Energy efficiency is more than skin deep: Improving construction quality control in new-build housing using thermography. *Energy and buildings, 66*, 222-231.

Tickner, J. A., Schettler, T., Guidotti, T., McCally, M., & Rossi, M. (2001). Health risks posed by use of Di-2-ethylhexyl phthalate (DEHP) in PVC medical devices: A critical review. *American journal of industrial medicine, 39*(1), 100-111.

Tzaferis, A., Liparakis, D., Santamouris, M., & Argiriou, A. (1992). Analysis of the accuracy and sensitivity of eight models to predict the performance of earth-to-air heat exchangers. *Energy and buildings, 18*(1), 35-43.

UnitedNations. (2004). Full political map of Nigeria. *Map No 4228.* Retrieved from http://www.vidiani.com/maps/maps_of_africa/maps_of_nigeria/full_political_map_of_nigeria.jpg

Van der Maas, J., Flourentzou, F., Rodriguez, J., & Jaboyedoff, P. (1994). *Passive cooling by night ventilation.* Paper presented at the European Conference on Energy Performance and Indoor Climate in Buildings.

Vanessa, S. J., Adams. (2014). Small scale seed drying methods. *Royal Botanical Gardens (KEW), 2018*.

Vanguard. (2009, 26/01/2009). Nigeria: 60 Million Citizens Now Own Power Generators. *The Vanguard*.

Vasili Gordeyev, Sean Hamill, Susannah Hogg, Mark Gilroy, Ruairidh Deans, & Dale Findlay. (2012). *Low Energy Building Design*. Retrieved from http://www.esru.strath.ac.uk/EnvEng/Web_sites/11-12/GROUP2/MyWebSpace/index.html

Versarien Technologies. (2015). Passive Heat Sinks. Retrieved from http://www.versarien-technologies.co.uk/passive-heat-sinks

Walsh, R., Kenny, P., & Brophy, V. (2006). Thermal mass & sustainable building-Improving energy performance and occupant comfort-A practical guide for designers–. *Irish concrete federation, UCD Energy Research Group, University College Dublin*.

Wang, Y., Liu, Y., Wang, D., & Liu, J. (2014). Effect of the night ventilation rate on the indoor environment and air-conditioning load while considering wall inner surface moisture transfer. *Energy and buildings, 80*, 366-374.

Watson, D., & Kenneth, L. (1983). Climatic Building Design: McGraw-Hill Book Company, New York.

WeatherSpark. (2016). Average Weather in Okigwe Nigeria. Retrieved from https://weatherspark.com/y/55000/Average-Weather-in-Okigwe-Nigeria

Whillier, A. (1967). Design factors influencing solar collector performance. *Low Temperature Engineering Application of Solar Energy*, 27-40.

WHO. (1983). Indoor air pollutants: exposure and health effects. *EURO reports and studies, 78*, 1-42.

WHO. (2016a). WHO facts sheet.

WHO. (2016b). *WHO Global Urban Ambient Air Pollution Database (update 2016)*.

Woodson, T. (2012). Earth-air heat exchangers for passive air conditioning: case study Burkina Faso. *Journal of Construction in Developing Countries, 17*(1).

WorldMap. (2016). Political Map Of Africa. Retrieved from http://www.worldatlas.com/webimage/countrys/afpoliticallg.htm

WWCI. (2016). Climate and Average weather in Nigeria. Retrieved from https://weather-and-climate.com/average-monthly-Rainfall-Temperature-Sunshine-in-Nigeria

Yakubu, O. H. (2017). Particle (Soot) Pollution in Port Harcourt Rivers State, Nigeria—Double Air Pollution Burden? Understanding and Tackling Potential Environmental Public Health Impacts. *Environments, 5*(1), 2.

Yannas, S., & Maldonado, E. (1995). PASCOOL handbook-Designing for summer comfort. *Architectural Association Graduate School, Londres*.

Zhai, X., Wang, R., Wu, J., Dai, Y., & Ma, Q. (2008). Design and performance of a solar-powered air-conditioning system in a green building. *Applied Energy, 85*(5), 297-311.

Zhang, C., Heiselberg, P. K., Pomianowski, M., Yu, T., & Jensen, R. L. (2015). Experimental study of diffuse ceiling ventilation coupled with a thermally activated building construction in an office room. *Energy and buildings, 105*, 60-70.

Appendix A: Climatic Data of study area

Macro weather data was obtained from the Umudike meteorological Centre. Data on soil temperature and sky temperature were obtained from site. Other measurements were carried out on site to verify the temperature and humidity of the micro climate of Ahaba Imenyi.

Table A. 1 Sky temperature profile for December

Day	6am (°C)	12pm	Night 11:30pm
21/12/2015	13.5	21.2	12.8
22/12/2015	3.4	19.2	1.5
23/12/2015	1.4	20.3	1.3
24/12/2015	2	18.7	3.2
25/12/2015	4	19.8	3.8
26/12/2015	4.1	20	3.4
27/12/2015	3.1	19.6	1.8

Table A. 2 Sky Temperature Profile for January

Day	6am (°C)	Afternoon 12pm	Night 11:30pm
01/01/2016	-7.8	18.4	-9
02/01/2016	-5.5	14.3	-7.2
03/01/2016	-6.1	15.8	-6
04/01/2016	-4.2	19.8	-5.5
05/01/2016	-7.1	21.1	-4.8
06/01/2016	-3.8	13.8	-5.7
07/01/2016	-4	16.2	-6.2

Table A. 3 Sky Temperature Profile for February

Day	6am (°C)	Afternoon 12pm	Night 11:30pm
04/02/2016	11.5	19.8	12.1
05/02/2016	12.6	20.5	10.7
06/02/2016	13.2	21.3	11.3
07/02/2016	11.1	20.8	10.4
08/02/2016	10.8	22.1	9.7
09/02/2016	9.8	25.8	8.2
10/02/2016	11.4	20.1	10.6

Table A. 4 Sky Temperature Profile for June

Day	6am (°C)	Afternoon 12pm	Night 11:30pm
09/06/2016	23.2	30.5	19
10/06/2016	18.6	19.8	19.6
11/06/2016	12.6	30.5	23.5
12/06/2016	16.5	20.5	21.8
13/06/2016	21.2	21.3	16.6
14/06/2016	14.4	24.8	22.5
15/06/2016	19.5	20.8	21.9

Table A. 5 Average Monthly ground temperature profiles at different depths

Month	1m (°C)	2m (°C)	3m (°C)	4m (°C)	Ambient (°C)
Jan	24.7	26	26.9	27.5	30.4
Feb	24.4	25.5	26.4	27	31.4
Mar	25	25.5	26.1	26.6	30.7
Apr	26.3	26	26.2	26.5	30.1
May	27.8	26.9	26.6	26.7	29.3
June	29.4	28	27.3	27	28
July	30.3	29	28.1	27.5	26.7
Aug	30.5	29.5	28.6	28	26.7
Sept	29.9	29.5	28.9	28.4	27.3
Oct	28.7	29	28.8	28.5	28.2
Nov	27.1	28	28.3	28.3	29.2
Dec	25.6	26.9	27.7	28	29.8

07030876788

UMUDIKE MONTHLY CLIMATIC DATA LATITUDE 05°29'N, LONGITUDE 07°33'E, ALTITUDE 122M ABOVE SEA LEVEL.
MAXIMUM AND MINIMUM TEMPERATURES IN DEGREE CENTIGRADE (°C)

MONTH	1990		1991		1992		1993		1994		1995		1996
JAN	Days	Rainfall	Days	Rainfall	Days	Rainfall	Days	Rainfall	Days	Rainfall	Days	Rainfall	Days
FEB	1	2	1	4.6	1	0	0	78.2	1	48.6	1	0.6	1
MAR	2	34.7	5	0	0	37.9	4	0	0	3.3	2	53.6	6
APR	2	67.2	6	110	7	94.7	9	136.8	8	145.5	9	97.7	6
MAY	10	187.2	12	145.8	8	183.3	10	161.7	12	140.8	10	336.7	15
JUN	15	304.4	21	207.4	13	102	17	296.2	14	404.7	15	275	12
JUL	11	208.7	18	229.6	13	456.6	22	145.6	14	180.4	16	350.8	19
AUG	25	342.2	21	408	25	224.7	23	210.4	24	242	22	377.5	22
SEP	19	318.4	24	318.9	21	275.4	20	345.4	26	481.4	24	451.4	26
OCT	21	271.6	18	505.5	24	260.2	21	347.7	24	454.9	17	465.7	18
NOV	18	195.8	15	206	18	298	13	337.1	19	485.9	20	342.2	17
DEC	11	0	0	55	3	37.4	3	82.8	6	16	4	0	0
TOTAL	4	26.6	2	0	0	15.7	2	0	0	21.8	1	0.7	1
NB.* = Means no data.	139	1958.8	143	2190.8	133	1980.9	144	2141.9	148	2626.3	141	2751.9	143

	1997		1998		1999		2000		2001		2002		2003		2004		2005		2006		2007
Rainfall	Days	Rainfall	Days	Rainfall	Days	Rainfall	Days	Rainfall	Days	Rainfall	Days	Rainfall	Days	Rainfall	Days	Rainfall	Days	Rainfall	Days	Rainfall	Days
8.5	2	0.4	1	45.6	4	14.8	2	0	0	3.1	1	0	0	0.2	1	17.3	2	76.6	3	0	0
0	0	1.8	1	98.1	4	0.9	1	7.8	1	107.1	3	37.9	2	11.9	2	126.7	5	81.9	3	62.9	2
65.7	6	35.6	5	203.4	10	13.6	5	175.9	8	68.5	7	119.5	5	22.4	4	64	6	131.9	6	35.5	5
198.1	11	114.2	9	192	13	164.5	13	224.1	13	259	11	159.8	11	134.5	9	141.3	11	136	9	78.4	9
320.9	14	311.3	18	319.9	14	153.6	14	194.3	17	436.3	16	231.4	14	217.6	11	222.4	17	202.8	15	444.9	17
349.2	22	402.6	21	296.6	19	265.5	20	522.7	16	240.1	16	282.4	18	279.4	18	264.4	18	237.3	15	354	18
279.5	17	243.2	21	284.4	23	265.2	21	273.5	17	359.8	23	447.5	26	309.5	18	277	24	303.4	16	187.6	18
191.8	18	310.7	20	382.2	18	216.9	16	179	24	333.7	21	372.6	19	304.3	21	225	21	133.7	15	464.8	26
239.1	19	287.6	23	395.3	24	277.5	23	317.2	23	238.5	18	340.8	20	324.9	19	336.7	17	483.1	20	319.1	18
255.5	19	195.8	15	433.7	26	228.4	19	277.1	16	247.5	18	180.2	13	249.1	16	323	18	237.4	19	339.6	19
108.7	8	70.1	3	50.1	4	75.9	3	18.6	2	57.8	3	69.2	5	52.5	4	45.4	6	14.2	1	112.1	8
22	3	2.6	1	0	0	3.8	2	0	0	0	0	0	0	5.1	1	8.6	2	0	0	25	2
2039	139	1975.9	138	2701.3	159	1680.6	139	2190.2	137	2351.4	137	2241.3	133	1911.4	124	2051.8	147	2038.3	122	2423.9	142

Figure A. 1 Climatic Data of Study area: Ambient Temperature

2002		2003		2004		2005		2006		2007		2008		2009		2010		2011		2012	
Rainfall	Days	Rainfall	Days	Rainfall	Days	Rainfall	Days	Rainfall	Days	Rainfall	Days	Rainfall	Days	Rainfall	Days	Rainfall	Days	Rainfall	Days	Rainfall	Days
0	0	13.4	2	62.8	2	0	0	0	0	0	0	13.4	2	62.8	2	0	0	0	0	0	0
62.9	2	0	0	62.8	4	78.2	5	60.8	4	62.9	2	0	0	62.8	4	78.2	5	60.8	4	88.2	7
35.5	5	168.4	8	47.8	4	34.7	4	111.4	8	35.5	5	168.4	8	47.8	4	34.7	4	111.4	8	57	3
78.4	9	219.8	16	100.5	12	126	10	105.8	8	78.4	9	219.8	16	100.5	12	126	10	105.8	8	142	17
444.9	17	373.5	18	416.2	15	213.5	13	347.7	15	444.9	17	373.5	18	416.2	15	213.5	13	347.7	15	233.7	16
354	18	352.3	19	236	14	459	18	239.5	13	354	18	352.3	19	236	14	459	18	239.5	13	213	14
187.6	18	310.2	20	306.3	18	276.9	16	236.5	22	187.6	18	310.2	20	306.3	18	276.9	16	236.5	22	362	24
464.8	26	327.4	22	287.4	19	420.7	19	345.1	24	464.8	26	327.4	22	287.4	19	420.7	19	345.1	24	161.8	19
319.9	18	404	20	205.5	18	309.3	19	424.7	23	319.9	18	404	20	205.5	18	309.3	19	424.7	23	349	25
335.6	19	211	13	311.1	14	349.2	21	242.8	11	335.6	19	211	13	311.1	14	349.2	21	242.8	11	244.6	16
112.1	8	6.7	2	23.7	7	78.2	6	12	3	112.1	8	6.7	2	23.7	7	78.2	6	12	3	58.5	6
25	2	8.9	1	0	0	4.6	1	9.6	1	25	2	8.9	1	0	0	4.6	1	9.6	1	0	0
2420.7	**142**	2395.6	141	2060.1	127	2350.3	132	2135.9	132	**2420.7**	**142**	2395.6	141	2060.1	127	2350.3	132	2135.9	132	1909.8	147

1990		1991		1992		1993		1994		1995		1996	
MAX.(°	MIN.(°C)	MAX.(°C	MIN.(°C)	MAX.(°C	MIN.(°C)	MAX.(°C	MIN.(°C)	MAX.(°C	MIN.(°C)	MAX.(°C)	MIN.(°C)	MAX.(°C	MIN.(°C)
33	23	32	20	32	19	32	20	32	22	32	19	33	23
34	22	33	24	35	22	34	22	33	23	34	22	34	24
36	24	33	24	33	24	33	23	33	23	33	23	32	24
34	24	31	23	33	24	33	23	32	23	33	24	32	23
31	23	31	24	33	23	32	23	31	23 *		*	32	23
30	22	30	23	30	23	30	23	30	23	31 *		30	22
28	22	29	23	28	22	29	22	28	22	30	23	29	21
28	22	28	22	27	22	29	23	29	23	29	23	28	22
29	22	28	22	30	22	30	23	29	23	28	23	28	21
30	22	29	22	30	22	31	22	30	22	30	22	30	21
30	23	31	23	31	21	31	23	31	22	32	22	31	20
31	23	31	21	32	20	31	20	32	18	32	22	32	22
31.2	***22.7***	***30.5***	***22.6***	***31.2***	***22***	***31.3***	***22.3***	***30.8***	***22.3***	***30.3***	***22.5***	***30.9***	***22.2***

Figure A. 2 Climatic Data of Study area: Rainfall and Ambient Temperature

1997		1998		1999		2000		2001		2002		2003		2004		2005		2006	
MAX.(°I	MIN.(°C)	MAX.(°C	MIN.(°C)	MAX.(°C	MIN.(°C)	MAX.(°C	MIN.(°C)	MAX.(°C	MIN.(°C)	MAX.(°C)	MIN.(°C)	MAX.(°C	MIN.(°C)	MAX.(°C	MIN.(°C)	MAX.(°C	MIN.(°C)	MAX.(	MIN.(°C)
33	22	32	21	32	23	32	23	33	21	32	21	33	22	33	21	33	19	33	24
35	20	36	24	32	24	35	22	35	23	34	22	33	24	35	23	35	23	33	24
34	23	35	24	32	23	35	23	34	24	33	24	34	24	36	24	34	23	34	24
32	23	34	25	32	23	33	24	33	24	32	24	34	24	32	24	34	24	33	24
31	23	33	24	32	23	32	24	32	24	32	24	32	23	32	22	32	23	31	23
30	23	31	23	31	23	31	23	31	23	30	23	30	23	30	23	31	23	31	22
29	23	30	23	30	22	30	23	29	23	30	23	30	23	29	22	29	23	30	23
29	23	29	23	30	22	30	24	29	23	28	23	29	23	29	22	30	22	29	22
30	23	29	23	29	22	30	24	30	23	29	22	30	22	30	22	31	23	29	22
31	23	30	23	30	22	31	24	31	23	30	22	31	23	31	23	31	22	31	22
31	22	32	23	31	23	33	25	32	23	32	23	32	23	33	22	33	23	31	23
31	22	31	24	32	22	32	21	32	22	33	21	32	20	33	21	32	22	32	20
31.3	**22.5**	**31.8**	**23.3**	**31.1**	**22.7**	**32**	**23.3**	**31.8**	**23**	**31.3**	**22.7**	**31.7**	**22.8**	**31.9**	**22.4**	**32.1**	**22.5**	**31.4**	**22.8**

2007		2008		2009		2010		2011	
MAX.(°C	MIN.(°C	MAX.(°C	MIN.(°C	MAX.(°C)	MIN.(°C)	MAX.(°C	MIN.(°C)	MAX.(°C	MIN.(°C)
34	21	31	20	33	23	35	23	33	20
35	24	35	21	34	24	35	24	33	23
35	24	34	23	34	24	34	24	34	24
32	23	32	23	33	23	34	24	33	24
32	22	32	23	33	23	32	24	32	23
30	22	30	23	31	23	30	24	30	23
30	22	29	22	30	22	30	23	30	22
29	22	29	22	29	23	30	23	29	23
30	22	30	23	30	22	30	23	30	23
30	22	31	23	31	23	32	23	30	23
31	23	32	24	32	22	31	23	31	23
32	22	33	22	34	23	33	22	33	21
31.7	**22.4**	**31.5**	**22.4**	32	22.9	32.1	23.3	31.5	22.6

Figure A. 3 Climatic Data of Study area: Maximum and Minimum monthly Ambient Temperature

UMUDIKE MONTHLY CLIMATIC DATA LATITUDE 05°29'N, LONGITUDE 07°33'E, ALTITUDE 122M ABOVE SEA LEVEL.
RELATIVE HUMIDITY IN PERCENTAGE (%).

	1992		1993		1994		1995		1996		1997		1998		1999	
MONTH	1500HRS	0900HR	1500HR	0900HR	1500HRS	0900HR	1500HR	0900HR	1500HR	0900HRS	1500HR	0900HR	1500HR	0900HR	1500HR	0900HRS
JAN	37	47	37	58	49	52	39	80	50 *		60	59	40 *	*	*	
FEB	34	68	46	74	46	71	44	76	54 *		63	61	43 *	*	*	
MAR	58	75	59	79	61	82	71	78	64 *		64	63	46 *	*	*	
APR	70	81	66	82	66	80	69	82	65 *		74	71	61 *	*	*	
MAY	70	83	74	84	72 *	*		81	70 *		78	82	67 *	*	*	
JUN	79	88	79	84	75 *	*		83	76 *		81	86	71 *	*	*	
JUL	83	89	82	89	81	87	80	87	78 *		79	86	79 *	*	*	
AUG	81	88	83	88	80	86	81	90	81 *		83	90	77 *	*	*	
SEP	78	86	78	88	83 *		76	85	79 *		80 *	*	*	*	*	82
OCT	75	84	74	83	85	82	77	84	73 *		77 *	*	*	*		81
NOV	63	81	70	77	58	78	57	77	52 *		78 *	*	*	*		63
DEC	48	67	53	43	38	80	62 *	*			68 *	*	*	*		
MEAN	***65***	***78***	***67***	***77***	***66***	***80***	***72***	***72***	***72***		***74***	***74***	***74***	***74***		

NB. = Means no data.*

2000			2001		2002		2003		2004		2005		2006
1500HR		0900HR	1500HR	0900HR	1500HR	0900HRS	1500HR	0900HR	1500HR	0900HR	1500HRS	0900HR	1500HRS
*		61	34	42	30	66	46	63	43	53	39	81	59
*		53	32	64	43	73	46	65	40	79	56	80	61
*		76	57	83	66	82	53	66	44	80	65	80	60
*		82	64	92	68	75	64	78	67	77	64	79	62
*		82	69	83	74	82	73	79	66	81	71	83	71
*		84	76	86	76	85	78	83	76	90	70	84	72
*		86	76	96	80	84	75	85	78	88	80	87	78
*		88	82	88	78	86	79	87	76	85	77	84	77
*		85	82	86	76	85	77	85	72	86	77	86	80
	74	84	73	86	78	78	73	82	74	84	71	84	72
	66	79	67	79	63	80	67	81	67	82	60	82	58
	46	75	52	60	40	73	57	80	57	79	56	70	40
		78	***64***	***79***	***64***	***79***	***66***	***78***	***63***	***80***	***66***	***82***	***66***

Figure A. 4 Climatic Data of Study area: Relative Humidity

Appendix B: Experimental Results from application of Passive cooling system

Table B. 1 Heat energy displacement in the roof attic as a result of insulation

Time	T_{attic}_uninsl(°C)	T_{attic}_insl(°C)	$Roof_{Uninsl}$ (kJs)	$Roof_{Insl}$ (kJs)
09:30:00	30.2	26.9	73.1	26.1
10:00:00	33.9	27.9	126.1	41.6
10:30:00	37.8	30.2	181.2	73.7
11:00:00	40.5	32.2	218.9	102.0
11:30:00	43.2	33.9	257.5	125.7
12:00:00	45.7	35.7	292.6	150.5
12:30:00	47.8	37.0	322.0	169.9
13:00:00	49.6	38.5	347.9	190.0
13:30:00	50.7	39.9	362.3	211.0
14:00:00	50.7	39.9	362.5	211.0
14:30:00	50.6	41.0	361.3	225.5
15:00:00	48.3	40.4	329.3	218.2
15:30:00	47.8	39.9	321.7	211.0
16:00:00	45.9	39.9	295.5	211.0
16:30:00	44.1	39.4	270.2	203.9
17:00:00	41.2	38.0	228.2	183.2
17:30:00	37.7	37.0	179.1	169.9
18:00:00	34.3	35.2	130.7	144.2
18:30:00	31.1	33.9	86.4	125.7
19:00:00	29.0	32.6	55.9	107.8

Table B. 2 Heat energy displacement in bedrooms due to roof insulation

Time	T_{in}_uninsl(°C)	T*in*_insl(°C)	kJs_uninsl	kJs_insl	$T_{thermostat}$	T_{lower}	T_{upper}
09:30:00	23.1	22.9	-27.3	-29.0	25	23	29
10:00:00	23.9	23.4	-15.3	-22.6	25	23	29
10:30:00	24.8	23.9	-3.1	-16.2	25	23	29
11:00:00	26.0	24.5	14.0	-7.2	25	23	29
11:30:00	27.5	25.3	35.0	4.0	25	23	29
12:00:00	29.1	26.2	58.4	17.1	25	23	29
12:30:00	30.8	27.1	81.5	29.7	25	23	29
13:00:00	32.3	27.9	103.1	41.5	25	23	29
13:30:00	34.0	28.8	126.6	54.2	25	23	29
14:00:00	35.6	29.7	149.6	66.8	25	23	29
14:30:00	37.2	30.6	172.6	79.2	25	23	29
15:00:00	38.4	31.2	188.6	88.1	25	23	29
15:30:00	39.3	31.8	202.4	96.1	25	23	29
16:00:00	39.9	32.1	210.2	100.9	25	23	29
16:30:00	40.3	32.4	216.8	105.1	25	23	29
17:00:00	40.4	32.6	218.0	106.8	25	23	29
17:30:00	39.8	32.3	209.7	103.7	25	23	29
18:00:00	39.1	32.0	199.4	99.4	25	23	29
18:30:00	37.8	31.4	180.5	90.7	25	23	29
19:00:00	35.8	30.5	152.3	77.5	25	23	29

Table B. 3 Energy usage in a bedroom due to modification of building Fabric

Time	T_{in}_Case(°C)	T_{in}_FF(°C)	Case (kJs)	FF (kJs)	$T_{thermostat}$	T_$_{lower}$	T_$_{upper}$
05:00:00	25.4	23.7	14.6	-41.1	25	23	29
05:30:00	25.4	23.7	14.1	-44.0	25	23	29
06:00:00	25.4	23.6	13.2	-47.0	25	23	29
06:30:00	25.2	23.5	6.6	-49.0	25	23	29
07:00:00	25.1	23.5	4.7	-50.1	25	23	29
07:30:00	25.2	23.5	5.4	-50.4	25	23	29
08:00:00	25.5	23.5	17.7	-48.8	25	23	29
08:30:00	26.2	23.7	37.9	-42.8	25	23	29
09:00:00	26.5	23.9	49.8	-34.6	25	23	29
09:30:00	26.9	24.2	62.8	-25.9	25	23	29
10:00:00	27.5	24.5	82.9	-16.8	25	23	29
10:30:00	28.3	24.9	107.1	-2.0	25	23	29
11:00:00	29.2	25.4	137.4	12.8	25	23	29
11:30:00	29.9	25.9	159.8	28.9	25	23	29
12:00:00	30.6	26.2	183.4	37.7	25	23	29
12:30:00	31.0	26.6	194.8	53.2	25	23	29
13:00:00	31.7	27.1	219.4	70.2	25	23	29
13:30:00	32.4	27.6	242.9	84.7	25	23	29
14:00:00	33.0	28.1	260.1	101.7	25	23	29
14:30:00	33.3	28.6	272.1	118.1	25	23	29
15:00:00	33.8	29.0	288.2	132.3	25	23	29
15:30:00	34.0	29.5	293.5	146.9	25	23	29
16:00:00	34.1	29.9	298.7	159.4	25	23	29
16:30:00	33.9	30.2	292.1	170.8	25	23	29
17:00:00	34.0	30.5	294.6	181.3	25	23	29
17:30:00	33.9	30.7	289.5	187.5	25	23	29

18:00:00	33.4	30.8	273.8	188.3	25	23	29
18:30:00	32.9	30.7	258.7	185.2	25	23	29
19:00:00	32.6	30.5	247.4	180.6	25	23	29
19:30:00	32.3	30.4	239.4	175.4	25	23	29
20:00:00	32.1	30.2	230.9	169.7	25	23	29
20:30:00	31.8	30.0	221.0	163.1	25	23	29
21:00:00	31.4	29.8	210.5	156.6	25	23	29
21:30:00	31.2	29.6	202.6	151.3	25	23	29
22:00:00	31.0	29.5	197.8	145.5	25	23	29
22:30:00	30.9	29.3	192.1	140.6	25	23	29
23:00:00	30.6	29.1	183.9	135.1	25	23	29
23:30:00	30.3	29.0	172.9	129.4	25	23	29
00:00:00	30.0	28.8	163.6	123.9	25	23	29
00:30:00	29.8	28.6	155.9	119.2	25	23	29
01:00:00	29.6	28.5	150.9	114.1	25	23	29
01:30:00	29.5	28.3	146.3	109.3	25	23	29
02:00:00	29.3	28.2	141.7	105.5	25	23	29
02:30:00	29.2	28.1	138.3	101.9	25	23	29
03:00:00	29.1	28.0	133.7	98.2	25	23	29
03:30:00	28.7	27.9	121.3	94.3	25	23	29
04:00:00	28.4	27.8	111.5	90.7	25	23	29
04:30:00	28.1	27.7	101.3	87.0	25	23	29
05:00:00	28.3	27.6	108.6	83.7	25	23	29
05:30:00	28.5	27.5	113.6	80.4	25	23	29
06:00:00	28.3	27.4	109.0	77.6	25	23	29
06:30:00	28.2	27.3	104.0	75.3	25	23	29
07:00:00	28.1	27.2	101.2	73.4	25	23	29

Table B. 4 Energy Use in spaces due to application of PPGPV Scenarios for shaded and unshaded air entry into cooling system

Time	T_{in}_CC$_1$(°C)	T_{in}_Sdaded(°C)	T_{in}_unshaded(°C)	kJs CC$_1$	kJs shaded	kJs unshaded	$T_{thermostat}$	$T_{\_lower}$	$T_{\_upper}$
00:00	26.2	26.1	27.1	37.6	36.0	67.7	25	23	29
00:30	26.0	26.0	26.9	32.7	34.0	61.6	25	23	29
01:00	25.9	26.0	26.7	29.4	33.4	55.9	25	23	29
01:30	25.7	26.0	26.5	21.3	32.6	50.3	25	23	29
02:00	25.6	26.0	26.4	19.6	32.2	44.4	25	23	29
02:30	25.4	26.0	26.2	13.1	31.1	38.8	25	23	29
03:00	25.1	25.9	26.0	3.3	29.8	33.4	25	23	29
03:30	25.0	25.9	25.8	1.0	28.6	27.8	25	23	29
04:00	25.0	25.8	25.7	-1.6	27.3	22.4	25	23	29
04:30	24.9	25.8	25.5	-4.9	26.2	17.7	25	23	29
05:00	24.6	25.8	25.4	-13.1	24.7	12.8	25	23	29
05:30	24.5	25.7	25.2	-16.3	23.3	7.9	25	23	29
06:00	25.0	25.9	25.1	0.0	27.8	3.0	25	23	29
06:30	25.4	26.0	25.0	13.1	32.5	-1.6	25	23	29
07:00	25.6	26.1	24.9	18.0	36.4	-4.5	25	23	29
07:30	25.7	26.1	24.8	21.3	36.2	-5.6	25	23	29
08:00	25.8	26.1	24.8	27.1	36.1	-5.2	25	23	29
08:30	26.5	26.1	25.0	49.0	36.7	-0.9	25	23	29
09:00	27.8	26.1	25.3	90.8	37.5	9.6	25	23	29
09:30	28.5	26.2	25.7	112.9	38.6	24.2	25	23	29
10:00	29.2	26.4	26.3	137.5	44.1	42.0	25	23	29
10:30	30.0	26.5	26.9	162.3	49.0	62.2	25	23	29
11:00	30.9	26.8	27.7	193.3	59.6	89.3	25	23	29
11:30	31.5	26.9	28.3	214.1	63.7	109.0	25	23	29
12:00	32.2	27.1	29.0	234.0	67.2	129.5	25	23	29
12:30	32.9	27.1	29.6	257.4	70.1	149.1	25	23	29
13:00	33.2	27.2	30.1	266.9	71.5	165.3	25	23	29

13:30	33.9	27.3	30.7	290.1	74.1	187.4	25	23	29
14:00	34.5	27.3	31.8	311.5	76.1	223.3	25	23	29
14:30	35.0	27.4	32.7	327.0	78.3	251.4	25	23	29
15:00	35.3	27.4	33.3	336.6	79.4	270.1	25	23	29
15:30	35.5	27.5	34.0	341.8	80.8	294.8	25	23	29
16:00	35.6	27.5	34.6	346.1	83.0	312.4	25	23	29
16:30	35.5	27.6	35.0	344.7	84.3	327.9	25	23	29
17:00	35.5	27.6	35.4	343.6	85.5	339.1	25	23	29
17:30	35.3	27.7	35.5	337.7	86.9	343.5	25	23	29
18:00	35.0	27.7	35.3	326.6	88.4	338.3	25	23	29
18:30	34.6	27.7	35.0	312.9	89.0	326.7	25	23	29
19:00	34.0	27.7	34.6	292.9	89.0	313.1	25	23	29
19:30	33.4	27.7	34.0	276.0	87.8	292.8	25	23	29
20:00	33.1	27.7	33.3	265.3	88.0	272.8	25	23	29
20:30	32.9	27.9	32.9	258.4	94.9	258.5	25	23	29
21:00	32.5	28.1	32.4	244.7	100.7	243.0	25	23	29
21:30	32.1	28.0	32.0	231.5	97.5	227.3	25	23	29
22:00	31.8	27.8	31.4	221.8	92.9	210.5	25	23	29
22:30	31.4	27.7	31.0	209.7	88.5	195.7	25	23	29
23:00	31.2	27.6	30.6	201.5	83.4	182.2	25	23	29
23:30	31.0	27.4	30.2	196.2	77.8	169.7	25	23	29

Table B. 5 Energy Use in spaces due to application of PPGPV and CNS at night compared to the case building

Time	T_{indoor} _CC_1 (°C)	T_{ind}_CNS (°C)	T_{ind} _PPGPV $_{(night)}$ (°C)	kJs CC1	kJs CNS	kJs PPGPV	$T_{thermostat}$	$T_{\_lower}$	$T_{\_upper}$
21:30	30.6	23.1	27.2	184.3	-62.1	70.5	25	23	29
22:00	30.5	23.0	27.2	178.3	-65.1	71.5	25	23	29
22:30	30.3	22.9	27.2	173.3	-68.7	72.1	25	23	29
23:00	30.1	22.8	27.2	167.5	-72.6	72.4	25	23	29
23:30	29.9	22.8	27.2	160.9	-71.9	72.5	25	23	29
00:00	29.7	22.8	27.2	154.3	-71.9	72.2	25	23	29
00:30	29.6	22.8	27.2	148.8	-73.5	72.0	25	23	29
01:00	29.4	22.7	27.2	144.6	-75.3	71.7	25	23	29
01:30	29.3	22.6	27.2	140.1	-78.8	71.2	25	23	29
02:00	29.1	22.6	27.2	135.5	-80.0	70.6	25	23	29
02:30	29.0	22.5	27.1	130.7	-82.1	69.7	25	23	29
03:00	28.8	22.5	27.1	125.7	-83.1	68.6	25	23	29
03:30	28.7	22.4	27.1	120.9	-84.8	67.5	25	23	29
04:00	28.6	22.4	27.0	116.2	-84.3	66.5	25	23	29
04:30	28.4	22.3	27.0	111.4	-86.9	65.2	25	23	29
05:00	28.3	22.3	27.0	108.1	-88.1	64.1	25	23	29
05:30	28.2	22.3	26.9	104.9	-88.8	62.8	25	23	29
06:00	28.2	22.3	26.9	103.5	-88.0	61.1	25	23	29
06:30	28.1	22.4	26.8	101.0	-86.6	57.4	25	23	29
07:00	27.9	22.4	26.6	94.1	-86.6	52.8	25	23	29

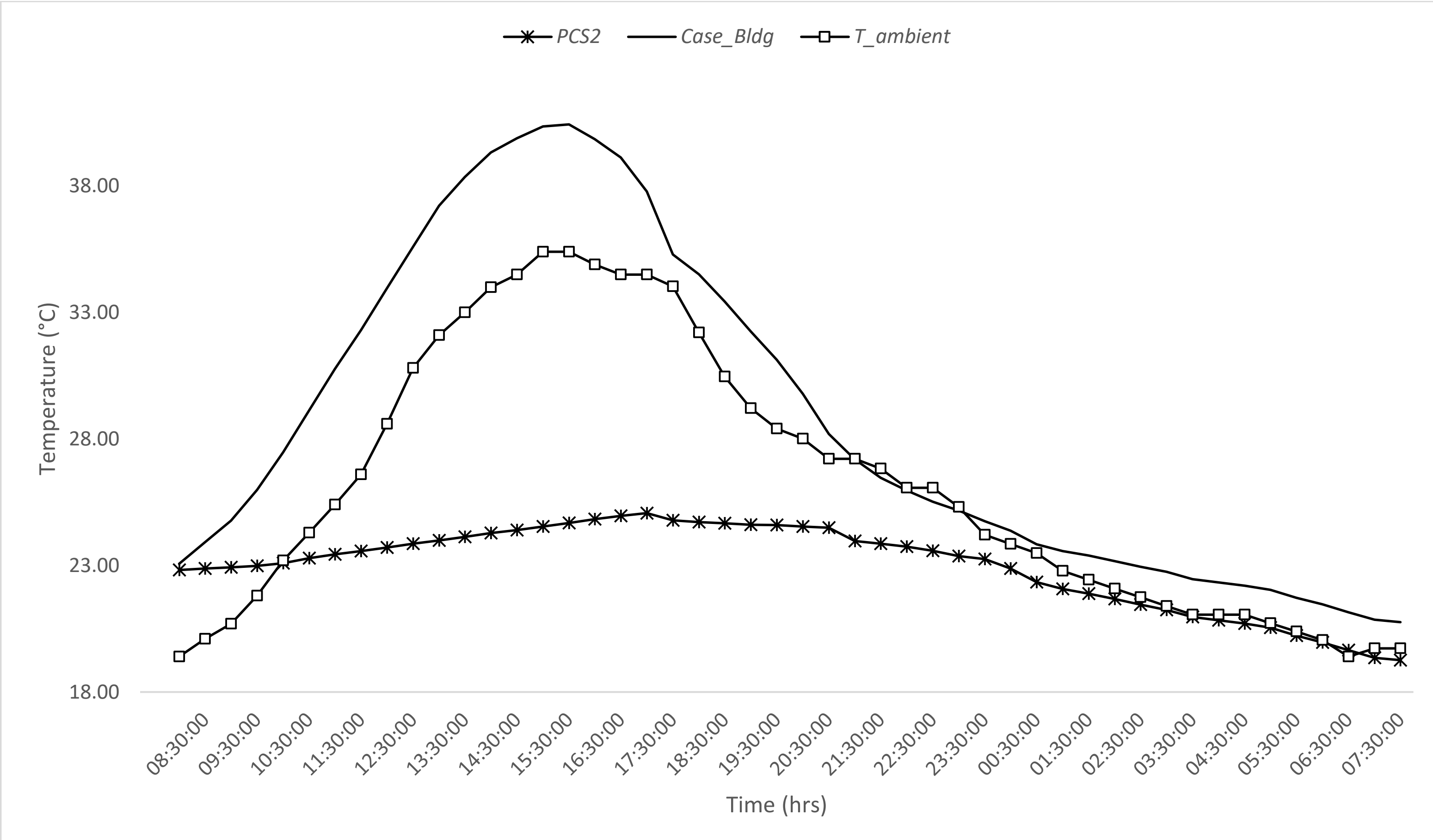


Figure B. 1 Day and Night Effect of the Application of Passive Cooling System on Indoor Thermal Environment compared to Case building