Investigating Design Solutions for High-Rise Social Housing in Kuala Lumpur with Reference to Thermal Comfort and Indoor Air Quality

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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.

Signed: Mohd Firrdhaus Mohd Sahabuddin

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List of Publications

- Gonzalez-Longo, Cristina and Mohd Sahabuddin, Mohd Firrdhaus (2019) *High-Rise Social Housing in Hot-Humid Climates: Towards an 'Airhouse' Standard for Comfort*. Applied Sciences, 9(23), 4985.

- Mohd Sahabuddin, Mohd Firrdhaus and Gonzalez-Longo, Cristina (2019) *Achieving Health and Comfort in High-Rise Residential Buildings by Using Dynamic-Hybrid Air Permeable Ceiling (DHAPC).* American Society of Heating Refrigerating and Air Conditioning Engineers (ASHRAE) Transactions, 125(2).

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<u>Motivating Publication</u>

- Mohd Sahabuddin, Mohd Firrdhaus and Gonzalez-Longo, Cristina, (2015) *Traditional Values and Their Adaptation in Social Housing Design: Towards a New Typology and Establishment of 'AirHouse' Standard in Malaysia*. ArchNet-IJAR: International Journal of Architectural Research, 9(2), pp.31-44. This publication was based on the dissertation for the MSc. Advanced Sustainable Design at the University of Edinburgh, supervised by Cristina Gonzalez-Longo.

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List of Abbreviations

A/C	Air-Conditioning
ACH	Air Change per Hour
AHU	Air Handling Unit
ANSI	American National Standards Institute
ASHRAE	American Society of Heating, Refrigeration, and Air-Conditioning
CFM	Cubic Feet per Minute
CIBSE	Chartered Institution of Building Services Engineers
MS1525	Malaysia Standard 1525
DOE	Department of Environment
OSHA	U.S. Occupational Safety and Health Administration National
NAAQS	U.S. National Ambient Air Quality Standards
NIOSH	Institute for Occupational Safety and Health
MET	Meteorology Department
HVAC	Heating, Ventilation, and Air-Conditioning
IAQ	Indoor Air Quality
IES	Integrated Environmental Solutions
UK	United Kingdom
UN	United Nations
USA	United States of America
U.S.	United States
KL	Kuala Lumpur
SEA	Southeast Asia
KS17	Knowledge Series 17 by CIBSE
CO_2	Carbon Dioxide
CO	Carbon Monoxide
NO_2	Nitrogen Dioxide
SO_2	Sulphur Dioxide
PM_1	Particles with a size (diameter) less than 1 micrometres (µm)
$PM_{2.5}$	Particles with a size (diameter) less than 2.5 micrometres (µm)
PM_{10}	Particles with a size (diameter) less than 10 micrometres (µm)

UBBL	Uniform Building By-Laws
BRE	UK's Building Research Establishment
SDBA	Street, Drainage and Building Act
GBI	Green Building Index
GreenRE	Green Real Estate
MyCREST	Malaysian Carbon Reduction & Environmental Sustainability Tool
PWD	Public Works Department of Malaysia
CIDB	Construction Industry Development Board Malaysia
VOC	Volatile Organic Compounds
TMH	Traditional Malay House
NHD	National Housing Development
UHLG	Ministry of Urban Wellbeing, Housing and Local Government
PPR	People's Housing Programme
DI	Dynamic Insulation
VSDI	Void Space Dynamic Insulation
MCLC	McLaren Community Leisure Centre
ISO	International Standard Organization
AC	Activated Carbon
OT	Operative Temperature
RH	Relative Humidity
AS	Air Speed
DHAPC	Dynamic Hybrid Air Permeable Ceiling
DHCBC	Dynamic hybrid Chilled Beam Ceiling

Nomenclature

A	Area [m^2]
°C	Temperature degree Celsius
H	Height [m]
k	Thermal conductivity [W/m·K]
L	Length [m]
ppm	Parts Per Million
R	Thermal resistance [m2K/W]
RH	Relative humidity [%]
T	Temperature [°C]
U	Overall heat transfer coefficient [W/m2.K]
V	Velocity [m/s]
w	Width [m]
C	Free air needed [cfm]
Pa	Atmosphere pressure [14.7 psia]
T_{db}	Dry-Bulb Temperature
µm	Micrometres
$µg/m^3$	Micrograms per metre cubic
^oN	Degree to the North
^oE	Degree to the East
m/s	Metre per second
am	Ante Meridiem
pm	Post Meridiem
Tn	Comfort temperature
To	Outdoor monthly mean temperature
ϑcom	Comfort temperature
ϑrm	Mean of the daily mean outdoor temperature
l/s	litre per second
kWh/year	Kilowatt hour per year
$kgCO_2/year$	Kilogram CO_2 per year
kW	Kilo-Watt

kWh	Kilo-Watt-hour
kg/m^3	Kilogram per metre cubic
m^3	Metre cubic
m^2	Metre square
m^3/s	Metre cubic per second
mm	Millimetre
m/h	Metre per hour
W/m^2K	Watts per square metre times Kelvin
m^2K/W	Metre squared Kelvin per Watt
$sqft^2$	Square feet square
fpm	Feet per minute

Abstract

An extensive programme of construction of high-rise social housing is being carried out in Kuala Lumpur which does not address in full the issues of thermal comfort and indoor air quality. This situation impacts human's health and comfort, and it becomes even more critical considering the climate change. As a hot-humid country, Malaysia experiences uniformly high temperature and humidity as well as low wind speeds. Approximately 75% of the time in the year air temperature and humidity lie outside the thermal comfort zone established by ASHRAE and CIBSE. As household incomes rise, residents resort to retro-fitting wall mounted split, air conditioning units to provide indoor comfort, a strategy that is neither cost nor carbon effective. The indoor and outdoor air quality conditions also surpass the World Health Organization (WHO) limits and there are insufficient local regulations on indoor comfort. Therefore, this research addresses the four main issues identified during the fieldwork: high temperature, high humidity, air pollution and low air movement with a proper and possible solution. Following a previous outline proposal of an 'Airhouse' Concept, several systems have been tested. The combination of 'Dynamic Hybrid Air Permeable Ceiling' (DHAPC) and 'Dynamic Hybrid Chilled Beam Ceiling' (DHCBC) could produce better indoor thermal comfort and air quality in the housing units, reducing the air temperature, humidity, airborne particle and gases as well as constantly providing an adequate airflow rate. This integrated system has been tested through physical and computer models and is based on a combination of dynamic insulation, hybrid ventilation and chilled beam techniques which reduces the ambient air temperature and humidity by up to 20%. The DHAPC alone could efficiently filter particulate matters (PM_{10} and $PM_{2.5}$) circa 90% from the incoming air intake. If this outcome can be delivered in practice, it would represent an overall saving of circa 66% in power consumption and carbon emission for cooling purposes. The system could be incorporated in the 'Airhouse' Concept, for efficiently providing thermal comfort and healthy indoor air quality in high-rise residential buildings in Kuala Lumpur and perhaps in other tropical countries. However, this is only one of the possible systems and the research should encourage further studies.

1.CHAPTER 1: Introduction

1.1 Research Area and Context

This research is about the environmental architectural design of high-rise social housing in Kuala Lumpur, Malaysia. At the moment, Kuala Lumpur accommodates 81.5% of the total number of high-rise buildings in Malaysia, 52% of which are residential buildings (CTBUH, 2019). In 2015, the government of Malaysia announced the construction of one million affordable housing units within the well-known social housing programme called People's Housing Programme (PPR), coordinated by the National Housing Department (NHD) of the Ministry of Urban Wellbeing, Housing and Local Government (UHLG) (G. Chen, 2015). According to the UHLG 2016 annual report, the government proposed 169 PPR projects all over the country with a total of 102,896 housing units (Ministry of Urban Wellbeing, 2016).

By December 2016, 81,352 units were built involving 115 different projects (MAMPU, 2016b). Out of 169, 33 projects were built in Kuala Lumpur from 1998 to 2016, providing 38,395 housing units within 121 blocks with the range from 10 to 21 storeys high (DBKL, 2019), suggesting that this city accommodates approximately 47% of the total PPR units in Malaysia and all of them are in high-rise format (JPN, 2016; KPKT, 2017). Although most of them were initially designed as naturally ventilated, the majority of their occupants have included inefficient mechanical ventilation (Figure 1.1) to achieve indoor comfort (A. Aflaki, Mahyuddin, & Baharum, 2016).

Figure 1.1: Current scenario of high-rise social housing in Kuala Lumpur

As a tropical country, Malaysia experiences high temperature, excessive humidity and low air movement much of the time. In urban areas, especially, these challenging factors are worsened by the poor air quality coupled with high energy demand. This research focuses on mitigating these challenges by using an energy-efficient ventilation system, low energy air cooling system and passive air filtering techniques. Two indoor comfort components – thermal and air quality (Pigliautile et al., 2019; Pistore, Cappelletti, & Romagnoni, 2019), are investigated in detail in this research. These components, for many years, have been studied in isolation by many experts, including architects and engineers (d'Ambrosio Alfano, Bellia, Fragliasso, Palella, & Riccio, 2019).

Other capital cities in the SEA region, such as Singapore and Bangkok, have also experienced the same problem (Aldossary, Ali, & Summ, 2016). More than half of the carbon emissions in the world, largely contributing to climate change, will be produced by Asian cities in the next 20 years (Halawa et al., 2018). The climate change implications in urban areas, including heat stress and air pollution, have serious impacts on human’s health and comfort (IPCC, 2018). It is estimated that 1.2 billion Asians will migrate to the cities over the next 35 years (ADB, 2019). It has been estimated that 30% of all international migration occurred in Asia and nearly 50% of international migrants came from Asia (ADB, 2019).

Four countries in Southeast Asia (SEA), namely Indonesia, Malaysia, Thailand and Vietnam, have collectively contributed 4% of the total global carbon emissions (Fulton, Mejia, Arioli, Dematera, & Lah, 2017). Malaysia ranked third in the SEA region, contributes seven tonnes of CO_2 in 2017 and will rise to over eight tonnes in 2030 (Fulton et al., 2017). To address this problem, its government has recently signed the Paris Agreement, committing to reduce 45% of carbon emissions by 2030 in accordance with the 2005 baseline (Fulton et al., 2017; UNFCCC, 2017). The high levels of carbon emissions are directly linked to increments in temperature (IPCC, 2018). The scientific report of Climate Change Scenarios for Malaysia 2001-2099 produced by the Malaysian Meteorological Department (MET), has projected a temperature increment of 1.1°C to 3.6°C by 2095 in Peninsular Malaysia (MET, 2009) including Kuala Lumpur that will be increased approximately 1.2°C by 2050 (ESRI, 2015).

A more recent report has found that the warmest year on the record was 2016 with the increment of ± 0.1°C (Meteorology, 2019). It was widely accepted that the El Niño had contributed to the hot weather in 2015 and 2016, but in 2017 (Figure 1.2), the hot weather was again taking place without the presence of El Niño. It was entirely because of the global warming which the temperature had increased more than 1°C since the pre-industrial period (IPCC, 2018; Meteorology, 2019).

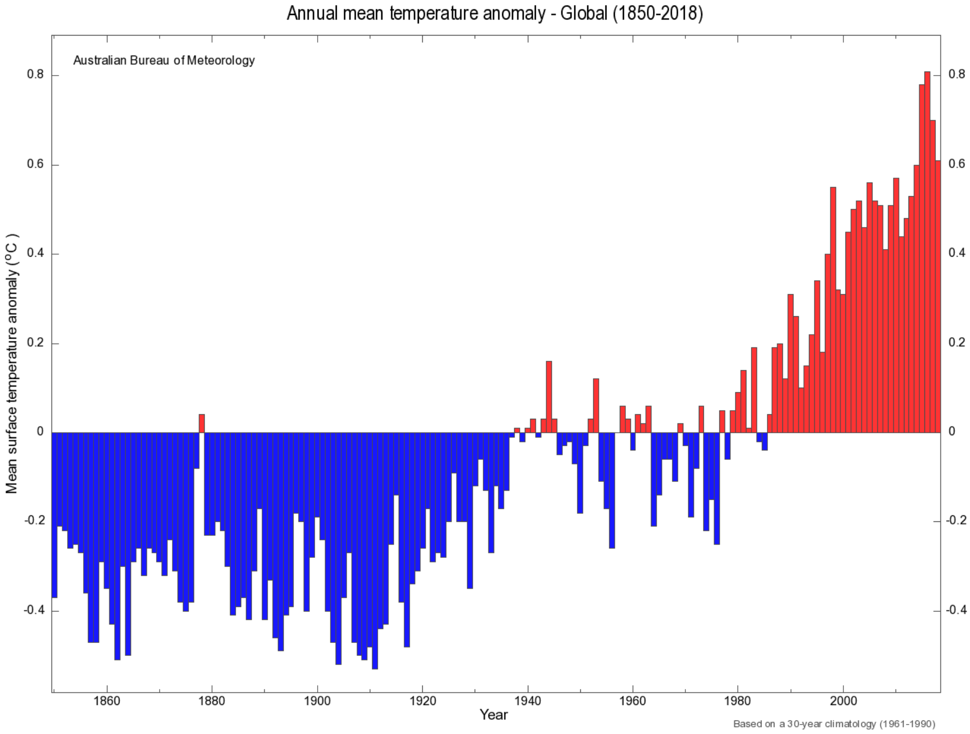


Figure 1.2: Annual global average temperature anomaly (Meteorology, 2019)

Building sector contributes to about one-third of the total global carbon emissions and consumes about 40% of the world's energy (Cehlin, Karimipanah, Larsson, & Ameen, 2019) and mostly utilised for achieving indoor comfort in buildings. In Malaysia, the emissions are mainly coming from the mechanical and electrical cooling systems, which have doubled from the 1970s, representing now the 25% of the total country's emissions (Lucon et al., 2014). Therefore, in this period, the construction of residential buildings has quintupled (Lucon et al., 2014). Thereafter, the appropriate building design in these residential buildings, particularly the high-rise buildings, is a key element to find solutions to reduce carbon emissions and to overcome the damaging effects of air pollution and indoor discomfort in future generations.

The World Health Organisation (WHO) has established that one in nine deaths (seven million per annum) is caused by fine particulate air pollution (Osseiran & Lindmeier, 2018), with 91% of the world's population living in cities where pollution levels exceed their guidelines (WHO, 2018a, 2018b). South-East Asia is a pollution hot-spot, frequently surpassing more than five times the WHO annual limits (Osseiran & Lindmeier, 2018) and the levels ($<20\mu g/m^3$ for PM_{10} and $<10\mu g/m^3$ for $PM_{2.5}$) are currently increasing at circa 1% per annum (WHO, 2018a). A study reported that the concentrations of $PM_{2.5}$ and PM_{10} in Kuala Lumpur were between 21 to $35\mu g/m^3$ and 44 to $56\mu g/m^3$ respectively (S. A. Rahman et al., 2015).

Positioned on the 'Intertropical Convergence Zone (doldrums), Kuala Lumpur's wind speed is relatively low (1.0 m/s to 3.0 m/s) (Milne, 2016) with air movement in the urban areas both inconsistent and unreliable (Mohd Sahabuddin & Gonzalez-Longo, 2017). When combined with the standard flat layout (single-sided), cross-ventilation driven by ambient air movement is not a particularly effective technique for providing evaporative cooling (Prajongsan, 2014). It suggests that both air pollution and temperature issues are worsened by the insufficient wind movement (Figure 1.3); the issue together with the high air temperature, excessive humidity, the presence of airborne particulate matter and urban roughness produce a series of challenges in order to provide health and comfort living in the city.

Therefore, in order to reduce carbon emissions and other effects of climate change, current building design, standards and practices have to transform, but without compromising the inhabitants' comfort and health. The design of appropriate ventilation systems, particularly in high-density residential buildings, is critical for this purpose. Although current building regulations, standards and green rating tools have proposed many natural ventilation strategies in Malaysia, they have not been able to acknowledge the current and future climatic conditions of Kuala Lumpur. At the same time, they are not able to address the required improvements in occupants' health and comfort as well as the reduction of carbon emissions. The 'Uniform Building By-Laws' (UBBL) – the mandatory building regulations in Malaysia, especially the clauses 39(1) and 40(1) that regulate the sizes of openings and light well requirements, were informed by the British building standards and have not been reviewed and further researched in accordance with the local climate conditions. These clauses, which have been in use for 33 years without revision, should be revised and improved in order to reduce carbon emissions while ensuring occupants' health and comfort. Likewise, other standards and green rating tools have also failed to devise strategies that could reduce airborne particulate matter and toxic gases as well as to prevent convective, conductive and radiative heat from entering and permeating high-rise residential units in Kuala Lumpur (Figure 1.3).

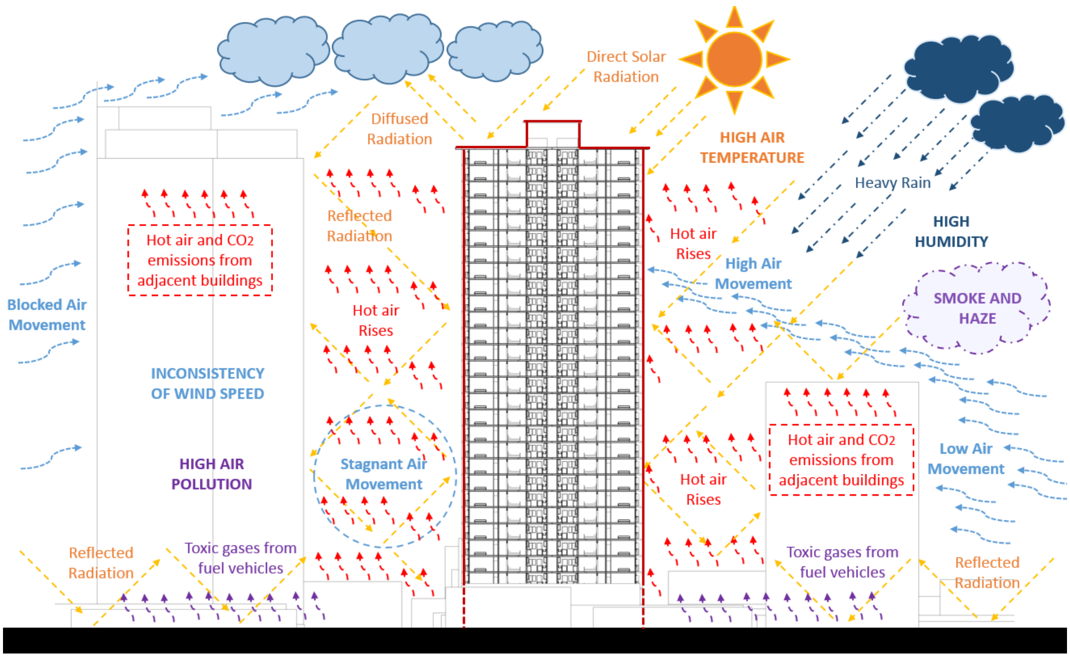


Figure 1.3: Factors affecting indoor comfort in a typical high-rise building within an urban area in a hot-humid climate

In tropical regions, cooling is more important than heating. The clear precedent that could lower the carbon emissions by introducing a design that could maintain indoor comfort temperatures without using any mechanical equipment is vernacular houses. The climatic adaptation of its design to the local climate has succeeded in achieving cooling and comfort (Lucon et al., 2014). This research was started in 2012 by exploring the introduction of a new proposed design concept called 'Airhouse'. It was based on the thermal comfort and natural ventilation strategies present in the vernacular Malaysian architecture (Mohd Sahabuddin & Gonzalez-Longo, 2015). The concept proposed that the percentage of openings in the building façade should be more than 15% depending on the height of the residential units. A full-height opening configuration was also proposed with three elements – main windows, fixed louvres and adjustable louvres. Fixed louvres are introduced at the upper level of the internal walls to allow air to circulate throughout the units at every time.

The proposed concept has also suggested that the depth of rooms should be decreased to enhance cross ventilation and the overhangs should be provided to protect all windows from solar radiation at any angles. This initial research proved that an appropriate envelope and plan layout configuration could assist to successfully achieve the acceptable operative temperature, increase the indoor air movement and significantly reduce energy consumption as well as carbon emissions. However, the previous research was entirely focused on the thermal comfort aspects. Therefore, this new research explores a more comprehensive concept which provides both comfort and health in high-rise living in a tropical climate.

This research has now continued with the in-depth investigation and analysis of the current practices, the identification of the critical problems to address and the exploration and testing of possible solutions. The current practices in building regulations and design have failed to achieve the required environmental conditions for health and comfort living. The result is that the building's occupants have to increase the amount of mechanical ventilation to achieve cooling shortly after they occupy the building.

On the other hand, building regulations in Malaysia, which concern the natural ventilation, should be revised in order to reduce energy consumption and carbon emissions as well as to deal with the challenges of heat stress and air pollution which affect the comfort and health of building occupants. This revision should take into consideration the critical conditions, which allow for ventilation to enhance air movement, reduce the airborne particulate matter and maintain the acceptable operative temperature and humidity. By improving the regulations and maximising the potential of ventilation, high-rise residential buildings in Kuala Lumpur would become healthy and comfortable places to live in and great contributors to the mitigation of climate change.

1.2 Aims and Objectives

This research is developed from the initial idea of wind harvesting technique for optimising thermal comfort using natural ventilation/ low energy approaches to design high rise buildings in the tropics to a wider consideration of comfort and health issues. It aims to define the actual environmental problems of the design of high-rise social housing in Kuala Lumpur and explore the potential energy-efficient and low carbon emissions systems to ensure health and comfort for the occupants. Considering the above, the hypothesis for this research is as follows: '*A new paradigm for the design of an environmentally-friendly ventilation and low-energy cooling system in high-rise social housing buildings in Kuala Lumpur that improves the comfort and health of the occupants and reduces carbon emissions*.'

The main objective is to find an effective low cost and low carbon technique, to improve thermal comfort and indoor air quality in the short to medium term. It is hoped that the introduction of electric vehicles may start to improve external air quality in the long term, however, the cyclical burning of agricultural land (DOE, 2016b), which is common across Asia (Fuller, 2018; H. A. Rahman, 2013), may delay this horizon. Therefore, this research tries to address these critical research questions:

a) What is the existing level of thermal comfort and indoor air quality in high-rise social housing buildings in Kuala Lumpur?
b) What are the key environmental problems to indoor discomfort and air pollution in Kuala Lumpur?
c) What is the optimum strategy or system that could be applied for reducing indoor discomfort and air pollution?
d) How feasible is the proposed system to reduce heat, humidity and air pollution as well as provide constant air movement?
e) What are the most effective design configurations of the proposed system for achieving best results of thermal comfort and indoor air quality?
f) How can the results contribute to the development of the 'Airhouse' Concept and how the research should continue?

The specific objectives of the research are:

a) To carry out in-situ data gathering to evaluate the performance of the existing and recently built high-rise social housing blocks in Kuala Lumpur concerning comfort and health.
b) To analyse the data and evaluate the results to identify the main problems in providing comfort and health to the occupants.

c) To address the problems found by identifying the most suitable system to test using physical and virtual modelling and the actual on-site conditions.
d) To develop an energy-efficient system that can reduce the air temperature and humidity as well as filter the airborne particles, providing adequate airflow rate for achieving comfort in high-rise social housing in Kuala Lumpur.
e) To evaluate the outcomes and suitability to address the problems of indoor discomfort and indoor air pollution in high-rise social housing.
f) To reflect on the outcomes to refine the 'Airhouse' Concept in order to produce integrated designs with energy-efficient ventilation, low-energy air cooling system and passive air filtering.

1.3 Research Methodology

This thesis follows a quantitative research approach, a quantitative method in its data collection with a deductive approach of analysis based on quantitative numerical data (Jonker & Pennink, 2010). In order to ensure that the aims and objectives established above are fully addressed, a methodology was planned and conducted with five main activities:

a) Literature review,
b) Fieldwork with in-situ data gathering,
c) Physical experiments,
d) Computational simulations and
e) Analysis and evaluation

An initial literature review stage, international and local standards, Malaysian building regulations and three local green rating tools were analysed. The review process was continued to the literature on other research aiming to tackle the issues of excessive heat, moisture and airborne particles as well as promoting the air movement. Through the literature review, two sets of requirements, each for thermal comfort and air quality were identified.

Two fieldwork campaigns were carried out, with a preliminary pilot study to get an overview of the actual scenario followed by two fieldworks to measure the actual thermal and air quality conditions in two selected social housing in Kuala Lumpur. Through these fieldwork studies, two sets of findings – thermal and air quality, were established. These sets of findings, then, were compared with the sets of requirements proposed in the previous activity (comparison 1).

This activity was continued with a computational simulation which completely measured the thermal comfort data for a year in this city. The data, then, were compared with the fieldwork findings to form the final actual thermal conditions for the selected social housing in Kuala Lumpur (comparison 2). The results of the analysis of the data gathered during the fieldwork informed the selection of the most suitable system to test. The system was selected by considering its capabilities in addressing the four major issues of thermal comfort and indoor air quality without neglecting the criteria of low cost, low energy efficiency and low carbon emissions.

A series of experiments were carried out using a reduced-scale physical model to test the performance of the new proposed system. These experiments completely evaluated the system by considering the main parameters of thermal comfort and indoor air quality in urban contexts such as temperature, humidity, airspeed (and airflow rate), particulate matter and toxicant gases from vehicles. The results of these experiments were compared to discover the effectiveness and readiness of the system in addressing the thermal and air quality issues using different materials and additional elements added in that system (comparison 3).

Computational simulations took place after that to verify as well as to refine the system to the optimum capacity. These simulations were used to determine the system's energy consumption and carbon emissions. This activity was started with an initial simulation (small scale) followed with the actual scale of the social housing building. The results from these simulations were compared with the results gathered in the previous activity (comparison 4).

The final activity involved analysis and evaluation of the results from the literature review, fieldwork studies, physical experiments and computational simulations (final comparison). The outcomes informed the definition of the proposed concept and further research. These activities that were explained before, were combined in different stages as follows and illustrated in Figure 1.4.

a) Stage 1 – building the research protocol and context of the research,
b) Stage 2 – finding the issues, gaps and potential solutions,
c) Stage 3 – defining actual issues and problems,

d) Stage 4 – developing a prototype,

e) Stage 5 – improving the prototype with additional technique in a full-scale building and real context, and

f) Stage 6 – establishing a new concept.

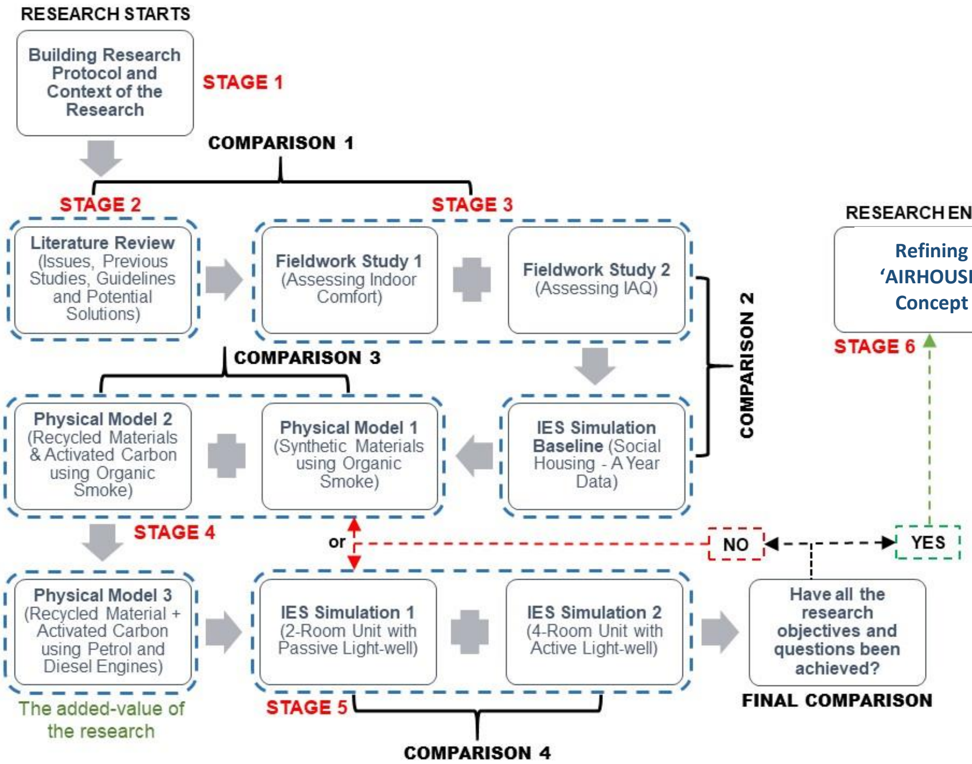


Figure 1.4: Flowchart of the research process

1.3.1 Stage 1: Building the Research Protocol and Context of the Research

This stage aimed to build the research context and background of the research. Using the literature review, the method for the data collection was based on a series of literature reviews on the main topics selected – health and comfort, and how these topics affect the current global scenario and local environment in Malaysia. The Malaysian building requirements such as regulations, standard and green rating tools were included and discussed in detail. The motivating factors of the research derived from vernacular buildings were also included in this stage.

The data analysis was carried out by several methods. Firstly, by observing the global and local climate change patterns that affect global warming and urban heat island; secondly, comparing the building requirements that are available in Malaysia and how these requirements suffice the challenges of providing health and comfort living in the country; and thirdly, discussing the findings proposed by the previous authors from other publications. The establishment of a concise research protocol which includes the research aims and objectives, research methodologies, thesis structure, limitations and the research significance and impact was made in this stage.

1.3.2 Stage 2: Finding the Issues, Gaps and Potential Solutions

For stage 2, another literature review process was conducted to define the issues, gaps and potential solutions in indoor comfort and indoor air quality (IAQ) studies. This stage explained the two crucial issues for this research – indoor discomfort and indoor air pollution. Examining some earliest until most recent studies about these topics has led to a conclusion about what has been achieved so far in dealing with the problems. A number of selected solutions found by many researchers were discussed in detail. These include solutions on reducing heat and moisture and airborne particles as well as enhancing air movement.

The data analysis used was through graphical diagrams and comparison tables. Each of the strategies was compared side-by-side with additional information such as the objectives of the strategies. The strategies' positive and negative impacts were also listed down with an easy-to-understand approach. This stage revealed the gap that is still unexplored in reducing heat, moisture and airborne particles in ambient air as well as promoting air movement in an optimum solution approach. A potential solution was suggested and proposed.

1.3.3 Stage 3: Defining Actual Issues and Problems

Stage 3 has three phases. During phase 1, fieldwork study 1 was conducted to evaluate the indoor comfort condition in high-rise residential buildings in Kuala Lumpur. The fieldwork campaign began with a pilot study on ten high-rise social housing in Kuala Lumpur to observe the current situation of the buildings and to initially suggest the problems associated with high-rise living in urban areas. It was then followed by the fieldwork study 1 which gathered a full set of data for indoor comfort parameters such as air temperatures, relative humidity and indoor airspeeds. Several points of measurement were defined which located at two different room conditions, three different heights and two different façade-facing conditions. One of the case studies was just completed and unoccupied, therefore, this fieldwork became a benchmark for the building. This fieldwork was conducted in the dry season or also called as the 'South-West Monsoon' because the highest ambient air temperatures (above 34°C) frequently occur during this period.

Using the Excel program, the collected data were transformed into graphical results to make it easy to analyse. These graphical results consisted of a number of bar charts that compared the selected parameters according to different room locations, heights and façade-facing conditions. The establishment of trend lines of air temperature, relative humidity and airspeed was according to different room locations, different heights and different façade-facing conditions. This method established the actual thermal condition benchmark for the newly completed and still unoccupied case study.

At phase 2, another fieldwork study was conducted to assess both thermal comfort and indoor air quality in high-rise residential buildings in Kuala Lumpur. Using the same samples in the fieldwork study 1, this fieldwork study started by defining the fieldwork protocol such as data collection period, duration of measurement, proposed equipment parameters and points to be measured. This study which examined the air quality in the case studies was conducted in the wet season or called 'North-East Monsoon'. In this season, outdoor air quality improves, but not indoor air because of the amount of time that people stay inside with poor ventilation.

Similar to the first fieldwork, this fieldwork also used graphical figures such as tables and trend lines for analysing the results. By combining these trend lines with the architectural drawings as background, the continuing pattern of the air quality from outdoor to indoor could be easily assessed. The establishment of trend lines from outdoor to indoor of particulate matter ($PM_{2.5}$ and PM_{10}), carbon dioxide (CO_2) and carbon monoxide (CO) was according to different point locations and different heights.

Finally, at phase 3, a computer-based model was simulated to predict the baseline data of indoor comfort conditions for a full year in Kuala Lumpur. Using the design parameters stated in the architectural drawings, a full-scale computerised model using a simulation software was constructed. The locations of housing units chosen were consistent with the units used in the fieldwork studies. The closest construction techniques used in the actual building were assigned to the model. This method gathered a full year data of indoor comfort parameters before comparison of the data with the results from the fieldwork studies could be made.

As mentioned before, this study used an environmental simulation software as one of the tools in the research methods. Thus, all of the analyses were simulated by the software before it was transferred to another program such as Microsoft Excel for further data analysing. For indoor comfort, the parameters simulated are consistent with the parameters measured in the fieldwork studies. This phase produced the full-year results of air temperature and relative humidity together with the total hours that fall within recommended ranges. These results then were compared and discussed with the fieldwork studies results.

1.3.4 Stage 4: Developing a New Prototype

Stage 4 also has 3 phases. It started with Test 1 to evaluate the performance of dynamic insulation and hybrid ventilation using synthetic insulations**.** In this phase, the highly recommended approach by many researchers was by using a reduced-scale model. The construction of the model started with a theoretical model diagram and after several modifications, the real reduce-scaled model was approved to be built. This test used two identical equipment placed in the outdoor chamber and indoor compartment of the test model. These instruments measured the parameters of indoor comfort and air quality such as air temperature, relative humidity, $PM_{2.5}$ and PM_{10} by using several ventilation protocols. The test procedure that controls the measuring procedures such as log time interval, options of ventilation protocols and synthetic insulations details was determined earlier.

The data analysis included all the readings recorded on the test sheet. The information gathered was then transferred to the Microsoft Excel program for generating a series of bar charts. Like other stages described before, these charts were sorted by comparing the performance of all reduction rates for all ventilation protocols. In this test, high reduction rates defined the performance of the test configurations. Ultimately, among all the configurations tested, a few were defined and studied in detail in the next tests. The selection criteria were based on the highest reduction rates achieved for indoor comfort and air quality factors – heat, humidity and airborne particle. The heat and humidity reduction rates were converted and tabulated on a psychrometric chart for better comparison.

In phase 2, Test 2 was conducted to improve the performance of the new proposed system using different insulation materials and an additional element to the system. Correspondingly as described in phase 1 of this stage, Test 2 also used the same physical model as used in Test 1. On the contrary, this test applied recycled insulations, activated carbon granules in a cartridge and used different airspeeds. Test 2 was a continuity from the previous Test 1, therefore, only configurations that were suggested from the previous test were being tested.

Test 2 used a similar approach to analysing data as described in Test 1. These identical and related characteristics of results were used to identify similarities in the results of the two tests. This analysis process of data was useful for exploring and forecasting the relevant circumstances in which the results or patterns could occur (Walliman, 2017). The tabulation of heat and humidity results on the same psychrometric chart suggested the improvement of the systems in terms of reducing the heat, moisture and particulate matter based on Test 1 and fieldwork studies results.

In phase 3, Test 3 was conducted to add the value of the research which also enhanced the performance of the newly proposed system with toxic gases from vehicles using different activated carbon techniques. In the same way, as tested in Test 1 and Test 2, this phase used the same methods and procedures except for the selection of air pollution substances. This test used substances that were produced by petrol and diesel engines. This test was crucial as it gave a value-added to the research contribution in different perspectives. It means that the proposed system was tested in-depth using several types of pollution sources from organic smoke to toxicant gases.

Like in phase 1 and 2, this phase used the same data analysis methods. The results were compared and tabulated on the same psychrometric chart. This stage rigorously tested the proposed system that not only catered a wide range of modern air pollution types but also the indoor comfort criteria.

1.3.5 Stage 5: Improving the Prototype with Additional Technique(s)

This stage has 2 phases which at phase 1, a computer-based model was developed to test and improve the thermal performance of the new proposed system in high-rise social housing typology with an energy-efficient air cooling technique. This Simulation 1 adopted the same environmental software used in the baseline simulation exercise. The model was based on the actual size and conditions of the selected samples used in the fieldwork studies. An energy-efficient air cooling technique was introduced in the model as a strategy to further reduce the heat and moisture in the supply air. This combination of passive air filtering technique, hybrid ventilation and energy-efficient air cooling strategy was simulated and analysed using an environmental software. A few other criteria such as different supply air temperature and different air flow rate were also tested with the system. The software generated a series of results such as total hours of operative temperature and relative humidity that fell between the selected international standard requirements. The total system energy results were also obtained from this exercise.

The results generated by the software were transferred into a Microsoft Excel program for in-depth data analysing. Simulation 1 suggested the initially added performance of the proposed system and then would be studied in detail in Simulation 2. In phase 1, the performance of a few configurations of the air cooling technique together with the passive air filtering strategy was assessed. A few options of the air cooling techniques were selected and carried forward for the next phase.

At phase 2, another simulation exercise was conducted to validate the results gathered in Simulation 1. A more accurate housing unit was developed and used in Simulation 2. Instead of two rooms were being tested in Simulation 1, this exercise modelled the entire housing unit with an additional element of active light-well. It means that the data collection in this phase was done in the most complete scenario in terms of the new proposed system (integration of fully tested passive air filtering technique and the energy-efficient air cooling strategy), actual building design conditions (full-scale housing unit with light-well) and climate contexts (hot-humid climate conditions).

Similarly, with other phases, this phase suggested the final performance of the new proposed system with its additional element for thermal improvement. The results gathered in this phase were compared and discussed. Ultimately, at this phase, all of the results gathered from the previous stages were also tabulated on the same psychrometric chart for a general overview of the proposed system. This is to illustrate the optimum performance that this proposed system could offer at the time of this thesis being written.

1.3.6 Stage 6: Refining the New Proposed Concept in Building Construction Industry

At this final stage, all the results were summarised and the key findings were refined to suit the previously proposed 'Airhouse' Concpet. This phase gathered all of the results obtained in Stage 1 to 5 and seek for potential adaptation on a social housing unit in Kuala Lumpur. The explanation of the system application in existing and new buildings were proposed in detail.

The explanation was illustrated through graphical diagrams. The application of the proposed system in the high-rise social housing design was outlined as a new 'Airhouse' Concept. Finally, a new concept in building industry in Malaysia is recommended. This establishment of the concept was not only for the Malaysian context but also for the tropical region entirely.

1.4 Thesis Structure

The thesis structure comprises of four steps of investigations. Figure 1.5 shows the research structure and outline where at the first step (Chapter 1) is about defining the research background and context, followed by determining the problem statement in the second step (Chapter 2 and 3). The research contributions are outlined in the third step (Chapter 4, 5 and 6) before the research concludes in the last step (Chapter 7).

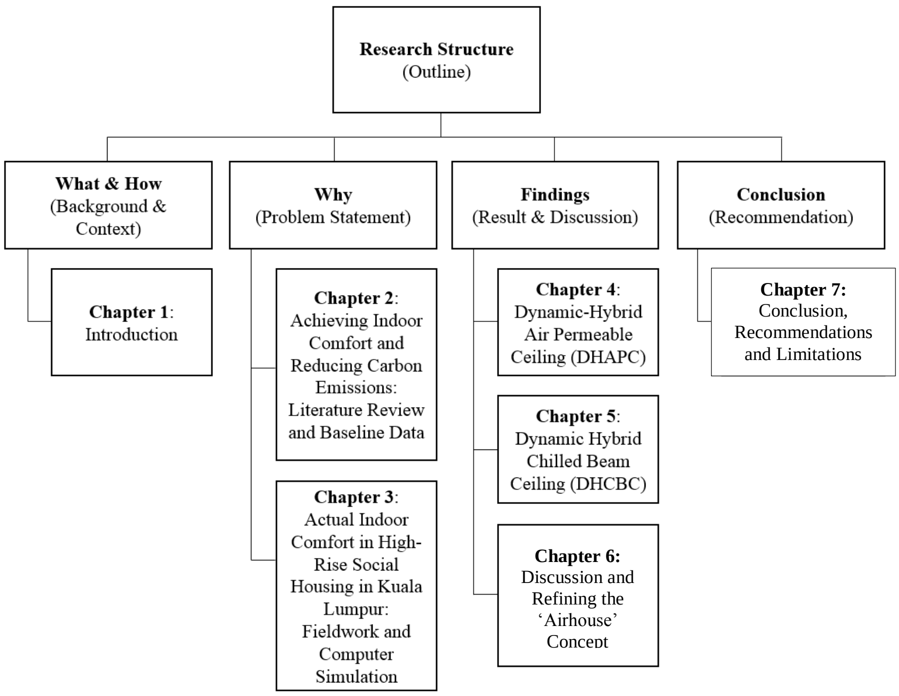


Figure 1.5: Research structure and outline

Chapter 1 thoroughly explains the background, overview and context of the research. The current scenario of global and local conditions regarding health and comfort are discussed in general. The research motivating factors are also included to give an insight regarding how this topic was chosen by the author. In addition, this chapter has also specifically structured the research protocol such as the hypothesis, the research aims, objectives and questions. The contributions of the research and limitations that need to be taken into account during the research progress are the complement of this chapter.

Chapter 2 explains in detail the indoor comfort and air quality issues in Kuala Lumpur. In this chapter, the conditions and potential of air temperature, relative humidity and air movement in the city are discussed. The Kuala Lumpur's comfort zone through standards (local and international) and regulations, previous studies and recommendations are also established. An overview of high-rise social housing in Kuala Lumpur is also included. At the end of this chapter, all of the relevant strategies that have been proposed by a number of researchers are explained in detail. The strategies are divided into four main areas that become the main problems and issues in high-rise living in tropical urban areas. Apart from proposing the gaps and potential solutions, at the end of this chapter, the probability of indoor comfort and air quality in a social housing block in Kuala Lumpur is also explained before the current implementation of the selected system is discussed.

Chapter 3 gathers all information on two fieldwork studies conducted in hot and dry seasons in Malaysia. The chapter starts with the protocol related to indoor comfort monitoring exercise such as the size of samples and placement of equipment that were applied in the case studies. The fieldworks assessed the current indoor comfort conditions in high-rise social housing in Kuala Lumpur. The first fieldwork findings are discussed and written comprehensively. Then it continues with the protocol of the second fieldwork study that measures the indoor and outdoor air quality in the same case studies. The results are discussed and explained in detail. The indoor air quality requirements from several institutions – international and local, are also determined and compared. Graphical findings and analyses are inserted to complement the chapter.

Chapter 4 investigates the new proposed system called 'Dynamic-Hybrid Air Permeable Ceiling' (DHAPC). This innovation is tested by using a reduced-scale model. Three stages of tests conducted to verify and validate the technique from many aspects – macro to micro, are explained in detail in this chapter. Thereafter, the improvement results achieved in the tests are tabulated and compared on a psychrometric chart.

Chapter 5 addresses the continuity of the DHAPC tests by adding up an energy-efficient strategy called 'Dynamic Hybrid Chilled Beam Ceiling' (DHCBC). Using environmental simulation software, the strategy's effectiveness and ability were measured and assessed. This chapter explains in detail the IES simulation protocol and its results on achieving the optimum indoor comfort conditions by using DHAPC and DHCBC combination. The reduction results of the total energy demand and CO_2 emissions when applying this system is also being proposed in this chapter. Finally, the integration of both systems has established a new refined 'Airhouse' Concept.

Chapter 6 discusses the application of 'Airhouse' Concept into the real context of high-rise social housing in Kuala Lumpur; physically and environmentally. The applications of the system in existing and new buildings are explained in detail in this chapter. This chapter also explains some additional benefits when applying the 'Airhouse' Concept in high-rise buildings.

Chapter 7 summarises every stage, methodology and key findings involved in this research into one complete but compact chapter. It discusses several challenges that may arise in implementing the concept and also predicts and suggests the implication of this system in Malaysia and other tropical countries. Several recommendations of future development and study are also introduced by suggesting some new areas for future research work for other researchers and other parties not limited only to the construction industry people, but also the scientists such as the physicists and chemists.

1.5 Significance and Impact of the Research

There is a lack of awareness and exploration of the energy-efficient system that can reduce the air temperature and humidity as well as filter the airborne particles, providing adequate airflow rate for achieving comfort in high-rise residential buildings. This system could solve the two crucial and demanding issues in many tropical cities – health and comfort. However, its adaptation in high-rise residential buildings is not yet discovered. Thus, this research aims to close the gap that exists in building construction, especially for high-rise residential buildings, by developing a system which could address four crucial indoor comfort issues in tropical urban areas – excessive temperature, humidity and airborne particles as well as low air movement. Therefore, the contributions of the present research to the body of knowledge are listed as follows:

a) To develop an innovative energy-efficient system and integrate the system with the building layout in high-rise buildings. This innovation will create a new high-rise housing typology for existing and new buildings which will not be exclusive to Malaysia but also applicable in countries with similar climates, such as in tropical regions.
b) To promote public awareness and enhance a positive attitude towards energy efficiency buildings by establishing a new design concept. This awareness will trigger a demand for the development of the concept for the housing industry and perhaps could promote in revising the mandatory building regulations in Malaysia.
c) To develop a system that can be cost-effectively retrofitted into the existing building stock in Malaysia. This initiative is derived from the relatively poor performance of the existing stock which led to the poor indoor thermal and health conditions.
d) To define a new benchmark for comfort and health standards in the national housing industry. The benchmarks need to be based on the indoor comfort and health conditions such as the required indoor temperature, humidity, airflow rate and the values of particulate matter. Fulfilling these criteria will confer that particular development has complied with the 'Airhouse' Concept.
e) To support and enhance the developing energy efficiency program in Malaysia. This research aims to produce a cost-effective energy-efficient building typology that will not compromise human's comfort and health.
f) By using a cost-effective retrofitting approach, this new proposed system will also increase the value of the existing building stock in many tropical

countries. This effort gives new hope to the existing building owners which would provide comfort and healthy living with low maintenance. Without hesitation, this contribution will give a value-added to the existing stock properties.

Given the above overview of the research context, in the next chapter, the indoor comfort and air quality issues in Kuala Lumpur are discussed in detail. This includes the overall conditions of air temperature, relative humidity and air movement in Kuala Lumpur and the potential solutions.

2.CHAPTER 2: Achieving Indoor Comfort and Reducing Carbon Emissions: Literature Review and Baseline Data

2.1 Definitions and Parameters

Indoor comfort constitutes acoustic, thermal, visual and indoor air quality (Pigliautile et al., 2019; Pistore et al., 2019). For many years these components have been researched in isolation by physiologists, engineers, architects, occupational health and industrial hygiene experts (d'Ambrosio Alfano et al., 2019). As explained in Chapter 1, this research focuses on thermal comfort and indoor air quality with the ultimate scope to maximise natural ventilation potentials.

2.1.1 Thermal Comfort

Thermal comfort is one of the most important aspects of daily living (Jamaludin, Mohammed, Khamidi, & Wahab, 2015; Lechner, 2014). It is defined as ‘that condition of mind which expresses satisfaction with the thermal environment’ (Fanger, 1970). The two established international organisations that provide guidelines on thermal comfort conditions are the ‘American Society of Heating, Refrigerating and Air-Conditioning Engineers’ (ASHRAE) and the ‘Chartered Institution of Building Services Engineers’ (CIBSE). As defined in ASHRAE Standard 55 – ‘Thermal Environmental Conditions for Human Occupancy’, thermal comfort is a ‘condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation’ (ASHRAE, 2013). The standard has set six primary factors that must be addressed when defining thermal comfort: metabolic rate, clothing insulation, air temperature, radiant temperature, airspeed and humidity (ASHRAE, 2013). They have mentioned that defining thermal comfort is complex and involves both ‘physiologically’ and ‘psychologically’ factors (ASHRAE, 2013; Pigliautile et al.,

2019) as different people in the same space have different perceptions of comfort, neither warmer nor cooler (CIBSE, 2012; Fanger, 1970).

The CIBSE has defined in their 'Environmental Design - Guide A' that thermal comfort is a person's sensation of warmth that is influenced by several parameters, from main physical parameters to personal factors. They have established four main physical factors in consequence: air temperature, mean radiant temperature, relative humidity and airspeed (Figure 2.1) (CIBSE, 2015). On the contrary, metabolic heat production and clothing are also listed as personal factors that could affect thermal comfort (CIBSE, 2015).

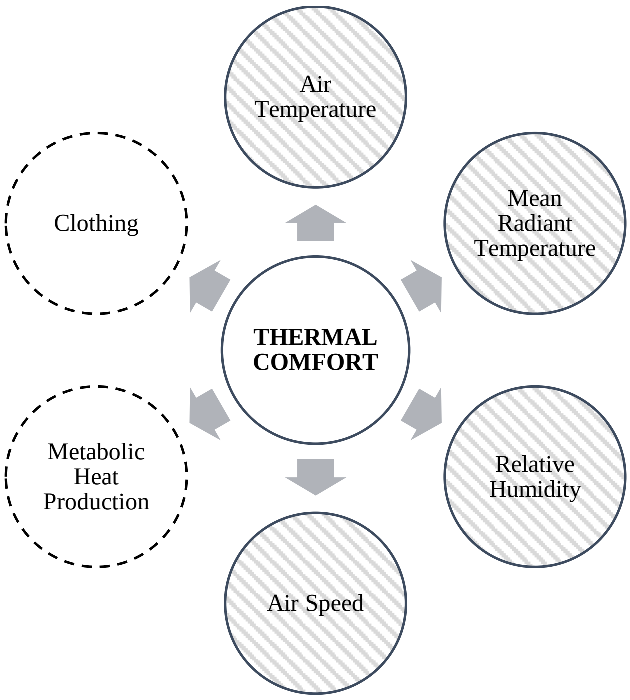


Figure 2.1: Factors for defining conditions for thermal comfort

For air temperature, the ASHRAE Standard 55 describes the sensation of this parameter as 'the temperature of the air surrounding the occupant'. Air temperature also means as the average temperature of the air surrounding the building where the correctness of this assumption is very dependent on the local micro-climate (CIBSE, 2015). Meanwhile, mean radiant temperature is known as 'the uniform surface temperature of an imaginary black enclosure in which an occupant would exchange the same amount of radiant heat as in the actual non-uniform space' (ASHRAE, 2013). It means that in indoor spaces, there are several elements such as ceilings, walls and floors that radiate different values of mean radiant temperatures (Figure 2.2). These temperatures should be considered when they differ greatly from the air temperature (Lechner, 2014). Hence, the combination of air temperature (T_{db}) and mean radiant temperatures (T_{1-7}) will produce a single average value to express their joint effect (CIBSE, 2015) (Figure 2.2), called the 'operative temperature'. According to ASHRAE Standard 55, the comfort zone is defined in terms of a range of operative temperatures that people find thermally acceptable (ASHRAE, 2013).

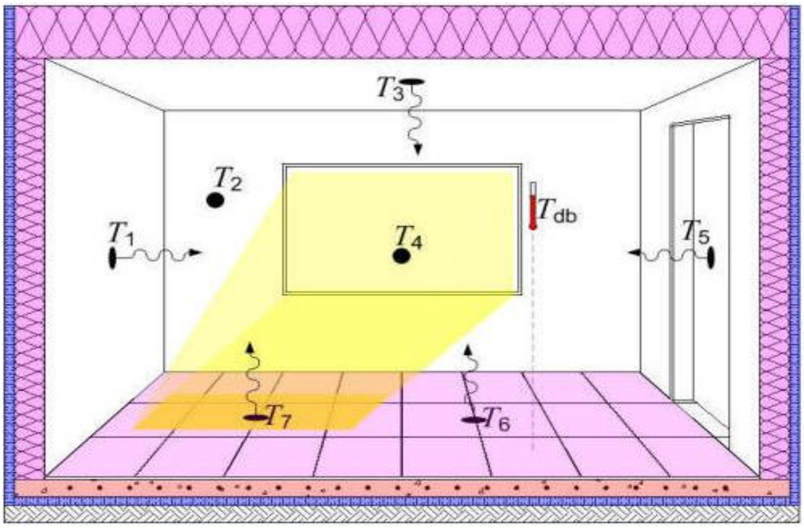


Figure 2.2: Mean Radiant Temperature (MRT) in practice (Bean, 2010)

Another thermal comfort factor that will be assessed in this research is relative humidity. The relative humidity is the percentage of humidity in the air relative to the saturation line, which is the maximum that it can hold (Bhattacharya & Milne, 2009). In tropical climate, it has a fairly noticeable effect on feelings of comfort (CIBSE, 2015; Djamila, Chu, & Kumaresan, 2014), however, when the operative temperature rises above 26°C to 28°C, the skin damp with sweat may become apparent especially for lightly clothed people (CIBSE, 2015). On the other hand, controlling the good range of humidity (40-70%) is also important in the context of microbiological growth which in high humidity environments, mould spores will develop and adversely affect health and wellbeing (CIBSE, 2015).

Airspeed – 'the rate of air movement at a point, without regard to direction', is another thermal comfort factor included in this research. In indoor spaces, this factor is crucial to stimulate evaporative cooling effect – heat-loss rate by both convection and evaporation (Lechner, 2014). It is widely accepted that in a hot-humid climate, using fan is one of the common methods to achieve thermal comfort (Lechner, 2014) and air movement is the main factor for achieving it (Givoni, 1994). Many researchers

(Lechner, 2014; Medinilha & Labaki, 2016; Prajongsan, 2014) used elevated airspeeds to increase the operative temperature limit for comfort zone.

For this research on high-rise residential buildings in Kuala Lumpur, the indoor thermal conditions will be evaluated, considering only the main physical parameters: air temperature, relative humidity and airspeed, because they can be measured with simple instruments and compared with ranges and limits set by established standards. However, for operative temperature, a specific equation need to be applied as follows: **(tr + (ta x √10v)) / (1+√10v)**. It derives from air temperature, mean radiant temperature and air speed which could be represented using dry bulb temperature as suggested in psychometric chart in ASHRAE 55 (ASHRAE, 2013).

2.1.2 Indoor Air Quality (IAQ)

Good IAQ is a basic requirement and essential in ensuring the health and comfort of occupants (CIBSE, 2012; WHO, 2010). It is defined as 'air with no known contaminants at harmful concentrations' (CIBSE, 2012) as determined by cognizant authorities (ASHRAE, 2016a). Cognizant authorities mean the organisation or agency that has the expertise and jurisdiction to establish and regulate concentration limits for airborne contaminants. Among the cognizant international authorities that establish guidelines to be used to improve IAQ in buildings are the World Health Organization (WHO), ASHRAE and CIBSE, whereas for local context, the Department of Environment Malaysia (DOE) is the main responsible organisation that specify the ambient air quality standard in Malaysia since 1989 (DOE, 2013). CIBSE, through its 'Knowledge Series' (KS17) – Indoor Air Quality and Ventilation', listed gaseous pollutants, volatile organic compounds, odours and particulate matter among the common contaminants and pollutants (CIBSE, 2012) (Figure 2.3). While ASHRAE Standard 62.1 – Ventilation for Acceptable Indoor Air Quality, has compared several guidelines pertinent to indoor environments. Among the common contaminants and pollutants found in buildings according to them include carbon dioxide (CO_2), carbon monoxide (CO), nitrogen dioxide (NO_2), nitrogen dioxide (NO_2), sulphur dioxide (SO_2), ozone (O_3), radon and particulate matter ($PM_{2.5}$ and PM_{10}). However, the 'New Malaysia Ambient Air Quality Standard' established by DOE has listed six types of pollutants that need to be considered which are PM_{10}, $PM_{2.5}$, SO_2, CO, O_3 and NO_2.

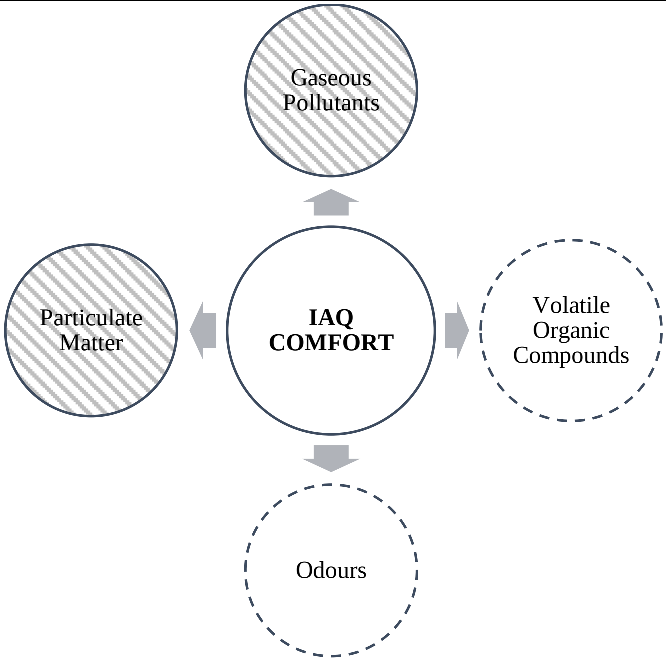


Figure 2.3: Categories of common contaminants or pollutants in indoor spaces.

Particulate matter has adversely affected the public health of urban populations in both developed and developing countries (WHO, 2006). Although PM_{10} is a widely reported measure (WHO, 2006), smaller particles ($PM_{2.5}$) also contribute to the health effects observed in urban environments (S. A. Rahman et al., 2015). Petrol and diesel engines generate similar materials in their exhausts but the proportions are different (Watkins, 1991). CO mainly produced by petrol engines and SO_2 emissions from diesel engines are much greater than petrol engines (Watkins, 1991). Like CO and SO_2, benzene is harmful to humans and there is no safe level of exposure that can be recommended (WHO, 2010). It presents in both outdoor and indoor air but generally higher indoor concentrations than outdoor (WHO, 2010). These two categories of air pollution are directly linked to urban living where particulate matter usually come from the combustion of wood and other biomass fuels (Fuller, 2018; Keywood, Ayers, Gras, & Boers, 2003; H. A. Rahman, 2013), and toxic gases come from vehicular engines (Cionita, Adam, Jalaludin, Mansor, & Siregar, 2014; Colls, 1997; Fuller, 2018; Watkins, 1991).

This research has the ultimate scope to maximise natural ventilation, thereafter, these two categories of pollutant – particulate matter (PM_{10} and $PM_{2.5}$) and gaseous pollutants (carbon monoxide, benzene and sulphur dioxide) will be studied in detail. In achieving acceptable IAQ and maximising the potential of natural ventilation, filtering the pollutants in outdoor air and removing the contaminants in indoor air become a priority in this research. Similar to thermal comfort parameters, these pollutants can also be measured with simple instruments and compared with ranges and limits set by several international and local standards.

2.2 Environmental Conditions in Kuala Lumpur

2.2.1 Thermal Comfort Conditions

Establishing Kuala Lumpur's actual outdoor thermal conditions provides the environmental context for the research. Located at the west coast of Peninsular Malaysia, at approximately 40 km from the Straits of Malacca (the nearest sea), the city is located at a latitude of 3.14°N and a longitude of 101.7°E (Daghigh, 2015) (Figure 2.4). Two main seasons are occurred – wet (November to March) and dry (May to September) (MET, 2019).

Due to its location near the equator line, Kuala Lumpur receives a uniform mean, low and high temperatures throughout the year (Jamaludin et al., 2015; MET, 2019). The mean, low and high temperatures are between 25°C and 30°C, 22°C and 26°C and 29°C and 35ºC respectively (Figure 2.5). For humidity, the mean humidity for the city is high between 70% and 90% and the lowest 40% (Figure 2.6). Being positioned on the 'Intertropical Convergence Zone' (ITCZ) or called 'doldrums', the city's mean wind speed is low (Leary, 1979) averaging from 1.5 m/s to 2.0 m/s (MET, 2017a; Milne, 2016) (Figure 2.7).

Figure 2.4: Map of Malaysia and the location of Kuala Lumpur (CIA, 2019)

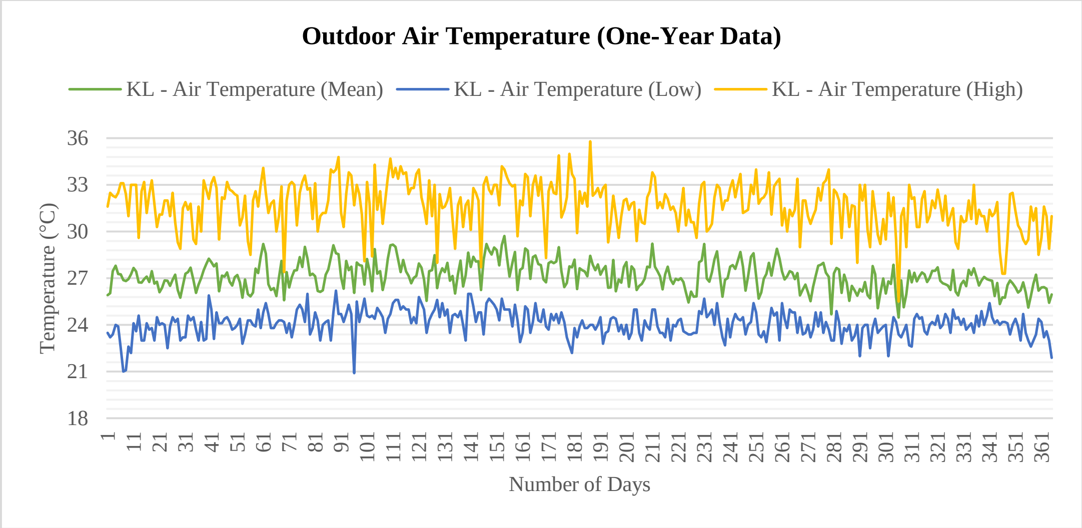


Figure 2.5: Outdoor air temperature (full year) for Kuala Lumpur (Milne, 2016)

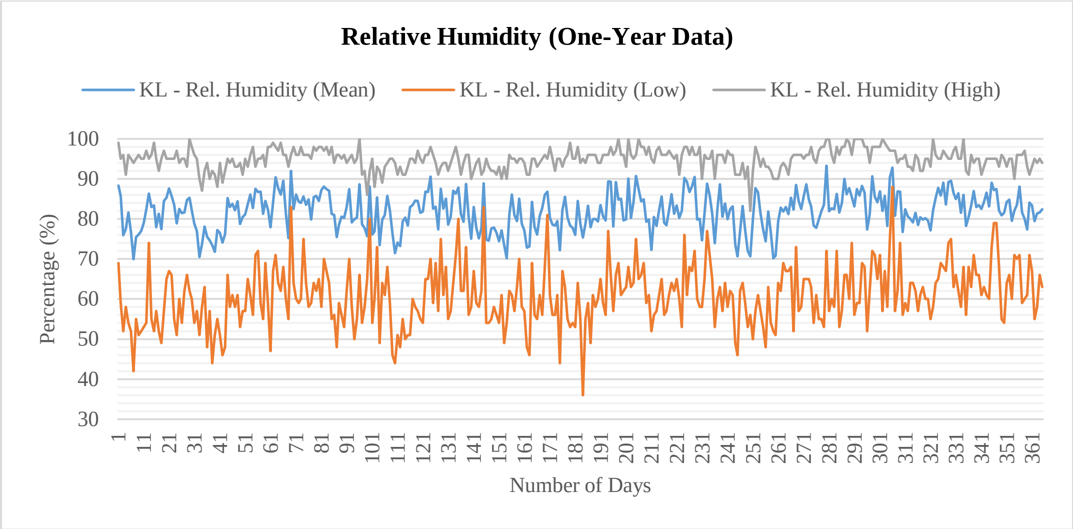


Figure 2.6: Relative humidity (full year) for Kuala Lumpur (Milne, 2016)

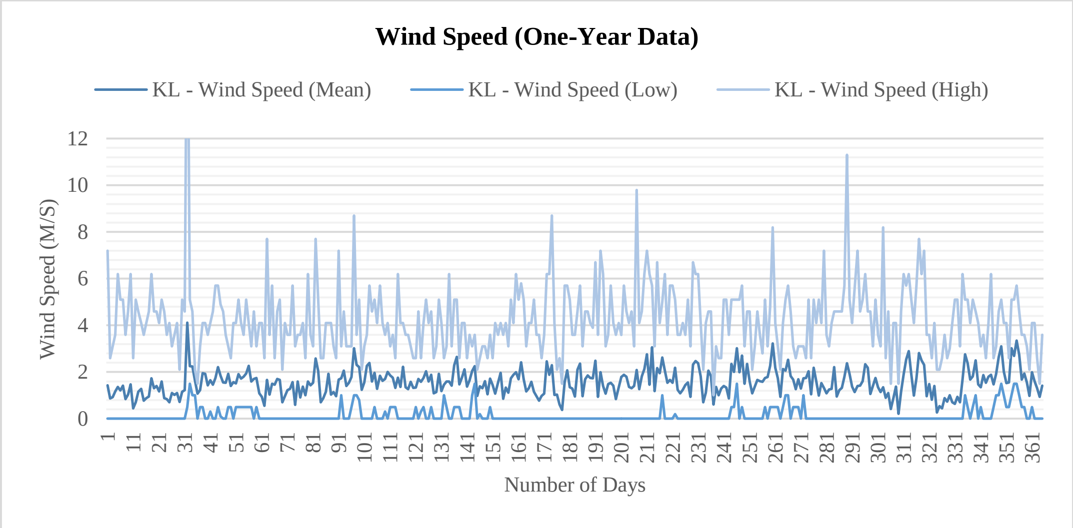


Figure 2.7: Wind speed (full year) for Kuala Lumpur (Milne, 2016)

Located near to equatorial line, this city has almost equal 12 hours period of day and night all year round. Generally, the daytime in Malaysia starts at 7 am and finishes at 7 pm. The high temperature of over 30°C usually starts from 9 am until 9 pm every day with peak times from 2 pm to 5 pm (Figure 2.8). However, from 9 am to 9 pm the humidity will reach as low as 40%. The city only experiences high humidity from 9 pm to 9 am which generally is above 70% (Figure 2.9). With a low diurnal temperature in between 5°C to 10°C (MET, 2019), Kuala Lumpur receives low air movement in between 1.5 m/s to 2.0 m/s and colder wind generally comes from the North (946 hours, 29%), North-West (593 hours, 18%) and East (430 hours, 13%) (Tang & Chin, 2013) (Figure 2.10). Due to the urban roughness, the wind movement in this city becomes non-uniform, inefficient and unreliable (Lechner, 2014; Mohd Sahabuddin & Gonzalez-Longo, 2017). As for comparisons, the suggested operative temperature range for naturally ventilated spaces according to Kuala Lumpur's outdoor mean temperature is between 24°C and 28.4°C (ASHRAE, 2013). Whereas, for relative humidity and airspeed, the ASHRAE Standard 55 is set below 65% RH and between 0.15 m/s to 0.80 m/s respectively.

This indicates that when using natural ventilation approaches without any assistance from a fan, the indoor comfort conditions are almost impossible to achieve (Mohd Sahabuddin & Gonzalez-Longo, 2018). Hence, in this kind of environment, constant air movement has an important role in determining the indoor thermal comfort. It could be deduced that the most crucial time for thermal comfort in Kuala Lumpur is between 9 am to 9 pm where the ambient air temperature will gradually increase and reach its peak. At the same time, the wind speed at this period will be significantly low where for stimulating evaporative cooling, it shall be constantly moving at a minimum rate. Generally, the three possibilities associated with indoor discomfort in high-rise residential buildings in Kuala Lumpur are high air temperature, high humidity and low air movement. The high ambient air temperature from urban heat island effects (Yusuf, Pradhan, & Idrees, 2014), is the result of the combination of direct solar radiation, diffuse radiation from the skydome and reflected radiation from both adjacent buildings and hard surfaces in urban areas (Mohd Sahabuddin & Gonzalez-Longo, 2017). It has increased heat penetration into indoor spaces through convection, conduction and radiation effects (Chenvidyakarn, 2013; Nave, 2012).

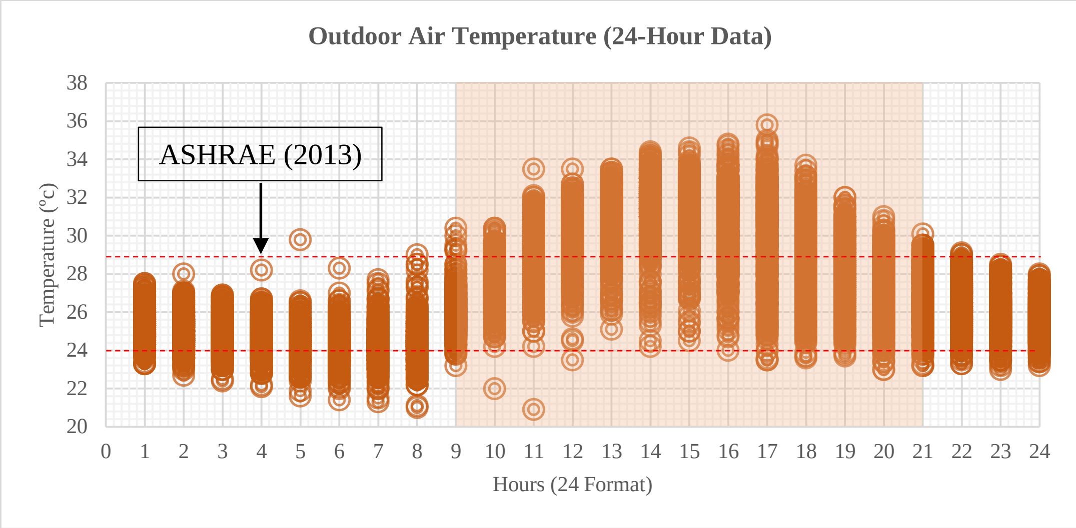


Figure 2.8: Outdoor air temperature (24-hour) for Kuala Lumpur (Milne, 2016)

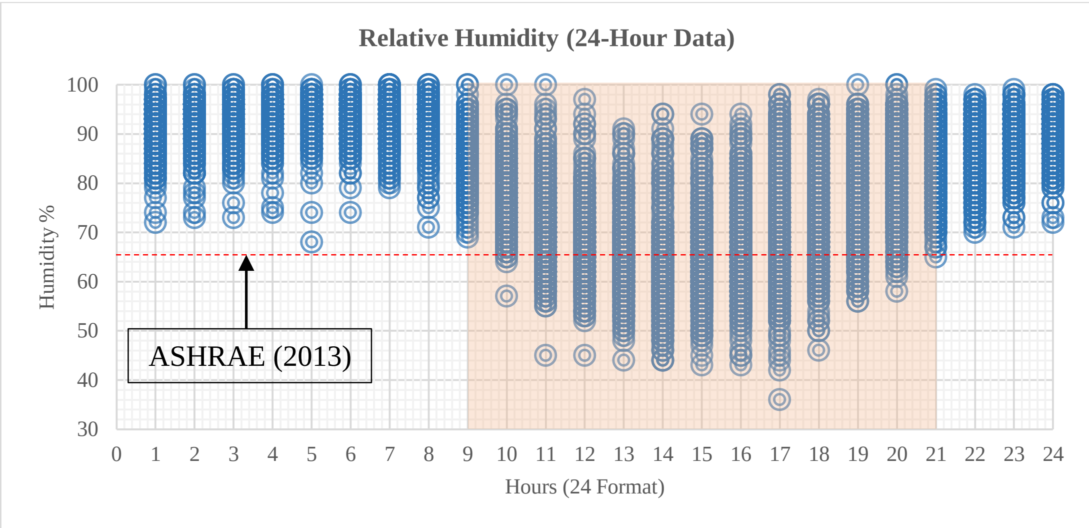


Figure 2.9: Relative humidity (24-hour) for Kuala Lumpur (Milne, 2016)

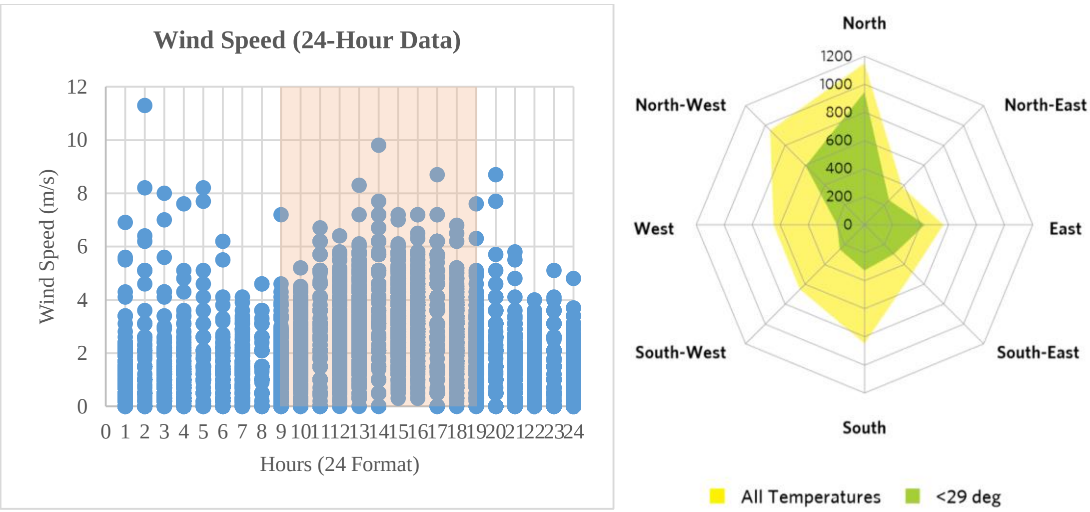
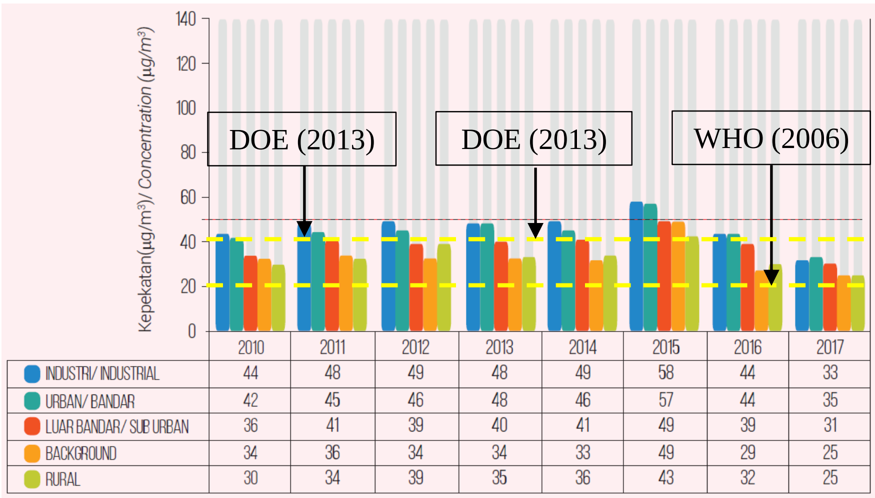


Figure 2.10: Wind speed and hours of wind direction for Kuala Lumpur (Milne, 2016; Tang & Chin, 2013)

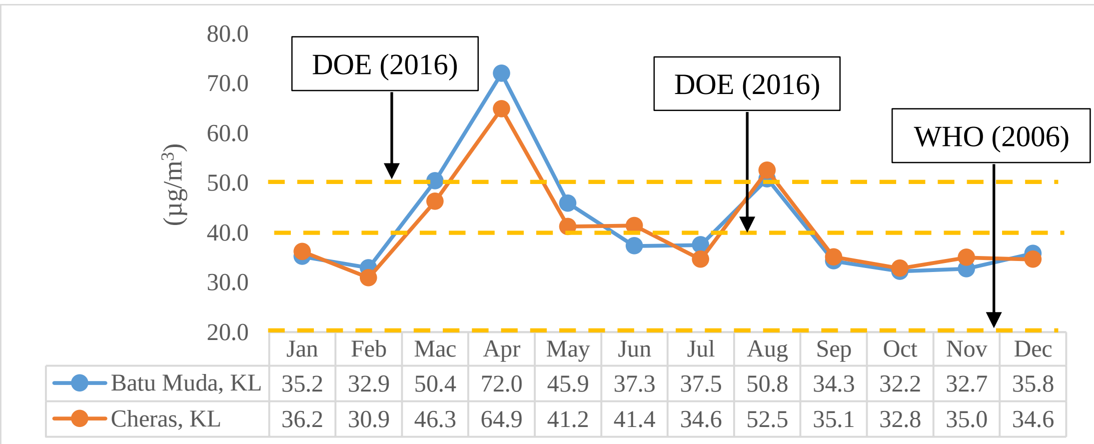
2.2.2 Outdoor Air Quality Conditions

Since 2000, DOE has continuously monitored four selected air pollutants – PM_{10}, SO_2, NO_2, O_3 and CO, in 65 locations in Malaysia (DOE, 2017). They have established the background data for the pollutants by different land-use: industrial, urban, suburban and rural (DOE, 2017). For particulate matter, the PM_{10} concentrations in industrial and urban areas were significantly higher compared to the other areas in Malaysia (DOE, 2015, 2016a, 2017) (Figure 2.11). The annual concentrations of the substance in urban areas from 2010 to 2017 were between 42 µg/m^3 to 57 µg/m^3 (DOE, 2017), which surpassed the DOE's standard for 2020 of 40 µg/m^3 (DOE, 2013) and WHO's standard of 20 µg/m^3 (WHO, 2006). Moreover, two datasets obtained from DOE in two air quality stations in Kuala Lumpur (Batu Muda and Cheras stations) have found that the PM_{10} concentrations during the dry season in Kuala Lumpur surpassed the WHO and DOE limits (Figure 2.12).



	2010	2011	2012	2013	2014	2015	2016	2017
INDUSTRI/ INDUSTRIAL	44	48	49	48	49	58	44	33
URBAN/ BANDAR	42	45	46	48	46	57	44	35
LUAR BANDAR/ SUB URBAN	36	41	39	40	41	49	39	31
BACKGROUND	34	36	34	34	33	49	29	25
RURAL	30	34	39	35	36	43	32	25

Figure 2.11: Annual PM_{10} average concentrations from 2010 to 2017 (DOE, 2017)



	Jan	Feb	Mac	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Batu Muda, KL	35.2	32.9	50.4	72.0	45.9	37.3	37.5	50.8	34.3	32.2	32.7	35.8
Cheras, KL	36.2	30.9	46.3	64.9	41.2	41.4	34.6	52.5	35.1	32.8	35.0	34.6

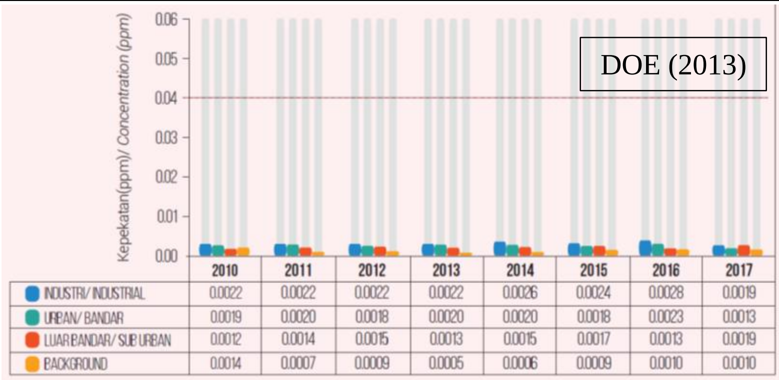
Figure 2.12: Monthly PM_{10} average concentrations in Kuala Lumpur for 2016

The major contributor to SO_2 emissions is petrol engines (Watkins, 1991). According to DOE, the annual average concentrations of SO_2 in Malaysia from 2010 to 2017 were significantly lower than the DOE limit of 0.04 ppm. The graphs also propose that the SO_2 concentrations in industrial and urban areas were higher than in suburban areas (Figure 2.13). Even though the SO_2 concentrations in urban areas were higher, the monthly SO_2 concentrations in Kuala Lumpur in 2016 were consistently recorded low than the DOE's limit. In general, SO_2 concentrations in this city could be considered insignificant and not at harmful levels.

Almost 85% of CO emissions come from vehicles especially petrol engines at low speeds (Watkins, 1991). Accommodating a high volume of motor vehicles makes CO concentrations in urban areas to be normally high. The annual average concentrations of CO in urban and industrial areas were higher than in other areas from 2010 to 2017 (Figure 2.14). However, the concentrations were still very low and below the DOE limit. The differences between urban and suburban areas seem to get closer due to the majority of the people live in suburban areas – commuting by cars from homes to workplaces.

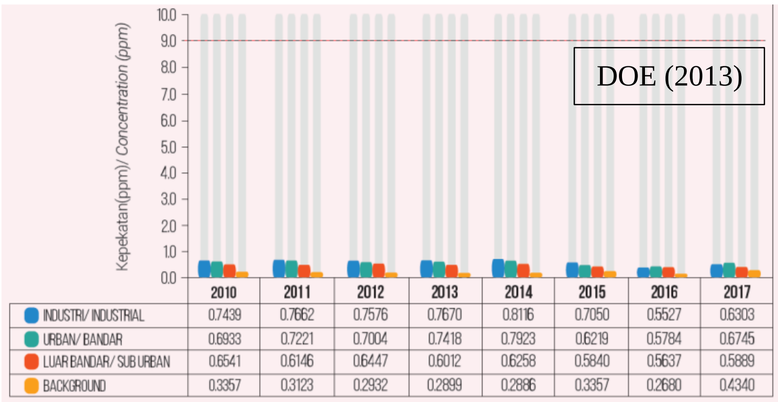
Like CO, NO_2 is another substance that comes from motor vehicles and nearly 70% was from petrol engines (Watkins, 1991). Urban and industrial areas are the locations with high NO_2 concentrations in Malaysia due to a high volume of motor vehicles and machinery (2.15). The concentration patterns are consistent from 2010 to 2017 which are far below from the DOE limit of 0.17 ppm. It could be deduced that the NO_2 concentrations in Kuala Lumpur are lower - 0.02 ppm to 0.05 ppm and do not reach harmful levels.

The other air pollution substance listed in the DOE standard is O_3. This substance is contained in many household items including aerosol deodorants and fridges (Fuller, 2018). This substance at ground level is hazardous and due to that, the 1987 Montreal Protocol was signed by many countries to control the production and use of ozone-depleting substances (Fuller, 2018). The concentration levels of O_3 in Malaysia are at moderate levels, especially for urban and industrial areas. In urban areas, the O_3 concentrations are consistently at half (0.05 ppm) of the DOE limit (0.1 ppm) from 2010 to 2015 (Figure 2.16). However, the level was significantly reduced in 2016 and 2017 at less than 0.02 ppm.



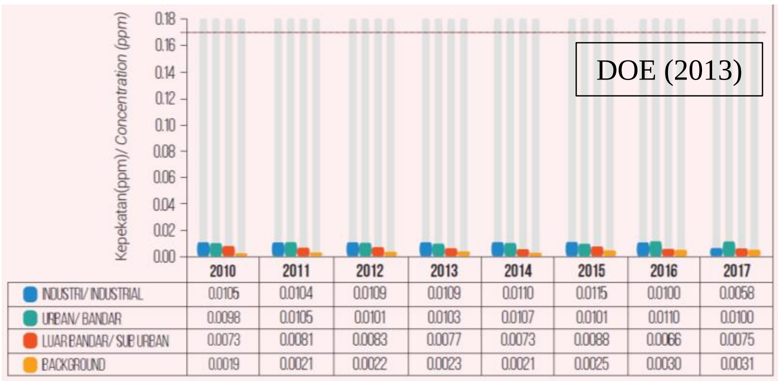
	2010	2011	2012	2013	2014	2015	2016	2017
INDUSTRI/ INDUSTRIAL	0.0022	0.0022	0.0022	0.0022	0.0026	0.0024	0.0028	0.0019
URBAN/ BANDAR	0.0019	0.0020	0.0018	0.0020	0.0020	0.0018	0.0023	0.0013
LUAR BANDAR/ SUB URBAN	0.0012	0.0014	0.0015	0.0013	0.0015	0.0017	0.0013	0.0019
BACKGROUND	0.0014	0.0007	0.0009	0.0005	0.0006	0.0009	0.0010	0.0010

Figure 2.13: Annual SO_2 average concentrations from 2010 to 2017 (DOE, 2017)



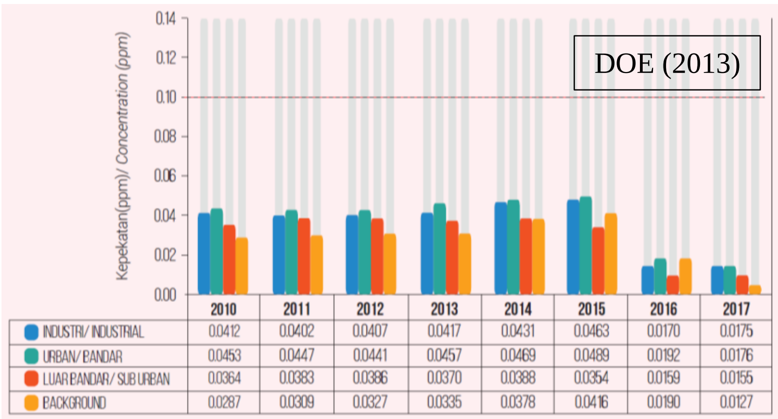
	2010	2011	2012	2013	2014	2015	2016	2017
INDUSTRI/ INDUSTRIAL	0.7439	0.7662	0.7576	0.7670	0.8116	0.7050	0.5527	0.6303
URBAN/ BANDAR	0.6933	0.7221	0.7004	0.7418	0.7923	0.6219	0.5784	0.6745
LUAR BANDAR/ SUB URBAN	0.6541	0.6146	0.6447	0.6012	0.6258	0.5840	0.5637	0.5889
BACKGROUND	0.3357	0.3123	0.2932	0.2899	0.2886	0.3357	0.2680	0.4340

Figure 2.14: Annual CO average concentrations from 2010 to 2017 (DOE, 2017)



	2010	2011	2012	2013	2014	2015	2016	2017
INDUSTRI/ INDUSTRIAL	0.0105	0.0104	0.0109	0.0109	0.0110	0.0115	0.0100	0.0058
URBAN/ BANDAR	0.0098	0.0105	0.0101	0.0103	0.0107	0.0101	0.0110	0.0100
LUAR BANDAR/ SUB URBAN	0.0073	0.0081	0.0083	0.0077	0.0073	0.0088	0.0066	0.0075
BACKGROUND	0.0019	0.0021	0.0022	0.0023	0.0021	0.0025	0.0030	0.0031

Figure 2.15: Annual NO_2 average concentrations from 2010 to 2017 (DOE, 2017)



	2010	2011	2012	2013	2014	2015	2016	2017
INDUSTRI/ INDUSTRIAL	0.0412	0.0402	0.0407	0.0417	0.0431	0.0463	0.0170	0.0175
URBAN/ BANDAR	0.0453	0.0447	0.0441	0.0457	0.0469	0.0489	0.0192	0.0176
LUAR BANDAR/ SUB URBAN	0.0364	0.0383	0.0386	0.0370	0.0388	0.0354	0.0159	0.0155
BACKGROUND	0.0287	0.0309	0.0327	0.0335	0.0378	0.0416	0.0190	0.0127

Figure 2.16: Annual O_3 average concentrations from 2010 to 2017 (DOE, 2017)

Based on the findings, it could be deduced that the main substances that have been dominating the air pollution in Malaysia and its urban areas are PM_{10} and $PM_{2.5}$. This is consistent with a long-term monitoring exercise (all year round) done by Rahman et al. (2015) from 2002 to 2011. Their study found that the annual average for PM_{10} and $PM_{2.5}$ were 48.4 µg/m^3 and 26.1 µg/m^3 respectively (S. A. Rahman et al., 2015). Both values surpassed the annual limits set by WHO. Accordingly, the PM_{10} and $PM_{2.5}$ particles have been widely studied by many researchers (Cionita et al., 2014; Keywood et al., 2003; Leh, Ahmad, Aiyub, Jani, & Hwa, 2012; Mediastika, 1999; Payus, Abdullah, & Sulaiman, 2013; S. A. Rahman et al., 2015), proposing that this substances are crucial to be included in this research.

The other monitoring work conducted by the DOE suggests that the annual average for PM_{10} from 2000 to 2015 in urban areas in Kuala Lumpur was 48.0 µg/m^3 (DOE, 2016a). Similarly, the value surpassed the WHO limits. It is undeniable that both PM_{10} and $PM_{2.5}$ concentrations in Kuala Lumpur, in outdoor spaces – short or long term, are well above the WHO recommendations (Table 2.1). Khan, F. et al. (2015) suggested that the concentrations of PM_{10} were higher during weekdays than weekends in Kuala Lumpur. This confirms that high traffic during weekdays has a big impact on PM_{10} concentrations in urban areas (Cionita et al., 2014; Khan et al., 2015).

Table 2.1: Comparison of fieldwork studies in Kuala Lumpur with WHO concentration limits

Parameters	**Duration**	**Rahman et al. (2002 – 2011)[1]**	**DOE Dataset (2000 – 2015)[2]**	**WHO Limits[3]**
Sampling Location		Outdoor	Outdoor	
Mean PM_{10} (µg/m^3)	(24 hours)	-	-	50.0
	(1 Year)	48.4	48.0	20.0
Mean $PM_{2.5}$ (µg/m^3)	(24 hours)	-	-	25.0
	(1 year)	26.1	-	10.0

Notes:
[1] Rahman et al. (2015)
[2] Department of Environment (DOE), Malaysia (2016)
[3] WHO Ambient Air Quality Guidelines (2006)

2.2.3 Critical Conditions for Indoor Comfort in Kuala Lumpur

Establishing Kuala Lumpur's outdoor thermal and air quality conditions provide the actual understanding of the critical issues regarding indoor comfort in Kuala Lumpur urban areas. Based on the findings discussed earlier, there are four crucial conditions that are related to each other that need to be considered in achieving indoor comfort in Kuala Lumpur. The conditions are high air temperature, high humidity, high air pollution and low air movement.

High ambient air temperature (above 30°C) especially from 9 am to 9 pm, decreases the possibilities of outdoor and indoor thermal comfort. Staying indoors is one of the best options to avoid this discomfort environment. However, without proper ventilation, heat will build-up in indoor spaces. Allowing the heat from ambient air through natural ventilation will consequently raise the meant radiant temperature of indoor surfaces. These surfaces will store heat and release it at night and creating high operative temperatures in both day and night hours. Thus, design effort should be made to optimise ventilation potential in indoor spaces (Yang, Qian, & Lau, 2013) that mitigate the effect of high ambient air temperature.

Even though humidity has minimum influence on indoor comfort (40 – 70%RH only), high daytime temperatures combined with the high humidity create great discomfort (Lechner, 2014). The high humidity prevents the occupants to cool themselves through sweating. Furthermore, in an environment that has an operative temperature above 26°C to 28°C, the skin damped with sweat may become apparent especially for lightly clothed people (CIBSE, 2015). In hot humid climates, reducing the indoor air temperature together with humidity or at least minimising it, is a big challenge (Roaf, 2012).

In an environment that has higher humidity but lower air movement, thermal comfort also seems difficult to achieve (Djamila et al., 2014). Air movement is the key factor for indoor comfort (Tahir et al., 2010) and the constantly moving air will ensure the condition (Mohd Sahabuddin & Gonzalez-Longo, 2018). Air movement stimulates thermal comfort through heat-loss rate by both convection and evaporation (Lechner, 2014). Supplying a constant air movement is very much demanded in this kind of climate.

Good air quality is mandatory in any habitable spaces. Kuala Lumpur, a city located in a hot and humid climate, accommodates high volume of traffic daily, therefore, its ambient air quality is generally not at satisfactory level. The air pollution in the city comes from many sources, locally – domestic open burnings, vehicles and construction activities (H. A. Rahman, 2013) and also regionally – haze from land clearing of agriculture activities in neighbouring regions (Fuller, 2018). Not only during the haze periods (normally during dry season), airborne particulate matter was also found as the major pollutant in normal days (Payus et al., 2013).

It could be deduced that the four common factors associated with indoor discomfort and unhealthy environment in high-rise residential buildings in tropical urban areas are high air temperature (Ardalan Aflaki, Mahyuddin, Manteghi, & Baharum, 2014; Jamaludin et al., 2015), high humidity (CIBSE, 2015; Lechner, 2014), high air pollution (Leh et al., 2012; Mohd Firrdhaus Mohd Sahabuddin & Cristina Gonzalez-Longo, 2019) and low air movement (Djamila et al., 2014; Jamaludin et al., 2015). These conditions are critical for achieving indoor comfort in Kuala Lumpur.

2.3 International Standards and Local Regulations

2.3.1 Thermal Comfort

Defining thermal comfort conditions in Southeast Asia (SEA) region dates back as early as 1953 (Hijazi, 2018), where a number of studies were established for the indoor temperature ranges in Singapore, Thailand, Indonesia and Malaysia. These studies were conducted in 1953 to 2014 and recommendations made were for mechanically, naturally and hybrid ventilated buildings (Table 2.2). These findings show a variety of thermal comfort temperatures with the lowest of 20.8°C to the highest of 31.0°C. However, it was found that the average lowest temperature for all the studies listed in Table 2.2 is 24.2°C and the average highest temperature is 28.6°C.

Table 2.2: Comfort ranges of the indoor thermal condition in SEA region (Hijazi, 2018; Mohd Sahabuddin, 2012; MS1525, 2014).

Year	Author(s)	Type of Study	SEA Country	Ventilation Approach	Temperature range (°C)
1953	Ellis	Field study	Singapore	Natural	24.4 to 29.4
1992	Busch	Field study	Thailand	Mechanical	23.0 to 28.0
1997	Zain Ahmed et al.	Field study	Malaysia	Hybrid	24.5 to 28.0
2000	Karyono	Field study	Indonesia	Hybrid	23.3 to 29.5
2000	Khedari et al.	Field study	Thailand	Natural	27.0 to 31.0
2001	Sapian et al.	Field study	Malaysia	Natural	26.0 to 29.5
2001	Ismail & Barber	Field survey	Malaysia	Mechanical	20.8 to 28.6
2005	Sh Ahmad	Simulation	Malaysia	Natural	23.6 to 28.6
2012	Mohd Sahabuddin	Simulation	Malaysia	Natural	25.0 to 27.0
2014	SIRIM	Simulation	Malaysia	Mechanical	24.0 to 26.0

Another method to define comfort temperature is by using equations. In 2002, Humphrey established an equation to predict comfort temperature (***Tn***) in a naturally ventilated building using outdoor monthly mean temperature (***To***) (Nicol & Humphreys, 2002). The equation is:

$$Tn = 11.9 + 0.534\,To \quad \textit{(Equation 2.1)}$$

In July 2017 (during dry season), Kuala Lumpur received an average outdoor air temperature of 29°C (MET, 2017b). Considering this and in accordance with the Humprey's equation, the comfort temperature that should be aimed for is 27.4°C.

CIBSE Guide A (2015) has also established two equations to predict the upper and lower margins of indoor comfort temperature in free-running operation buildings. The equations are:

a) Upper margin: $\vartheta com = 0.33\,\vartheta rm + 20.8$ *(Equation 2.2)*

b) Lower margin: $\vartheta com = 0.33\,\vartheta rm + 16.8$ *(Equation 2.3)*

where ϑcom is the comfort temperature (°C) and ϑrm is the mean of the daily mean outdoor temperature (°C).

Based on the equations and the daily mean outdoor temperature in Kuala Lumpur that was 24°C (Milne, 2016). The lower margin of the comfort temperature is 24.7°C and the upper margin is 28.7°C. Therefore, building designers and architects should aim for indoor comfort temperature (in naturally ventilated buildings) with the range of 24.7°C to 28.4°C (CIBSE, 2015). Even though the equations were developed using the data collected primarily in European office buildings, the indoor comfort temperatures suggested are in line with the average lowest and highest temperatures established in all ten studies in Table 2.2. For relative humidity and airspeed, the ranges provided by the CIBSE Guide A are 40% to 70% RH and 0.15 m/s to 0.50 m/s respectively (Table 2.3).

ASHRAE Standard 55 has also set different figures for comfort criteria. Using its 'acceptable operative temperature ranges for naturally conditioned spaces' diagram (Figure 2.17), the suggested temperature range according to Kuala Lumpur's mean monthly outdoor air temperature of 27°C (Milne, 2016) is between 24.0°C and 28.4°C (ASHRAE, 2013). This figure 'is based on an adaptive model of thermal comfort that derived from global database of 21,000 measurements taken primarily in office buildings' (ASHRAE, 2013). For relative humidity and airspeed, the standard has set below 65% RH and between 0.15 m/s to 0.80 m/s respectively (Table 2.3).

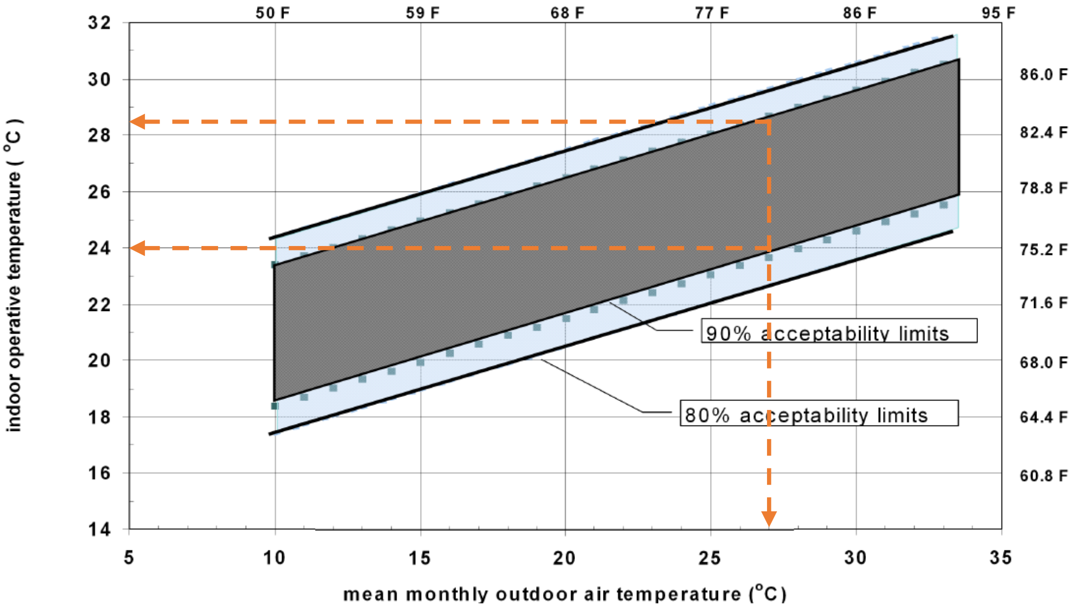


Figure 2.17: Acceptable operative temperature ranges for naturally conditioned spaces (ASHRAE, 2013)

In Malaysia, at the moment, only Malaysian Standard (MS1525) - 'Energy Efficiency and Use of Renewable Energy for Non-Residential Buildings', set the indoor design conditions for air temperature (24°C to 26°C), relative humidity (50 to 70%RH) and airspeed (0.15 to 0.50 m/s) (MS1525, 2014). Unlike CIBSE and ASHRAE standards, these design conditions are for air-conditioned spaces only.

Table 2.3: International and local guidelines for thermal comfort in Kuala Lumpur

Parameters	**CIBSE Guide A (2015)**	**ASHRAE 55 (2013)**	**MS1525 (2014)**
	Recommended Thermal Comfort Criteria		
Operative Temperature	24.7 – 28.7ºC	24.0°C – 28.4ºC	24.0°C – 26.0ºC
Relative Humidity	40 – 70 %RH	<65 %RH	50 – 70 %RH
Air Speed	0.15 – 0.50 m/s	0.15–0.80 m/s	0.15 – 0.50 m/s

For this research purposes, the thermal comfort conditions set by ASHRAE Standard 55 and CIBSE Guide A will be used as the main references and for comparison purposes. The selection of these standards is because of their global reputations as leading organisations in HVAC studies. For SEA region, the ASHRAE Standard 55 used 2,680 data samples to develop thermal comfort criteria that were collected in Singapore, Thailand and Indonesia (De Dear, 1998).

2.3.2 Indoor Air Quality

As a major issue worldwide, which urgently needs to be addressed, many organisations have produced guidelines and recommendations to measure and monitor the limits for various types of airborne pollutants. Some guidelines are designed for industrial environments [the U.S. Occupational Safety and Health Administration (OSHA) and National Institute for Occupational Safety and Health (NIOSH)], some are for outdoor environments [National Ambient Air Quality Standards (NAAQS)], and others are general [World Health Organization (WHO)] or indoor residential environment-related (Canadian) (ASHRAE, 2016a). Even though most of the standards have established the air quality conditions for outdoor environment, the use of the recommendations for an indoor environment is also applicable because the exposure limit in outdoors is the same as indoors (WHO, 2006).

The DOE has carried out the Environmental Quality Reports in 2015, 2016 and 2017 which have found that the particulate matter (PM_{10}) was the predominant pollutant that caused unhealthy conditions during the dry season in Peninsular Malaysia (DOE, 2015, 2016a, 2017). The reports have also suggested that the daily concentrations of PM_{10} for Klang Valley (including Kuala Lumpur) were higher than other stations in suburban and rural areas (DOE, 2016c). Hence, particulate matter (PM_{10} and $PM_{2.5}$) and their limits in established international and local standards will be discussed in detail.

WHO, through its 'air quality guidelines for particulate matter, ozone, nitrogen dioxide and sulphur dioxide', has set the annual limits for PM_{10} and $PM_{2.5}$ which are not more than 20 µg/m^3 and 10 µg/m^3, respectively (WHO, 2006). For the 24-hour period, the limit for PM_{10} is 50 µg/m^3 and $PM_{2.5}$ is 25 µg/m^3. Whereas, the CIBSE KS17 only sets the limits for PM_{10}, that should not be more than 50 µg/m^3 (annual limit) and 150 µg/m^3 (24-hour limit). ASHRAE 62.1 using NAAQS standard has proposed 50 µg/m^3 and 15 µg/m^3 for PM_{10} and $PM_{2.5}$ for annual limits. For 24-hour limits, the standard recommended 150 µg/m^3 and 65 µg/m^3 for PM_{10} and $PM_{2.5}$ respectively (Table 2.4).

In 2013, Department of Environment Malaysia (DOE) has published a new 'Malaysia Ambient Air Quality Standard' which has listed six air pollution substances namely PM_{10}, $PM_{2.5}$, sulphur dioxide (SO_2), nitrogen dioxide (NO_2), ground-level ozone (O_3) and carbon monoxide (CO) together with their standard limits (Table 2.5). This new standard was established in order to replace the older 'Malaysia Ambient Air Quality Guideline' that was implemented since 1989. There are three interim targets (IT) which are interim target 1 (IT-1) in 2015, interim target 2 (IT-2) in 2018 and the full implementation of the standard in 2020 (DOE, 2013). In 2020, the organisation has set that PM_{10} and $PM_{2.5}$ annual limits are 40 µg/m^3 and 15 µg/m^3 respectively. For 24-hour limits, the targets for 2020 are 100 µg/m^3 (PM_{10}) and 35 µg/m^3 ($PM_{2.5}$) (Table 2.5).

Table 2.4: International and local ambient air quality guidelines and standards

Parameters	**WHO [1] (2006)**		**CIBSE KS17 [2] (2012)**		**ASHRAE 62.1 [3] (2016)**		**DOE Malaysia [4] (2013)**	
	1 year	24-Hrs	1 year	24-Hrs	1 year	24-Hrs	1 year	24-Hrs
	µg/m^3		µg/m^3		µg/m^3		µg/m^3	
PM_{10}	20	50	50	150	50	150	40	100
$PM_{2.5}$	10	25	-	-	15	65	15	35

Notes:
[1] WHO Ambient Air Quality Guidelines (2006)
[2] Indicated exposure limits for selected airborne pollutants (2012)
[3] The concentration of interest for selected contaminants (2016)
[4] New Malaysia Ambient Air Quality Standard (Department of Environment Malaysia) (2013)

Table 2.5 New Malaysia Ambient Air Quality Standard (DOE, 2013)

Pollutants	Averaging Time	Ambient Air Quality Standard		
		IT-1 (2015)	**IT-2 (2018)**	**Standard (2020)**
		µg/m^3	**µg/m^3**	**µg/m^3**
Particulate Matter with the size of less than 10 micron (PM_{10})	1 Year	50	45	40
	24 Hour	150	120	100
Particulate Matter with the size of less than 2.5 micron ($PM_{2.5}$)	1 Year	35	25	15
	24 Hour	75	50	35
Sulfur Dioxide (SO_2)	1 Hour	350	300	250
	24 Hour	105	90	80
Nitrogen Dioxide (NO_2)	1 Hour	320	300	280
	24 Hour	75	75	70
Ground Level Ozone (O_3)	1 Hour	200	200	180
	8 Hour	120	120	100
***Carbon Monoxide (CO)**	1 Hour	35	35	30
	8 Hour	10	10	10

*mg/m^3

For this research purposes, the guidelines set by WHO will be used for the main reference and comparison. The selection of these guidelines is because of the organisation that has high reputation as a well-known organisation in dealing with health issues across the world. Their operation started in 1946 to promote health, keep the world safe, and serve the vulnerable. They have employed approximately 7,000 representatives in 150 country offices, in six regions including Southeast Asia (WHO, 2019).

2.3.3 Regulations and Green Rating Tools

In shaping building designs that emphasise indoor comfort – thermal and air quality, it needs a set of building regulations, standards and green rating tools with comprehensive information and tailored with the local climate. The mandatory building regulations in Malaysia which are the 'Uniform Building By-Laws' (UBBL), gazetted in 1984 and these are based on the recommendations provided by the UK's Building Research Establishment (BRE) (Mohd Sahabuddin & Gonzalez-Longo, 2017); these recommendations were previously applied in Kuala Lumpur and Singapore, both British colonies until 1957 (Said, 2011). However, the UBBL does not take Malaysia's hot-humid climate and the issues concerning air pollution and carbon emissions in full account (Mohd Sahabuddin & Gonzalez-Longo, 2017).

In terms of ventilation, the regulations establish that the minimum size of openings for natural ventilation purposes in residential buildings should not be less than 10% of the total clear area of the room (UBBL, 2013), a requirement which has remained unchanged for 33 years. There have been recent developments concerning the use of green rating tools in Malaysia, which are helping to improve the sustainable design of buildings and the health of their occupants. Reviewing these existing regulations and green rating tools could explore the full potential of residential buildings in Kuala Lumpur that could substantially reduce carbon emissions while ensuring a comfortable and healthy internal environment for the occupants especially in high-rise residential buildings.

The UBBL is contained within the 'Street, Drainage and Building Act' (SDBA) 1974. The requirements for natural ventilation in residential buildings are established in the 3rd part of the regulations: 'Space, Light and Ventilation' under clauses 39(1), 39(4), 40(1) and 40(2). However, they are only concerned about the proportion of windows and size of light-wells and also not specifying any regulations on achieving healthy indoor air quality.

Clause 39(1) states that 'every room designed, adapted or used for residential purposes, shall be provided with natural ventilation by means of one or more windows having a total area of not less than 10% of the clear floor area of such room and shall have openings capable of allowing a free uninterrupted passage of air of not less than 5% of such floor area' (UBBL, 2013). Clause 39(4) determines that 'every watercloset, latrine, urinal and bathroom should be provided with natural ventilation by means of one or more openings having a total area of not less than 0.2 sqm' from the room's total area (UBBL, 2013). For buildings that are more than eight storeys high, clause 40(1), establishes that the minimum size of light-wells should not be less than 15 sqm, being the minimum width 2.5 metres, and clause 40(2) requires the minimum size of each light-well for lavatories, water closets and bathrooms shall be 5.5 sqm and 2.0 metres minimum width (UBBL, 2013).

Malaysia, like many other countries, has recently developed several green rating tools. Three most popular green rating tools used by both private and public sectors are the Green Building Index (GBI), the Green Real Estate (GreenRE) and Malaysian Carbon Reduction & Environmental Sustainability Tool (MyCREST). However, so far only GBI and GreenRE were being in use for residential buildings (Malaysia Green Building Confederation - MGBC, 2014; REHDA, 2015).

The first green rating tool used in Malaysia was the GBI, initiated in 2009 by a private organisation, the Malaysian Green Building Corporation (Malaysia Green Building Confederation - MGBC, 2014). Until October 2015, approximately 327 buildings have been rated by GBI and 41% of them were residential (Malaysian Green Building Corporation - MGBC, 2017). Although the tool refers to UBBL 1984 for a minimum percentage of openings, in its latest version for 'Residential New Construction' published in 2014, some natural ventilation strategies have been proposed. These include the provision of light-wells to promote the stack effect (as can be seen, already considered by UBBL), open plan layouts to promote cross-ventilation, shading devices or overhangs to protect windows from sun radiation and naturally ventilated public spaces. This rating tool also encourages the use of low 'Volatile Organic Compounds' (VOCs) materials and finishes to reduce the indoor air pollutants, but in terms of thermal comfort, there is no minimum air movement and indoor air temperature recommendations have been made.

Another private organisation, the 'Real Estate Housing Development Association', created GreenRE in 2013 (REHDA, 2015). This tool proposes several strategies to enhance natural ventilation in residential buildings. In addition to the strategies previously proposed by GBI such as the use of open-plan layouts to promote cross-ventilation and the provision of public spaces naturally ventilated, GreenRE encourages a more appropriate orientation of buildings, so that they face prevailing winds. The latest version of the tool, 'Design Reference Guide for Residential Building and Landed Home' published in 2015, recommends a provision of no less than 0.6 m/s average air movement in indoor spaces (REHDA, 2015) and avoiding VOC materials to achieve good indoor air quality. In the case of GBI, there are no recommendations for the minimum percentage of openings or indoor air temperature set.

MyCREST was created by a collaborative effort of several government agencies such as the Ministry of Works, Public Works Department of Malaysia (PWD) and the Construction Industry Development Board Malaysia (CIDB) in 2016 (CIDB, 2016). This document at the moment is available only for non-residential buildings. In order to maintain good quality in the indoor air, this tool requires that all naturally ventilated spaces should be 'permanently open to and within 7.6 metres of the operable wall or roof openings and that operable area is at least 4% of the net occupiable area' (CIDB, 2016).

This figure is much lower than the 10% required by Clause 39 in UBBL and these researchers have considered that the minimum opening percentage in high-rise residential buildings should not be considered equally and should have a variety of sizes depending on the location and height (Mohd Sahabuddin & Gonzalez-Longo, 2015). MyCREST proposes that the minimum average of air movement for naturally ventilated spaces should be no less than 0.6 m/s. Similar to the other two green rating tools, MyCREST considers that the sources of air pollution are mainly from materials that contain VOC only (CIDB, 2016).

This entire situation in the current scenario is concerned about the regulations and green rating tools, needs some clarification concerning the parameters they consider. Although there are significant improvements in the recent development of MyCREST tool, Malaysia needs to address the need for a revision of its building regulations so that residential buildings are designed to minimise their carbon emissions and improve the health and comfort of the occupants. Table 2.6 compares the indoor comfort initiatives established in the regulations, standards and the green rating tools used in Malaysia, as discussed above.

Table 2.6: Comparison of indoor comfort strategies in the regulations, standards, and green rating tools in Malaysia

Areas		Recommendations (Latest Version)	UBBL (2013)	*MS1525 (2014)	GBI (2014)	GreenRE (2015)	MyCREST (2016)
Mandatory	Regulations (Ventilation)	• (%) of openings of the clear floor area – Clause 39(1)	10%	-	-	-	4%
		• (%) of uninterrupted openings – Clause 39(1)	5%	-	-	-	-
		• Every toilet /bathroom should be naturally ventilated – Clause 39(4)	0.2 sqm/wc	√	√	√	√
		• Light-well or wind chimney for promoting stack effect – Clause 40(1)	$15m^2$ (>8 stories)	√	√	-	-
Thermal Comfort	Air Movement	• Suggest internal air speed	-	0.15-0.50 m/s	-	>0.6 m/s	0.6 m/s
		• Use vented skylights	-	-	-	-	√
		• Promote ventilation in between rooms	-	-	-	-	√
		• Use cross ventilation	-	√	√	√	√
		• Implement open plan arrangement	-	√	√	√	√
		• Roof space should be ventilated	-	-	-	-	√
		• Buildings layout should face prevailing winds	-	√	-	√	√
		• Suggest louvres and wing walls	-	√	-	-	√
		• Suggest fans for constant air movement	-	√	-	-	√
	Air Temperature	• Suggest preferred internal air temperature	-	24-26 ^{o}C	-	-	-
		• Methods for reducing heat from the incoming air intake	-	-	-	-	-
		• Methods for removing heat from indoor spaces	-	-	-	-	-
	Relative Humidity	• Suggest preferred internal humidity	-	50-70%	-	-	-
		• Methods for reducing moisture in the incoming air intake	-	-	-	-	-
		• Methods for removing moisture from indoor spaces	-	-	-	-	-
IAQ	Indoor Air Quality (IAQ)	• Methods for reducing particulate matter and toxic gases from the incoming air intake	-	-	-	-	-
		• Methods for removing indoor contaminants from indoor spaces	-	-	-	-	-

Note: √ - Specified without a detailed recommendation
** - For air-conditioned spaces*

2.3.4 Revisit the Proposed ‘Airhouse’ Concept in 2012

In Chapter 1, ‘Airhouse’ Concept has been explained in general as the motivational factor of this research. The idea of the concept came from a previous study done by the author for a Master’s dissertation (Mohd Sahabuddin, 2012). It derives from traditional values of Malaysian vernacular architecture that emphasises natural ventilation strategies in its design to achieve thermal comfort. There are four climatic adaptations of this architecture that have been referred; 1) built on stilts for promoting stack effect, 2) full-length windows at body level for cross ventilation, 3) double roof concept for ventilating hot air, and 4) using lightweight materials for reducing heat radiation at night.

A series of simulation modelling has been conducted to assess the impact of the climatic adaptation of traditional Malay houses on indoor comfort conditions. Using IES simulation, two traditional houses were analysed and compared with PPR (first generation) housing units located at level 1 and level 10. Two common areas were selected which were the living hall and kitchen area. The parameters included air temperature, relative humidity and indoor airflow rate.

Table 2.7 shows the total external wall area and its opening areas percentage. TMH 1 has 16.5% opening areas and TMH 2 has 17.9% opening areas. Meanwhile, PPR first generation unit has only 8.9% opening areas. The two cases of Malay houses have larger opening areas compared to PPR unit. The size and location of opening areas are two key factors that can allow air to enter the building sufficiently which will differentiate the performance of indoor comfort conditions.

Table 2.7: External wall areas and openings percentage in the case studies.

Case Studies	Total Wall Areas (m^2)	Total Opening Areas (m^2)	Opening Percentage (%)
TMH 1	485.9	80.0	16.5
TMH 2	259.0	46.4	17.9
PPR First Gen.	117.4	10.5	8.9

Based on Figure 2.18, the mean air temperatures in the traditional Malay houses (TMH 1 and TMH 2) have lower results than PPR 1 (1^{st} floor And 10^{th} floor) by a 1.7°C margin (Mohd Sahabuddin, 2012). These results show that the large opening area at the perimeter walls and roof in Malay houses work well in promoting natural ventilation. Meanwhile, the minimum air temperatures in the Malay houses are lower than PPR 1 cases by a 1.5°C margin. This concludes that the lightweight materials used in a Malay house can release heat readily and cool the house at night.

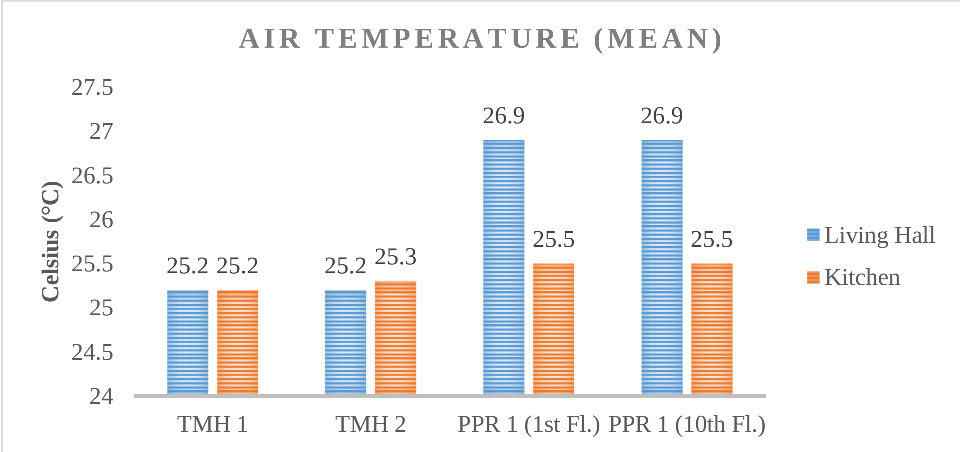


Figure 2.18: The mean air temperature of TMH and PPR first-generation houses

Figure 2.19 shows the comparison of the mean relative humidity of TMH and PPR first generation houses. The mean relative humidity in PPR units recorded lower than the Malay houses by 5.9%. From the results, it can be deduced that the Malay houses have a high level of humidity and low temperature, while PPR units have the opposite. ASHRAE 55 suggests that the recommended level of indoor humidity in Malaysia should be less than 65%. Therefore, the relative humidity of the TMH and PPR units are not at the recommended level. These results are consistent with the fieldwork studies and IES simulation results mentioned in Chapter 3.

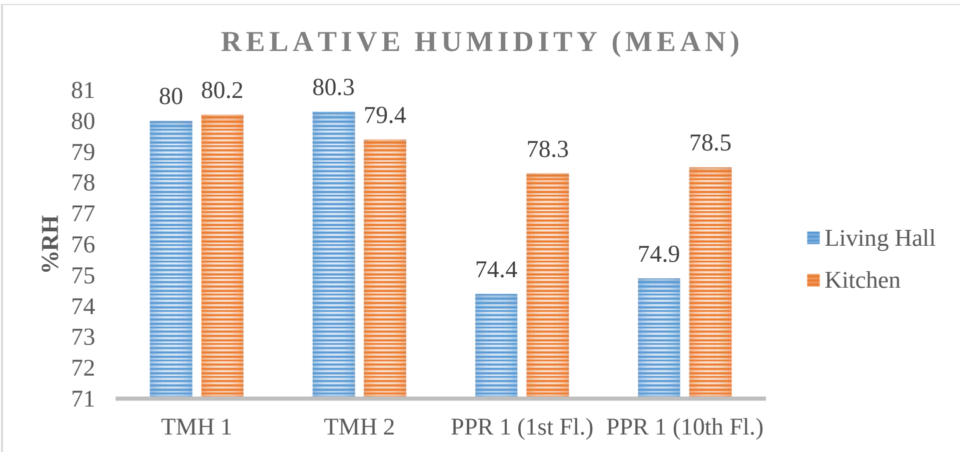


Figure 2.19: The mean relative humidity of TMH and PPR first-generation houses

Figure 2.20 shows the mean airflow rate in all cases. The traditional Malay houses recorded higher airflow rates compared to both PPR first generation units. The most significant value of airflow rate was recorded in the TMH 2 with 1,450.3 l/s, compared to PPR unit at 10th floor with only 31.7 l/s. The differences in terms of air movement in both Malay house cases are tremendous. The air movements leaving and entering the house are significantly higher than PPR units. These findings are vital because of the air movement, for instance, reduces the effects of humidity and air temperature (Saini, 1970) in traditional houses.

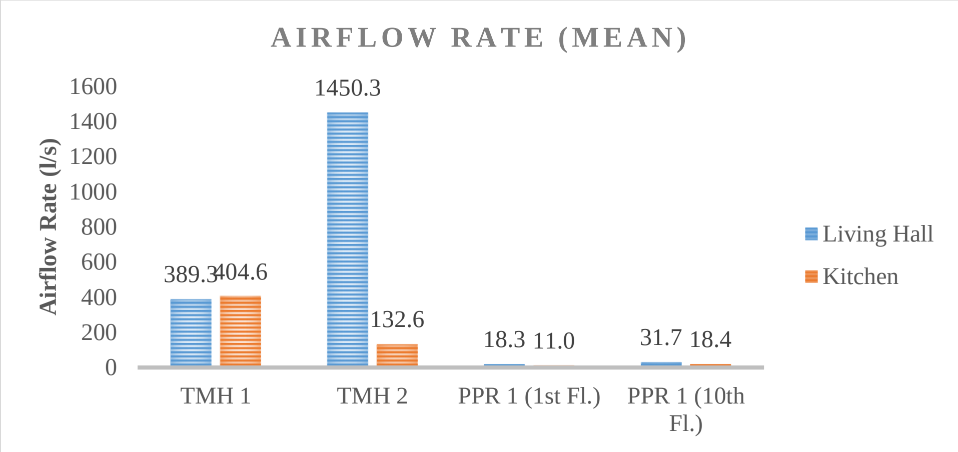


Figure 2.20: The mean airflow rate of TMH and PPR first-generation houses

Based on all the results defined in previous research (Master's dissertation) (Mohd Sahabuddin, 2012), the proposed 'Airhouse' Concept was established as listed in Table 2.8. The air temperature ranges from 25°C to 27°C. The relative humidity should be below 60% RH and the air movement should be between 0.30 m/s to 1.5 m/s. Meanwhile, the total energy consumption for 'Airhouse' Concept is set below 5,000 kWh/year and less than 2,500 kgCO_2/year for carbon emission.

Table 2.8: Design conditions of 'Airhouse' Concept (2012) for naturally ventilated building

Parameters	**Airhouse Conditions**
Recommended Air Temperature	25 – 27 °C
Recommended Relative Humidity	30 – 60%RH
Recommended Air Movement	0.30 – 1.5 m/s
Recommended Energy Consumption	< 5,000 kWh/year
Recommended Carbon Emissions	< 2,500 kgCO_2/year

The establishment of 'Airhouse' Concept in 2012 was totally focused on natural ventilation strategies, in which the air was designed to efficiently flow across the house compound. In promoting air movement and cross ventilation, the four components of opening – bottom louvres, windows, top louvres and high louvres, were suggested in 'Air house'. Moreover, the unit plan layout should be in proportion of 1.5x for walls parallel to the corridor, and 1x for walls perpendicular to the corridor (Table 2.9) as compared with the PPR first generation where the depth plan layout was implemented (Figure 2.21). However, the research was done regardless of the actual air quality conditions in Kuala Lumpur. Thus, the concept that has been proposed in 2012 needs to be refined and re-established using the latest results from this research.

Table 2.9: 'Airhouse' (2012) design parameters for naturally ventilated buildings in Malaysia (Mohd Sahabuddin & Gonzalez-Longo, 2015)

'Air House' Design Parameters	
Proportion of Opening Components (Bottom Louvres : Windows : Top Louvers : High Louvres)	2x : 2x : 1x : 1x
Opening Areas for Walls Facing Outside (1st Floor to 10th Floor)	15% to 25% (from total external wall area)
Opening Areas for Walls Facing Inside (1st Floor to 10th Floor)	25% to 50% (from total external wall area)
Opening Areas for Walls Facing Outside (11th Floor and above)	10% to 20% (from total external wall area)
Opening Areas for Walls Facing Inside (11th Floor and above)	20% to 45% (from total external wall area)
Proportion of Plan Unit Layout (Parallel Wall : Perpendicular Wall)	1.5x : 1x
Range of Overhang's Depth	0.6 - 1.0 meter
Breaks between Units	2.0 meters
Recommended Materials	Prefabricated, Lightweight and Low Thermal Mass

Figure 2.21: The unit plan layouts for the PPR first-generation (left) and the new proposal made in 2012 (right) (Mohd Sahabuddin, 2012)

2.3.5 Regulations to Be Changed

Although current building regulations, standards, green rating tools and the 'Airhouse' design concept have proposed many thermal comfort strategies, they have not been able to acknowledge the current and future climatic conditions of Kuala Lumpur. At the same time, they are not able to address the required improvements in occupant's health and comfort as well as the reduction of carbon emissions. Methods on reducing heat, humidity and contaminants from outdoor air intake as well as removing them from indoor spaces are among the initiatives that need to be added in their documents.

The UBBL, especially the clauses 39(1) and 40(1) that regulate the sizes of openings and light well requirements, were informed by British building standards and have not been reviewed and further researched in accordance with the local climate and environmental conditions. These could not provide acceptable ventilation by natural means in high-rise residential buildings where weaker stack effect due to lower temperature differences and heat build-up at the top of the light-wells might happen at certain levels (Kotani, Satoh, & Yamanaka, 2003; Prajongsan, 2014). These clauses, which have been used for 33 years without revision, should be revised and improved in order to reduce carbon emissions while ensuring occupant's comfort and health. Likewise, the standards (MS1525:2014) and green rating tools (GBI, GreenRE and MyCREST) have failed to devise strategies that could reduce airborne particulate matter and toxic gases as well as to prevent convective, conductive and radiative heat from entering and permeating high-rise residential units in Kuala Lumpur.

As per clause 39(1), the minimum size of openings for ventilation purposes in a residential building in Malaysia should not be less than 10% of the total clear area of the room. However, this sole figure seems to be inappropriate to provide ventilation and filter airborne particulate matter from entering indoor spaces in high-rise residential buildings due to different heights factor. Clause 40(1) of UBBL sets the requirement for a light-well of 15 sqm in buildings higher than eight storeys, which could not provide acceptable ventilation by natural means in high-rise buildings due to weak stack effect and the absence of wind-force ventilation. Further studies should be carried out to test the appropriateness of these requirements to achieve suitable ventilation while ensuring the health of the building occupants and increase comfort levels in indoor spaces.

Building regulations in Malaysia, which are concerned about the natural ventilation, should be revised in order to reduce energy consumption and carbon emissions as well as to deal with the challenges of heat stress and air pollution which affect the comfort and health of building occupants. This revision should take into consideration the critical conditions, which allow for passive and low-energy strategies to constantly enhance air movement, reduce the airborne particulate matter and maintain the acceptable operative temperature in indoor spaces in urban areas.

2.4 Achieving Indoor Comfort in High-Rise Buildings in Urban Areas

2.4.1 Thermal Comfort Strategies

Among the main causes of climatic stress in Malaysia are solar radiation and humidity that cause indoor discomfort (Ardalan Aflaki, Mahyuddin, Al-Cheikh Mahmoud, & Baharum, 2015; Tahir et al., 2010). They should be controlled (Sujatmiko, Dipojono, Soelami, & Soegijanto, 2015) and reduced (Lubin, 2016). Preventing solar radiation and humidity from entering indoor spaces is the most important thing to be emphasised in building design (Lechner, 2014). Reducing indoor air temperature and at the same time removing (or at least minimising) relative humidity is a big challenge in hot humid climates (Roaf, 2012).

Heat – the main element preventing thermal comfort, could be transferred by three mechanisms: 1) conduction, 2) convection, and 3) radiation (Nave, 2012). Nave (2012) explained that conduction is ‘heat transfer by means of molecular agitation within a material without any motion of the material as a whole’. Meanwhile, convection is ‘heat transfer by mass motion of a fluid such as air or water when the heated fluid is caused to move away from the source of heat, carrying energy with it’ and thermal radiation is ‘energy transfer by the emission of electromagnetic waves which carry energy away from the emitting object’.

Solar radiation does not only come directly from the sun. Diffuse solar radiation and reflected (from neighbouring buildings) radiations may also occur (Mohd Sahabuddin & Gonzalez-Longo, 2017). Therefore, the strategies in combating high air temperature and high humidity in indoor spaces should focus on reducing the direct, diffuse and reflected solar radiation – preventing them from permeating indoor spaces through conduction, convection and radiation and removing heat and moisture accumulated in indoor spaces. Among the potential strategies are insulated walls, passive cooling strategies and dehumidification techniques.

Reducing Air Temperature

Nave (2012), through a vacuum flask principle, suggested that the conduction and convection of heat can be controlled by a vacuum space. The strategies of the cavity and solar walls, which also has a vacuum space in between layers, seem substantially able to prevent heat from permeating indoor spaces. Nonetheless, these strategies are inefficient to cut-off the electromagnetic waves that allow thermal radiation to occur (Nave, 2012). Therefore, the strategy of 'silvered wall', a thin layer of evaporated aluminium sheet could effectively block the waves (Nave, 2012). A study has found that transient heat transfer through insulated walls behaves differently according to the placement of the insulation whether on the outside surface or the inside surface (Zain, Taib, & Baki, 2007). This strategy, however, will cater for controlling heat only. This insulation strategy should be improved to cater for the indoor air quality and ventilation issues in high-rise buildings.

The passive cooling technique has been used worldwide since ancient times (Hijazi, 2018) and should address three parameters; heat gain prevention, heat gain modulation and heat dissipation (Givoni, 1994). This can be done by removing the heat by enhancing passive cooling strategies. Lechner (2012) has suggested four types of passive cooling systems: 1) cooling with ventilation, 2) radiant cooling, 3) evaporative cooling, and 4) earth cooling. According to him, there are two theories of passive cooling, first, to remove the heat from the building by heat sink, and second, to modify one of the thermal comfort factors (air temperature, humidity, mean radiant temperature and airspeed). The second technique is better because people will feel more comfortable (Lechner, 2014).

Night-flush cooling is a technique that uses air movement (ventilation) to remove heat from the indoor spaces at night (Lechner, 2014). However, this technique is best implemented in hot and dry climates with a large diurnal temperature of more than 11°C (Lechner, 2014). One of the rules for night-flush cooling is windows should be opened at night and closed during the day. In hot-humid climate, with many infectious insects and excessively high humidity at night, this rule may not be suitable to be implemented. Furthermore, insufficient and unreliable wind movement (especially at night) is another constraint for this technique in tropical cities (Mohd Sahabuddin & Gonzalez-Longo, 2017) that will not sufficiently allow the air to flow into indoor spaces due to air-lock entries (Lenchek, Mattock, & Raabe, 1987).

Similarly to night-flush cooling, earth cooling that uses wet earth as a heat absorber is not suitable in humid climates because condensation on earth tubes might cause biological activity that leads to health risk (Lechner, 2014). Direct radiant cooling that uses roof structure to cool the building by radiation to the night sky may be useful for low-rise (single or two-storey) buildings only. However, indirect radiant cooling that uses the night sky to cool heat-transfer fluid – which then cools the building, may be suitable for medium or high-rise buildings (Lechner, 2014).

Passive cooling through water elements is one of the common features in buildings to allow evaporative cooling with ventilation which later will reduce air temperatures and improve thermal comfort (Lechner, 2014; MS1525, 2014; Safarik, 2016). However, according to Lechner (2014), the evaporating water technique is suitable for low humidity areas only which in high humidity areas like Kuala Lumpur, water elements would produce some negative impacts such as breeding areas for mosquitoes. This claim has been supported by a study suggesting that evaporative cooling on their own is not recommended for hot-humid climates as the performance is not acceptable in high humidity (Abd Manaf, Durrani, & Eftekhari, 2018a).

Reducing Humidity

Reducing humidity in humid regions is very desirable for thermal comfort. There are two ways of removing moisture from the air, the first method is by cooling the air below the dew point temperature. This technique will condense out moisture from the air to be in liquid form (Lechner, 2014). The conventional air-conditioning system applies this method. The second method uses a drying agent or called ‘desiccant’. Among the materials that can absorb large amount of moisture are silica gel, natural zeolite, activated alumina and calcium chloride (Lechner, 2014).

However, using desiccant technique involves two difficulties which the first is when the water vapour is absorbed, heat will be released. This suggests that placing a desiccant in a room will contribute more heat and therefore, additional cooling technique is required to lower the temperature. Another problem of using desiccant is that the material soon will be fully saturated with water and stops dehumidifying. It needs to be regenerated by drying off the water. This technique is presently used in the heat exchangers that recover heats (latent and sensible) (Lechner, 2014). The recent development of air conditioner was developed which manipulates desiccant as part of cooling technique. This technique called 'desiccant evaporative cooling' (Abd Manaf, Durrani, & Eftekhari, 2018b).

From the strategies mentioned earlier, it could be deduced that the integration of external shading devices and insulations are among well-known and common strategies that have been suggested in buildings in hot-humid climate to prevent heat from entering indoor spaces. However, the options in reducing moisture in the air are very limited (Abd Manaf et al., 2018b). Finding a technique that can solve both thermal comfort issues of heat and moisture should be studied in detail.

There are other factors that should be taken into account in indoor spaces such as heat and moisture from the occupant's household equipment (Environmental Health Directorate, 1995). Even our bodies, when inactive, will release heat through perspiration, conduction, convection, and radiation at a rate of 90 watts (Nave, 2012). These internal heat gains in a compact housing layout cause indoor discomfort and poor indoor air quality. Therefore, a mechanism to channel out this accumulated heat, moisture and particles will be studied in detail in this research.

Enhancing Air Movement

Malaysia is located near to the equator line, experiences low wind movement across the country especially in midland areas (MET, 2019). The effect of low air movement is worsen in high-density areas like Kuala Lumpur (Yuan & Ng, 2012). In satisfying the air movement requirement, most of the urban population have installed the air-conditioning system in their houses and for the low-income population, ceiling fans are the prime option (A. Aflaki et al., 2016). With the current building construction technology that only focuses on aesthetics rather than function, houses are designed with imitating the temperate climate housing models – no overhangs or awnings, fixed casement windows with limited function, no permanent ventilation access like vent blocks either on façade or roof compartment and heavyweight materials that absorb heat during the day and release it at night. This method has made houses in Kuala Lumpur become heat accumulator boxes. In this scenario, constant air movement is the decisive factor for thermal comfort – to stimulate evaporative cooling and to remove contaminants from indoor spaces.

Many studies have been conducted to improve air movement in buildings. Wind catchers and wing walls, for example, are recommended to be used to catch and redirect the winds into indoor spaces (CIDB, 2016). In the case of high-rise buildings, these techniques can be used to catch, collect, and channel the wind into the indoor spaces for thermal comfort (Mohd Sahabuddin & Gonzalez-Longo, 2017).

Air wells or solar chimneys could improve ventilation performance in indoor spaces (Ding, Hasemi, & Yamada, 2004). These strategies that function as ventilation shafts can effectively increase the indoor air velocity up to 36 per cent (Prajongsan, 2014). According to Lechner (2014), a solar chimney is useful to increase ventilation by stack effect especially for places that lack wind movement. He added that solar chimneys should be exposed to the sun and paintings in black might improve its performance.

However, solar chimney, when exposed to the sun, can heat up the building. It must be positioned outside the thermal envelope or in a free-standing form (Lechner, 2014). This statement is consistent with a study by Chung et al. (2014) where it was found that air convection will happen in solar chimney and directly increase the room air temperature because both are connected (Chung, Ahmad, Ossen, Hamid, & Baharvand, 2014). Thus, a mechanism that can make the air inside the solar chimney constantly and efficiently moving should be taken into consideration.

In the urban context, porous structures could lead to better urban ventilation which will improve air quality at the pedestrian level (Yuan & Ng, 2012). Another similar concept of building porosity is 'pilotis' (buildings built on stilts) that has been widely implemented in Malaysia including high-rise residential buildings. This concept was found to be capable to improve the micro-climate of the surrounding areas that become pleasant because of adequate airflow around ground level to offset the heat accumulation (Sapian, Majid, Hanita, & Hokoi, 2012).

One of the low-energy devices that can supplement constant air movement in indoor spaces is using fans. This strategy will naturally reduce around 5°C of indoor temperature than the outside temperature (Springer, 2017). Some researchers have recommended fans as a necessary requirement to acquire comfort through evaporative cooling (CIDB, 2016; Lechner, 2014; MS1525, 2014). Lechner (2014) added that the rules for comfort ventilation in hot and humid climates are depending on fans for maximising airflow, lightweight materials, shading devices, insulations and operable windows. Alung’at (2017) suggested that buildings, in which natural ventilation conditions are either insufficient or unreliable, depending on mechanical ventilation is a necessity. He added that achieving the required air movement using fans, vents or ducts could eliminate the problems caused by stale and stagnant air (Alung'at, 2017).

Given the above findings, the implementation of fans in indoor spaces and light-wells for mitigating the issues of insufficient and unreliable wind movement in Kuala Lumpur is appropriate. Thus, an integrated strategy of natural and mechanical mechanisms should be studied in detail in providing a constant airflow rate without ignoring the thermal comfort and indoor air quality requirements.

2.4.2 Indoor Air Quality Strategies

Filtering Air Pollution

The DOE has targeted that the limit for PM_{10} level in Malaysia in 2020 is below 40 µg/m^3. A study by Leh et al. (2012) has identified that Kuala Lumpur is having a moderate level of air quality. The authors also recommended that ‘special attention should be given to the higher density zones, and air polluted areas such as industries, which are potentially generating more negative impacts on human health’. The ideas of high-rise buildings sit on stilts and have porous structure could be used to move the airborne particulates away from the high-density areas in Kuala Lumpur. A study has been done and proved that a high speed of airflow, which also could move particles away, can be expected at ground level by introducing ‘pilotis’ or stilts in high-rise residential buildings (Sapian et al., 2012).

Another study conducted by DOE found that inadequate ventilation was the major cause of indoor air pollution in Malaysia (DOE, 2015). Airborne particles such as PM_{10}, which was found as the major pollutant in Kuala Lumpur during the dry season (Leh et al., 2012), could possibly be cleaned by using two passive strategies such as electrostatic precipitator, which could be placed on the surface of an 'egg-crate' shading device, and biodynamic material that can absorb particles. The electrostatic precipitator is believed to be able to reduce 98 to 99 per cent of particulate particles (Kolenbrander et al., 2004a) and the biodynamic material has a potential to cut the air pollution by 75 per cent (Gray, 2016).

'Photo-catalytic paints or coatings' is another simple but yet effective solution to mitigate air pollution especially NO_2 and NO (Fuller, 2018). This technique requires the building façade to be painted with paints and it is very efficient when exposed in the sunlight. After several trials, with various conditions, this technique achieved a degree of success. However, there is a vast volume of pollution in cities and it was found that the pollution spent very little time to make contact with the surfaces – less than 1% of air volume in a city (Fuller, 2018). However, the limitation of this technique is that it requires regular painting after wash off to make it still relevant.

In 2016, Dutch designers – Daan Roosegarde (Delft Technology University), and Bob Ursem (Dutch Green Tech Company European Nano Solutions), created a giant air purifier called the 'Smog Free Tower'. This innovation can attract and suck in small pollution particles by sending positive ions into the air. The particles then will attach to a grounded-negatively charged surface before the lower part of the tower expels the clean air (Cerini, 2016). This method could improve the surrounding air quality by 75%. Recently, in Northern China, a 100-metre air purification tower has been built for trial. It claimed to be able to clean 10 million cubic metres of air each day. However, an article written by Lewis (2018) has argued that only 0.01% of the air of a modest city (100 km^2) being released from the giant air purifier (Lewis, 2018). Suggesting that the air purifier is not capable to clean the air in the city even in the long term period.

According to a study in 1999, there are three ways to reduce particulates from entering indoor spaces which are by using fences, vegetation and angled surfaces like jalousie windows (Mediastika, 1999). According to her study, she found that jalousie windows were proven could reduce PM_{10}. As a comparison, porous barriers with a parallel angle to wind direction could reduce 1% to 1.5 % of PM_{10} and solid barriers with oblique angle to wind direction could reduce 3% more than porous barriers (Mediastika, 1999). That is approximately the maximum reduction of PM_{10} if only windows are used for filtering purposes.

Even though trees can reduce air pollution by 5% (Fuller, 2018), they also could worsen the air pollution by reducing the dispersion of traffic exhaust (Salmond et al., 2016). In addition, different types of trees emit different pollution substances such as VOCs (Fuller, 2018). Another study done in Berlin found that trees such as pine and eucalyptus could add 5% to 10% of the city's ozone level (Churkina et al., 2017). Therefore, relying on trees for reducing air pollution is not a wise solution.

Wet scrubber, a mechanism usually been used at power plants and facilities that emit SO_2 and H_2S, can eliminate particulates from the air with 94% efficiency. The system works with some principles such as dirty air from the factory to enter the scrubber before it will pass through a layer of steam which in this part, large particles will be trapped in a filter and the clean air will be released from the scrubber system (Kolenbrander et al., 2004b). Another positive aspect of the system is, it can process the polluted steam droplets into sludge, which can be used for making bricks.

Another strategy for mitigating air pollution is called dynamic insulation. This technique uses a fan to suck the fresh air into the room through the porous insulation which also filters particles, heat and moisture (B. Taylor & Imbabi, 1998). Having hybrid ventilation and filter membrane in its system, the four indoor comfort issues highlighted could possibly be solved using this strategy.

Referring to the potential solutions that have been proposed by a number of researchers, most of them were not tested in high-rise format and could tackle on one or two issues only except dynamic insulation strategy. As described in detail in this chapter, the challenges of high-rise residential buildings in Kuala Lumpur are dealing with four main issues – high air temperature, high humidity, low air movement and air pollution. Staying indoors is one of the common actions taken by the urban population to reduce exposure to outdoor air pollution. However, to stay in comfort and healthy conditions, buildings should be equipped with a system that can constantly supply cool and clean air with low energy and carbon emissions.

2.4.3 Case Studies: High-Rise Residential Buildings in the South-East Asia Region

One of the best examples of residential high-rise buildings in the hot-humid region is 'The MET' in Bangkok, Thailand (Figure 2.22). The tower, which stood at 230.6 metres high, was designed by WOHA Architects in Singapore. This building has a porous façade and open interspaces, which allow wind movement to get through to residential units and urban surrounding. This approach increases the wind movement where at the ground level, the wind speed is almost zero but at 65 metres above ground, the airspeed is increased up to 6.13 m/s (Oswald & Riewe, 2013).

Even though during Bangkok's dry season the natural ventilation in this building does allow for air movement flows into its indoor spaces, the opening design seems not to be satisfying the requirements of noise, air filtering and rain protection (Prajongsan, 2014). Based on this argument, an applicable building fabric, such as porous façade, with appropriate building system could possibly improve the indoor environment which complies with external influences.

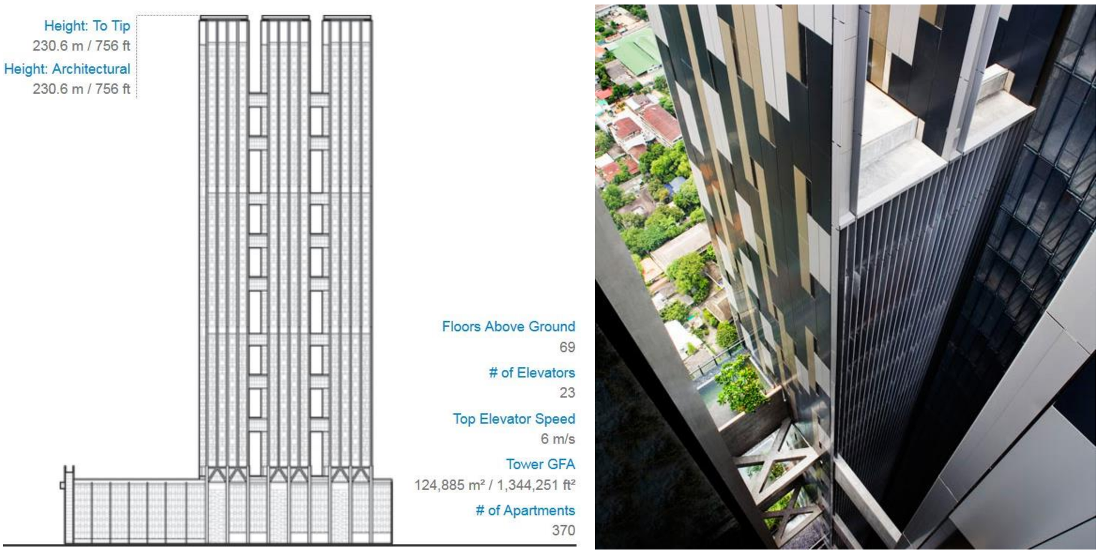


Figure 2.22: 'The MET' elevation and its porous structures (CTBUH, 2019)

'Moulmein Rise', another project that was designed by WOHA Architects, is a residential high-rise building that has a height of 102 metres. Figure 2.23 shows the innovative design of 'monsoon windows' that could allow cool wind to flow in, whilst keeping the rain out (Wong & Hassell, 2009). Wong and Hassell (2009) suggested that in Singapore, during rains, the temperature will decrease between 24°C to 27°C and the cool wind is often accompanied by traces of rain. Therefore, a special window design, which inspired by traditional Malay houses, has been implemented in order to harness the cool wind (Ali, 2007).

Furthermore, it was reported that this type of windows is significantly successful to air the apartments, especially when residents are not at home, through horizontal steel grille ledges even though the regular windows are closed. They also claimed that on the 19th floor, the indoor environment was quite breezy, resulting from these ledges that allow wind permeates into indoor spaces. Even though this technique could prevent driving rain, it could not prevent heat, moisture and airborne particles, especially in urban areas.

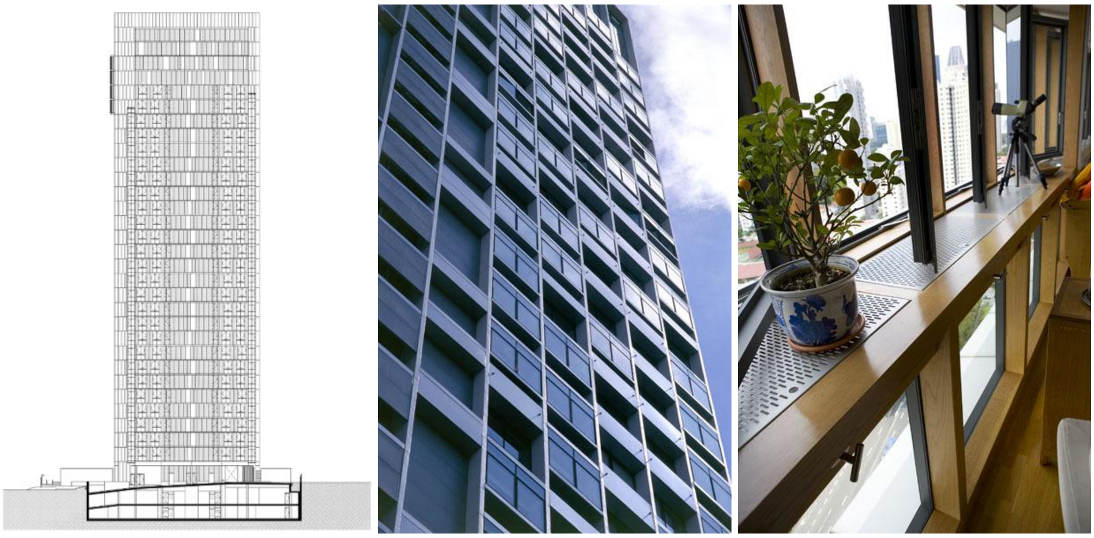


Figure 2.23: 'Moulmein Rise' elevation and its 'Monsoon Window' details (Ali, 2007; Wong & Hassell, 2009)

‘The Hansar, another green high-rise residential building in Bangkok, is another sustainable skyscraper that has been designed by WOHA Architects apart from the MET and Moulmein Rise. Completed in 2011, this tower implements natural ventilation, perforated indoor and outdoor façade and shaded with green elements (Wong & Hassell, 2012). In response with the temperate building models that have been erected in many tropical cities, this 45-storey building adapts vernacular and passive responses to climate into its form by bringing fresh air and nature in its spaces (Wong & Hassell, 2012). The design of this building emphasises the units located around a central core and courtyard to maximise cross natural ventilation for the apartments and its bathrooms. According to the designers, this building will allow maximum access of light and air which makes it possible to provide comfort without using air-conditioning systems (Wong & Hassell, 2012). Sunshades are integrated with balconies that keep the interior cool at all times (Figure 2.24). These apartments are naturally ventilated and connected with naturally lit corridors that reduce the energy use substantially (Wong & Hassell, 2012). These precedents – The MET, Moulmein Rise and The Hansar, are among the best exemplars of high-rise residential buildings in the South-East Asia region. However, there is no detailed study conducted to date on these building which makes it unjustified how these aspirations have been achieved. Furthermore, these buildings were designed to meet the requirement of medium and high-income groups of people which have minimum restrictions on the financial burden.

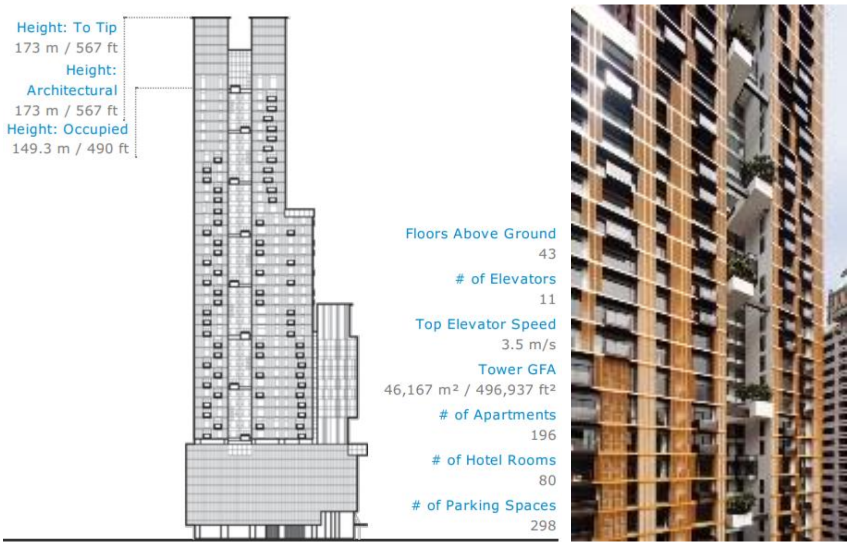


Figure 2.24: 'The Hansar' elevation and its external sunscreens (CTBUH, 2019; Wong & Hassell, 2012)

Similarly, in Kuala Lumpur, there are many green high-rise residential buildings being constructed. However, the approaches and strategies implemented are most likely similar to the case studies highlighted. Due to the high land values in urban areas, many residential buildings are built in high-rise format to solve the problems of housing woes for the low-income group which have very limited financial capabilities. Thus, its effectiveness is doubtful in naturally ventilated buildings where according to the literature reviews, it has been proven that climate change and air pollution have directly given severe impacts on the occupant's comfort and health. In a new challenging era of rapid urbanisation with a high volume of vehicles and industries, allowing outside air is obviously permitting the hot and polluted air in (Mohd Firrdhaus Mohd Sahabuddin & Cristina Gonzalez-Longo, 2019). Thus, a more radical approach of strategies should be investigated, studied and proven through scientific methods in achieving the most important aspects of indoor comfort (thermal and health) in residential high-rise buildings in Kuala Lumpur and its tropical region.

2.4.4 Case Studies: High-Rise Social Housing in Kuala Lumpur

The People's Housing Programme (PPR) is one of the Malaysian government's initiatives to relocate squatters and solve the housing woes of the low-income groups (Ministry of Urban Wellbeing, 2015). In 2015, the government announced the construction of one million affordable housing units within the PPR programme, coordinated by the National Housing Department (NHD) of the Ministry of Urban Wellbeing, Housing and Local Government (UHLG) (G. Chen, 2015). According to the UHLG 2016 annual report, the government proposed 169 PPR projects all over the country with a total of 102,896 units. By December 2016, a total of 81,352 units had been built, involving 115 different projects (MAMPU, 2016b; Ministry of Urban Wellbeing, 2016). Out of 169, 33 projects were built in Kuala Lumpur from 1998 to 2016, providing 38,395 housing units within 121 blocks with the range if 10 to 21-storeys high (DBKL, 2019). It is suggesting that this city accommodates approximately 47% of the total PPR units in Malaysia and all of them are in high-rise format (JPN, 2016; MAMPU, 2016a).

Since its creation in 1998, NHD has developed two generations of PPRs, with different designs: the first one extended from 1998 to 2008 and the second, was started in 2010 and it is still being implemented (BERNAMA, 2013; Ismail, Jabar, Janipha, & Razali, 2015) (Figure 2.25). The main reason for the design change was to make improvements on shared facilities such as multi-purpose halls, chaplaincy, child nurseries, playgrounds and open areas (BERNAMA, 2013). However, the designs did not seem to take full account of the actual indoor conditions of these residential units as the residents seem to confront several problems including thermal comfort and health issues (Samad, Zainon, Rahim, Lou, & Karim, 2016; N. Zaid & Graham, 2011) and they had to add individual air conditioning units shortly after occupying the buildings. Some PPR buildings in Kuala Lumpur have been subjected to several studies (Ismail et al., 2015; Samad et al., 2016; S. M. Zaid, 2015), but none of them has looked into indoor comfort (thermal and IAQ) so far, even though these components are crucial for the quality of life of the residents (Ismail et al., 2015).

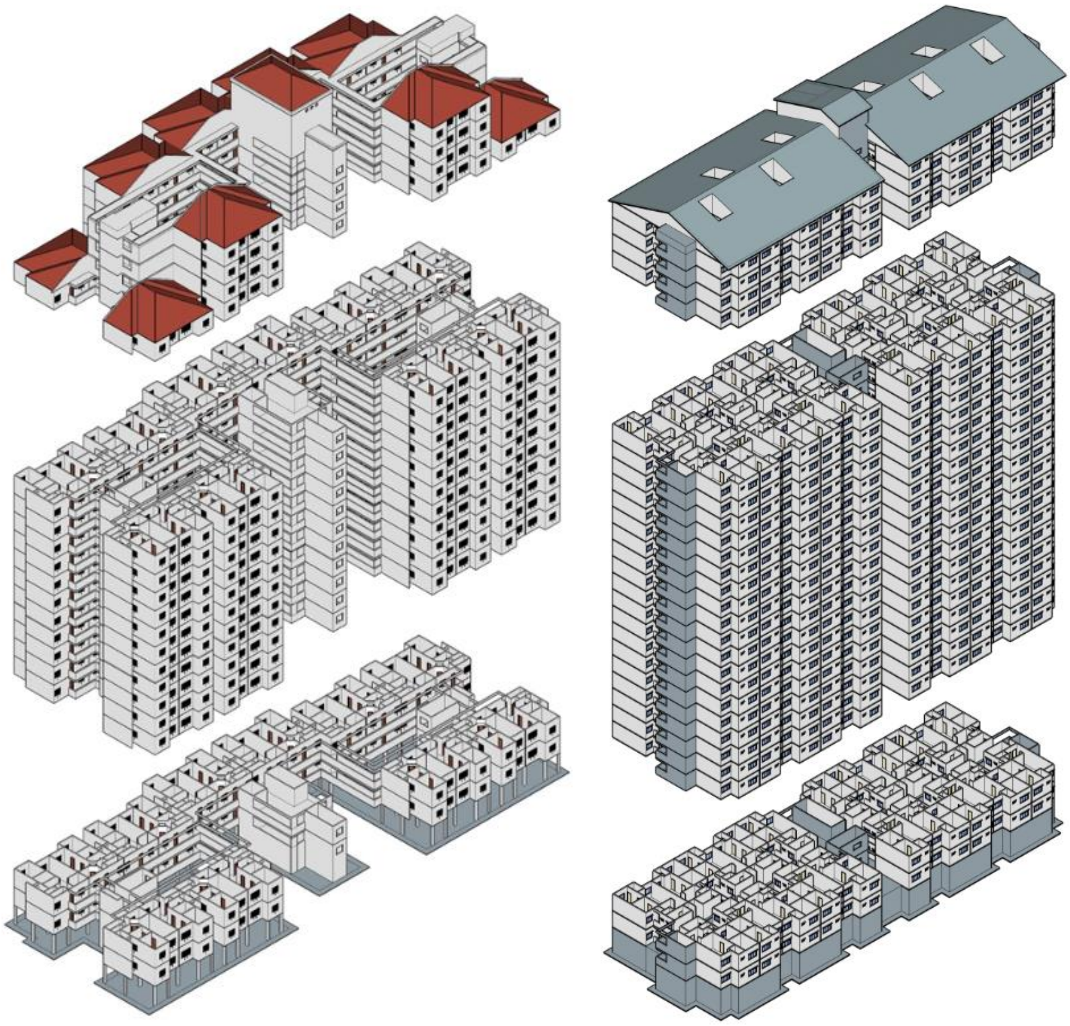


Figure 2.25: The arrangement of the housing units (layout plan) in PPR first-generation (left) (Appendix 1A) and PPR second-generation (right) (Appendix 1B)

Between these two PPR generations, several major differences can be seen such as the arrangement of the housing units, the implementation of passive ventilation techniques, the attachment of the buildings on the ground level and the selection of windows materials. In terms of plan layout, the PPR first generation implemented a more open layout. Every level accommodates 20 housing units and these units were arranged abutting two corridors, surrounded two large atriums located in the middle of the block (Figure 2.25 and Figure 2.26). Meanwhile, in the PPR second generation, the 20 housing units were arranged abutting a single corridor. Meaning that they were facing each other in compact layout. For ventilation and natural lighting, eight light-wells were provided where at each floor, two units shared one light-well (Figure 2.25 and Figure 2.26).

Figure 2.26: The implementation of atrium and light-well in PPR first generation (left) and PPR second-generation (right)

Figure 2.27: The attachment of the buildings on ground level for PPR first generation (left) and PPR second generation (right)

The other difference of these two generations is the attachment of the buildings on the ground level where the PPR first generation was designed to sit on stilts (pilotis), creating a vacant space for multipurpose usage such as vehicle parking, function hall and space for business activities (Figure 2.27), while the PPR second generation was designed to make full use of the ground level for accommodating housing units, maintenance office, supporting spaces such as shops, chaplaincy and hall as well as rooms for services.

Other major differences between these two buildings were the design and material selection of window components. The windows design in the PPR first generation was based on glass louvres with wood frame equipped with horizontal reinforcing bar for security, while in the PPR second generation, windows were designed as single glaze with side-hung aluminium casement (Figure 2.28). The window panels in the PPR second generation, when completely shut will give a high degree of airtightness compared to the glass louvres windows. This will reduce the potential of natural ventilation and increase the possibilities of indoor discomfort. Thus, a fieldwork study to evaluate the actual thermal and indoor air quality conditions in these buildings is highly demanded.

Figure 2.28: The selection of windows materials in PPR first generation (left) and PPR second-generation (right)

In determining that indoor discomfort was affecting these social housing buildings, in 2017, a pilot study was conducted on ten PPR developments located at the northern and southern regions of Kuala Lumpur (Figure 2.29). The developments were PPR Wahyu, PPR Beringin, PPR Batu Muda, PPR Intan Baiduri, PPR Kerinchi, PPR Kg Limau, PPR Pekan Batu, PPR Pekan Kepong, PPR Bukit Jalil and PPR Permai (Figure 2.30 to Figure 2.39). During the visits, the first development of PPR second generation which was PPR Seri Aman, was just being completed and still unoccupied.

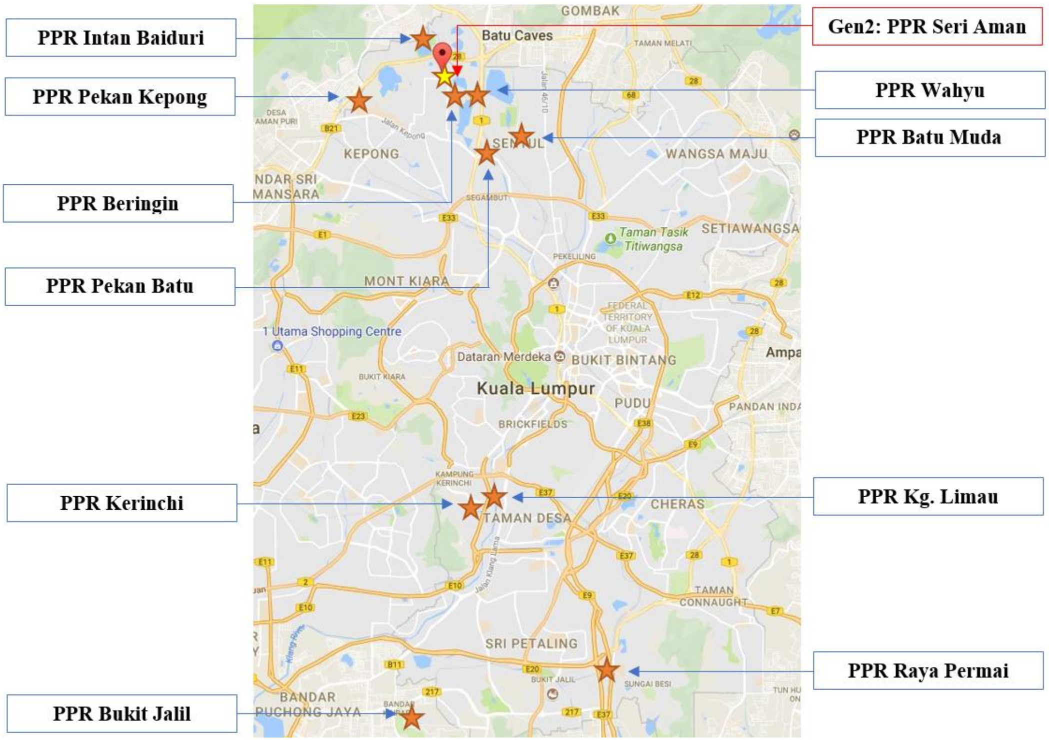


Figure 2.29: The location of the selected PPR developments in Kuala Lumpur


Figure 2.30: PPR Wahyu, Kuala Lumpur

Figure 2.31: PPR Beringin, Kuala Lumpur

Figure 2.32: PPR Batu Muda, Kuala Lumpur

Figure 2.33: PPR Intan Baiduri, Kuala Lumpur

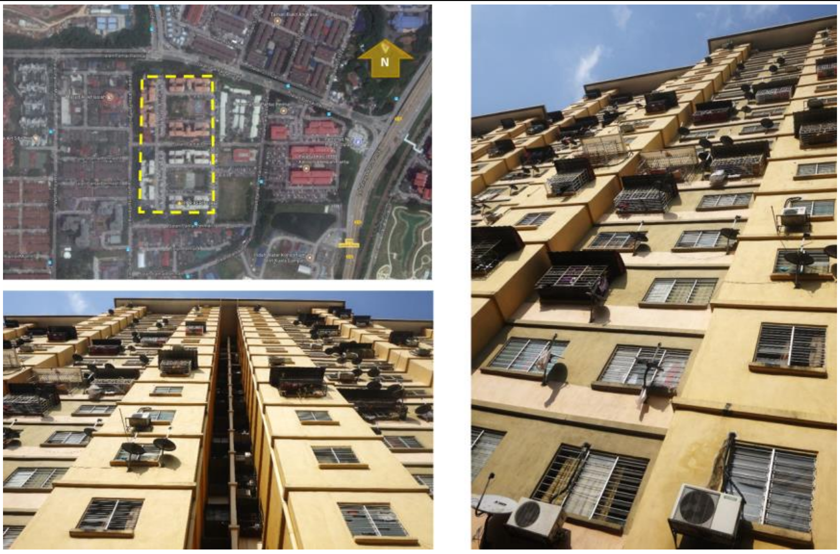


Figure 2.34: PPR Kerinchi, Kuala Lumpur

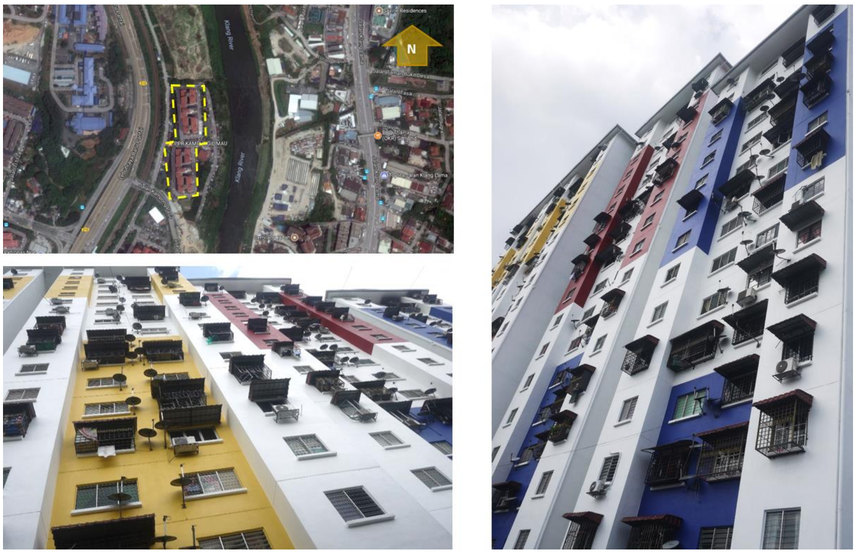


Figure 2.35: PPR Kg Limau, Kuala Lumpur

Figure 2.36: PPR Pekan Batu, Kuala Lumpur

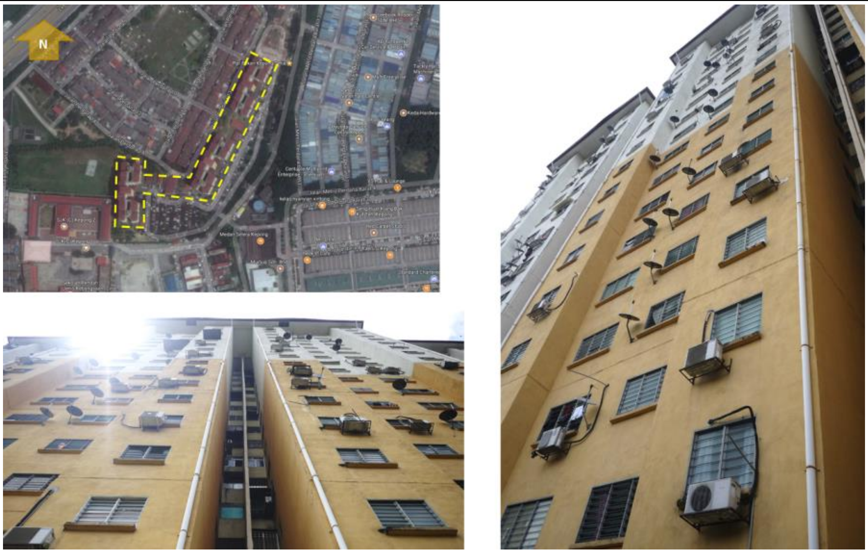


Figure 2.37: PPR Pekan Kepong, Kuala Lumpur

Figure 2.38: PPR Bukit Jalil, Kuala Lumpur

Figure 2.39: PPR Raya Permai, Kuala Lumpur

From the observation on the façade of these PPR buildings, it could be deduced that in all cases, there were a significant number of awnings and air-conditioning systems being installed, suggesting that indoor discomfort was actually happening in these PPR developments regardless of their locations. This was consistent with the findings claimed by many researchers where indoor comfort issues - thermal comfort and health issues, were affecting the majority of the PPR residents (Ismail et al., 2015; Mohd Sahabuddin & Gonzalez-Longo, 2015; Samad et al., 2016; N. Zaid & Graham, 2011; S. M. Zaid, 2015).

Considering the PPR first generation that was terminated since 2008 (Ismail et al., 2015), this research took the PPR second generation as the prime case study. The compact design of the PPR second generation was a new improved design from the previous open-plan design. However, as mentioned before, the main reason for the design change was to make improvements on shared facilities (BERNAMA, 2013) without taking into consideration of indoor comfort conditions. It means that the actual indoor comfort conditions in this new design were still unexplored.

Thus, this research tried to predict the probabilities of the indoor comfort of this design based on previous research. Figure 2.40 shows the probability of the air temperature, wind speed performance and pollutants concentration in the PPR second generation that has been designed according to the mandatory regulations set by UBBL. For air temperature, a study has suggested that the air temperature at 10 metres high in high-rise residential building was 1.2 per cent higher than the air temperature at 42.8 metres high (Ardalan Aflaki et al., 2014). Another study in Korea found that indoor air temperatures are higher for lower-floor units than the air temperature in the higher-floor units (Jo & Lee, 2006). These findings suggested that people at higher altitude will experience lower temperature. Thus, a decreasing pattern of air temperature (dotted-red line) was plotted in Figure 2.38.

According to the Malaysian Meteorology Department through their measurement from 2010 to 2016, the average wind movement in Kuala Lumpur was 1.1 m/s (MET, 2017a). This measurement was recorded at 10 metres high. Another study in 2014 suggested that at 42.8 metres high, the wind movement in Kuala Lumpur was 4.4 m/s (Ardalan Aflaki et al., 2014). Meanwhile, in Bangkok – another megacity in the South-East Asia region, at 65 metres further street level, there is a high circulation of air of 6.13 m/s (Oswald & Riewe, 2013). When using these findings, and matching them in Figure 2.40, an increasing pattern of wind movement could be plotted (dotted-blue line).

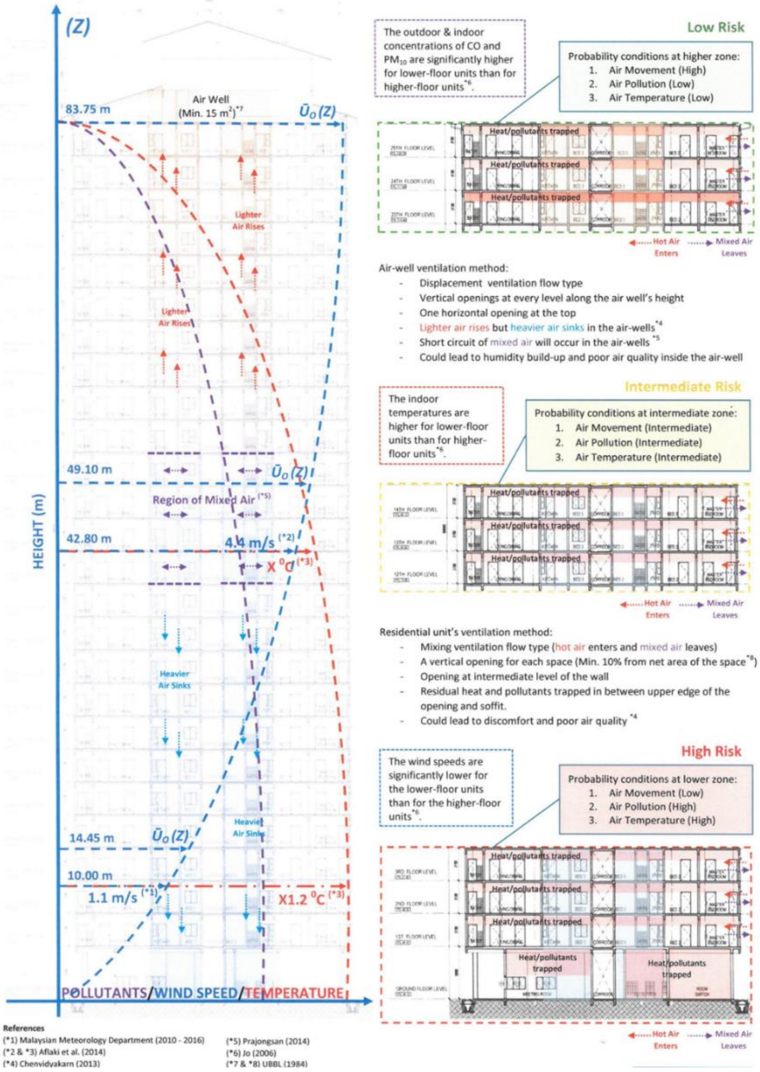


Figure 2.40: Probabilities of air temperature, wind speed and pollutants concentration in high-rise residential building (Appendix 1C)

In terms of air pollution, especially for PM_{10} and CO, Jo et al. (2006) suggested that the outdoor and indoor concentrations of the substances were higher for lower-floor units than the higher-floor units. Similarly, with the air temperature pattern, the air pollution pattern is also decreasing from the street level to the rooftop level. There are a few other elements that can contribute to indoor comfort in high-rise residential buildings. Many high-rise residential buildings in Malaysia use two types of ventilation method, the temperature-induced stack ventilation using light-wells or atriums or air-wells; and wind-induced single sided ventilation for the rooms located at outward façade (A. Aflaki et al., 2016). As the hot air rises due to low moisture content and heavier air sinks (Chenvidyakarn, 2013), the performance of temperature-induced stack ventilation in the light-wells may reduce and become ineffective.

This theory is proven by a research done in 2014 using a simulation model of a high-rise residential building in Bangkok (Prajongsan, 2014). It was suggested that a short circuit of mixed air in the light-wells will contribute to high humidity and poor air quality at the lower part of the light-wells (Prajongsan, 2014). Thus, referring to Figure 2.34, there are three probabilities of zones that can be predicted in the PPR second generation building in Kuala Lumpur - the high-risk zone (lower level), medium risk zone (intermediate level) and low-risk zone (upper level). This research, therefore, will include two fieldworks that assess indoor comfort conditions in two types of high-rise social housing blocks (PPR first and second generations) in Kuala Lumpur to verify these probabilities.

In the urban context, pollution is obviously a major concern in naturally ventilated buildings (Passe & Battaglia, 2015). In the case of Kuala Lumpur, there are a large number of variables that may be determining the difference in indoor particulate concentrations in high rise residential buildings. However, given the relatively high external $PM_{2.5}$ and PM_{10} concentrations (Mohd Firrdhaus Mohd Sahabuddin & Cristina Gonzalez-Longo, 2019; Mohd Firrdhaus Mohd Sahabuddin & Cristina Gonzalez-Longo, 2019), increasing ‘natural’ ventilation to provide evaporative cooling is likely to produce a commensurate decrease in indoor air quality. For this reason, achieving indoor comfort in indoor spaces requires the optimisation of the right temperatures, humidity and air movement while reducing the concentrations of airborne particulates and toxicant gasses (Mohd Sahabuddin & Gonzalez-Longo, 2018).

2.5 A New Strategy to Improve Indoor Comfort in Hot-Humid Climate Using Dynamic Insulation

2.5.1 Dynamic Insulation

As explained earlier, dynamic insulation (DI) is known to have a great potential in solving the four issues arisen in this research – high air temperature, high humidity, high air pollution and low air movement. This technique is a term that has been coined to describe the incoming air stream being delivered through an insulation matrix above an air-permeable ceiling (or wall) to act primarily as an energy efficiency technique, especially in temperate climates (Craig & Grinham, 2017; Halliday, 1997). DI, however, has the additional advantage of providing a large volumetric filter membrane that can filter air pollution (B. J. Taylor, Webster, & Imbabi, 1998), and heat and moisture at the same time (Craig & Grinham, 2017; Halliday, 1997).

Even though many strategies have been proposed to reduce air temperature, humidity, air pollution and to improve air movement, they have not tackled all the issues in a single study. Given the above literature, DI is believed to be able to solve all the four issues regarding indoor comfort without neglecting the energy efficient impact and low carbon emissions (Figure 2.41). This system provides a constant, cool and clean air at the same time by applying fans and filter membrane. The selection of ceiling area to be studied is due to the availability of this surface area in most naturally ventilated buildings which should be fully utilised for placing ventilation systems. Ceilings that have large surface areas can distribute air evenly. DI system, for instance, will get more benefit as large filter areas will reduce clog problems of the filter membrane. Given the above reasons, this research will study in detail the performance of DI located in ceiling compartment for solving the problems highlighted.

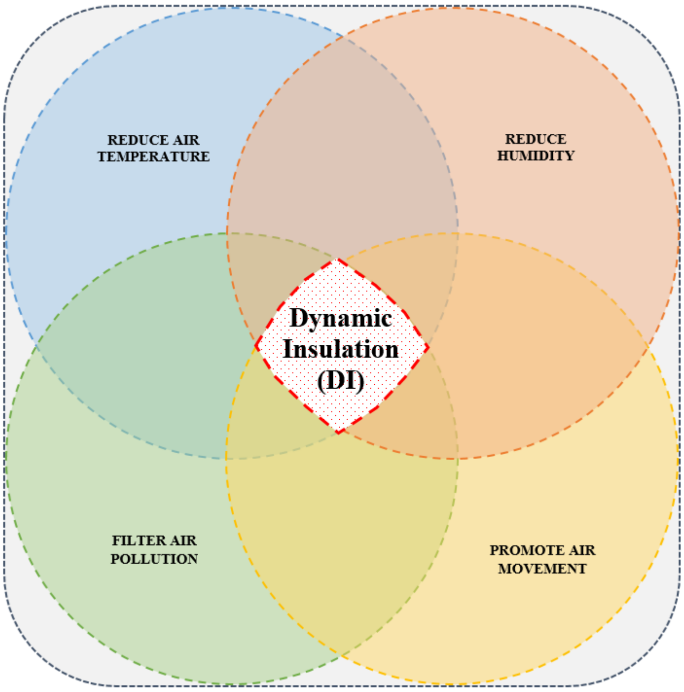


Figure 2.41: DI potentials on improving indoor comfort conditions

2.5.2 Precedents

The term 'insulation' was patented in 1943 in the USA (Acuff, 1943). This invention relates to an insulating structure using raw materials such as rock wool, slag wool, fibrous glass for heat insulation of dwellings and buildings (Acuff, 1943). Meanwhile, the term 'dynamic insulating systems' was patented in the same country in 1966 (Strimling, 1966). This invention relates to improved insulating techniques whereas the previous invention was to isolate an environment from its ambient surroundings but this system 'includes the environment within a chamber defined by the inner walls of a double-walled enclosure' (Strimling, 1966). In 1970, a detailed terminology of dynamic insulation using raw materials such as fabric was explained. The dynamic insulation was scientifically proven could efficiently absorb heat when the airflow is fast enough (Crockford & Goudge, 1970).

The implementation of dynamic insulation in Europe was aggressively started from the 1960s to 1980s (Halliday, 1997). It was used for a new ventilation system for livestock buildings in Norway, Canada, Sweden, Denmark, Finland and Switzerland; based on an idea for recovering heat using a layer of porous insulation, divided the shed into a room and an attic (Halliday, 1997). This concept used a fan to suck the fresh air into the room through the porous insulation. The fresh air was then warmed by the heat-conducting through the material in the opposite direction (Craig & Grinham, 2017). This system was called 'Motstrømstak' in Norwegian, 'Porenlüftung' in German and finally British researchers (Taylor and Imbabi) later settled on the term 'dynamic insulation'. The research in dynamic insulation dated back to the 70s and has been dominated by Dr Mohammed Salah-Eldin Imbabi and his co-workers (M. S.-E. Imbabi, 2012).

In the 1980s to 2000s, a number of research were carried out to examine the heat-recovery of open-pore and fibrous materials (B. Taylor & Imbabi, 1998; B. J. Taylor & Imbabi, 1997) and then its application from shed to homes (B. J. Taylor & Imbabi, 2000), offices (B. J. Taylor & Imbabi, 1999) and sports facilities (Halliday, 2000). The goal was to save energy while providing adequate fresh air. As it was designed for the temperate climate, researchers turned their attention to the air-filtration elements when some studies showed inconclusive results where the interior temperature tended to fall when fresh air was increased (Craig & Grinham, 2017).

In 2006, a study was conducted on a modern high-rise residential block in Abu Dhabi, United Arab Emirates (UAE) using dynamic insulation product called 'Energyflo™'. This product was used as the filter of a mock-up cell which was set up on the window of a housing unit. The outer cell dimensions are 600 mm × 600 mm centre-to-centre and the cell is 95 mm thick, excluding 2 mm × 22.5 mm air gaps to either side. The study has found that the cell thus improves indoor air quality by allowing the ventilation rate to be increased without cost penalty and very efficiently filtering the incoming air of airborne particulate matter. The observed temperature drop as warm fresh air flows through the cell varies from 2°C to 4°C in the evening and early morning; and up to 6°C to 12°C during the hottest part of the day, but the average drop is 3°C. In UAE, Elsarrag et al. (2006) suggested that dynamic insulation could be effective in extreme hot-humid climates.

In 2012, Imbabi developed a new type of 'parietodynamic' insulation called 'Void Space Dynamic Insulation' (VSDI). This passive-active dynamic insulation system has been designed for all climates which can eliminate the risk of interstitial condensation and over-heating during the summer without the support of a fan to drive the airflow (M. S.-E. Imbabi, 2012). The test was conducted using a simulation software where cold winter (20°C - inside, 0°C - outside) and hot summer (20°C - inside, 40°C - outside) conditions were applied. The system applies a small air inlet located at the lower part of the outer wall which allows the air to be confined within a co-planar space and distributed bi-directionally and uniformly inside the wall before the air was supplied via a mid-ceiling inlet vent to the indoor space (M. S.-E. Imbabi, 2012). However, constant airflow is the key to the success of the dynamic insulation (Etheridge & Zhang, 1998) and it is crucial for the ventilation of buildings in order to achieve air circulation and prevent backflow and air-lock entries in indoor spaces (Lenchek et al., 1987). On the other hand, in tropical countries especially in the urban areas, this constant air element is not consistently and reliably available and a mechanism that could provide a constant airflow is indispensable.

On the contrary, the VSDI system has been designed and applied for an isolated room but not for a room in multiple formats, where mostly only one external wall (façade) is available. In addition, the bi-directional airflow system and large areas of the co-planar void will reduce the airflow efficiency. In addition, the mid-ceiling air supply vent at the top was a spotted-type which does not allow for the airflow to be distributed evenly throughout the space. There are also human activities (respiration, cooking, electrical appliances, smoking, etc.) that affect the operative temperature and humidity and contribute in reducing the indoor air quality and comfort (Environmental Health Directorate, 1995). Without active mechanical devices, these internal emissions are impossible to be removed efficiently by natural means and a constant airflow is indispensable in providing health and comfort condition in indoor spaces (Mohd Sahabuddin & Gonzalez-Longo, 2018; Mohd Firrdhaus Mohd Sahabuddin & Cristina Gonzalez-Longo, 2019).

Several later studies conducted from 2015 to 2017 have examined several areas where dynamic insulation could possibly be paired with. The areas are micro-scale, latent and transient heat transfer; and infiltration of particles (Craig & Grinham, 2017). They suggested that dynamic insulation studies from the 1960s have shared some common features such as the use of raw insulation materials with additional materials are needed in the building envelope as well as the incorporation of an air-mixing cavity.

They also suggested that air filters are needed to improve indoor air quality and should be incorporated into the dynamic insulation system (Craig and Grinham, 2017). Another common feature of the research on dynamic insulation is the implementation of the system in vertical walls (Craig & Grinham, 2017; Elsarrag, Aboulnaga, Peacock, & Imbabi, 2006; M. S.-E. Imbabi, 2012), something seemed unpractical considering that occupants tend to place furniture and decorations near or on the walls. This approach might consequently disrupt the performance of the system or otherwise giving restrictions to the occupants on the wall usage. In order to overcome all the issues mentioned above, the dynamic insulation system needs to ensure indoor air quality and comfort as well as allowing for constant airflow (directional airflow). The use of directional airflow concept in housing units is recommended for mitigating the risk of airborne contaminants being released from a high-polluted area (Jennette, 2014; Olmsted, 2008) such as kitchens and bathrooms.

It can be concluded that many researchers have agreed that air pollution could be filtered by using dynamic insulation (Alongi & Mazzarella, 2015; Di Giuseppe, D'Orazio, & Di Perna, 2015; Elsarrag et al., 2006; Halliday, 1997; M. Imbabi, Campbell, & Lafougere, 2002; M. S. Imbabi & Peacock, 2003; B. J. Taylor et al., 1998), which also could reduce heat and humidity (Craig & Grinham, 2017; M. S.-E. Imbabi, 2012; Mohd Firrdhaus Mohd Sahabuddin & Cristina Gonzalez-Longo, 2019; Mohd Firrdhaus Mohd Sahabuddin & Cristina Gonzalez-Longo, 2019). It could be deduced that this method can improve indoor comfort issues in Kuala Lumpur, hence, it could be the best solution for high-rise buildings in hot-humid climates.

Conventionally, dynamic insulation integrates mechanical or hybrid ventilation into its system, hence, this strategy has a great potential in solving the four main indoor comfort issues in Kuala Lumpur. However, most of the dynamic insulation research was so far focused on the countries with cold and temperate climates but this technique has not been developed in tropical countries, including Malaysia. It could be deduced that the study on this topic mainly focused on the countries that experience a temperate climate.

After all, this study found that the design strategies of high-rise residential buildings in Kuala Lumpur should consider four design aspects in achieving indoor comfort – maintaining the ranges of comfortable temperature and humidity, reducing the air pollution and accelerating the air movement in indoor spaces. With these four considerations, a good healthy indoor comfort in Kuala Lumpur could potentially be achieved. Thus, the residential high-rise buildings in Kuala Lumpur, in the future, could successfully adapt to climate change and urbanisation. Even though there are a number of studies and strategies that have been conducted and proposed by many researchers and organisations, there is still no one optimum strategy that could be relied on to reduce the air temperature, humidity and air pollution, and to promote air movement at the present moment.

Referring to the above findings, this research will try to test a new dynamic insulation concept called the new ‘Airhouse’ Concept – a combination of dynamic insulation, hybrid ventilation, radiant cooling and active light-well. This concept combines the dynamic insulation in ceiling compartment and the hybrid ventilation where the air will flow in by assistance of a fan, filtered through the air filter and dynamic insulation membrane, cooled by radiant cooling and dispersed equally throughout the depressurised indoor space before the mixing indoor air will be taken out to the depressurised light-well using an extraction fan (Figure 2.42).

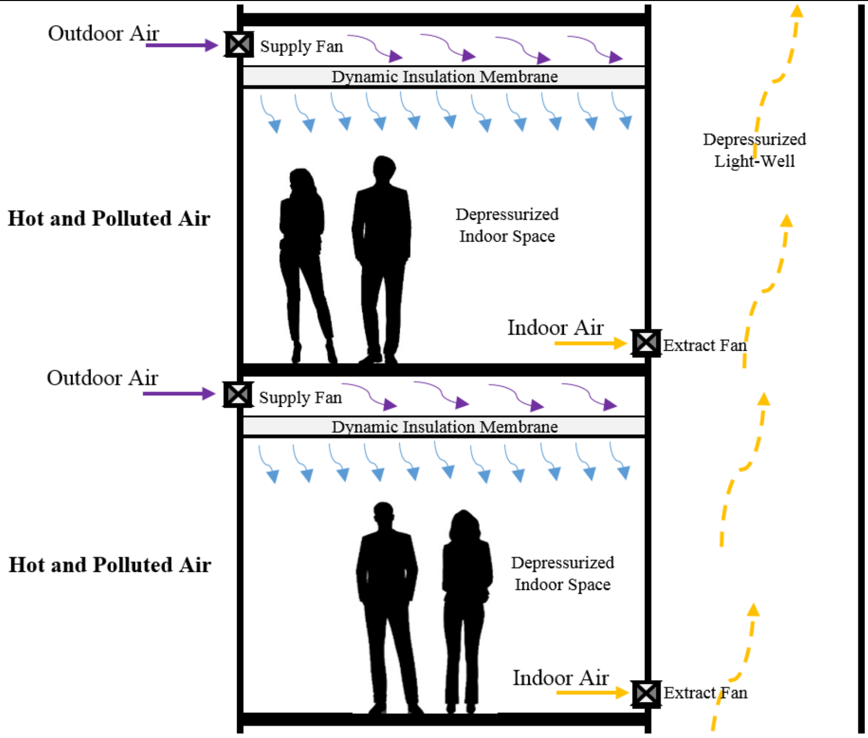


Figure 2.42: Schematic design concept of the proposed system

2.5.3 Case Studies

In the 1960s, dynamic insulation emerged as a building concept (Halliday, 2000). The porosity element of materials was investigated and recommended as a positive attribute for application in buildings. Then in 1965, the concept's basic thermal principle and mathematical technique that can predict its effectiveness was published in 1965 (Halliday, 2000). At that time, the application of dynamic insulation was only implemented in agricultural buildings especially in Austria, Canada, Norway and Sweden.

In the same period, Trygve Græe from the Norwegian University of Agriculture has developed dynamic insulation in ceiling compartment in farm buildings. His innovation works through airflow that was drawn naturally by stack ventilation under the eaves, pass through the loft that filled with hay layers. The air, then, preheated by the stored material before entering the ground floor (where the animals were kept) and to the lower level before drawn out through a sealed pipe which vented at a high level (Halliday, 2000) (Figure 2.43). This concept was largely used in Scandinavia countries especially in animal houses which need a high constant demand for ventilation combined with high moisture production. Later in Norway, the same principle was applied in schools, sports buildings and care buildings.

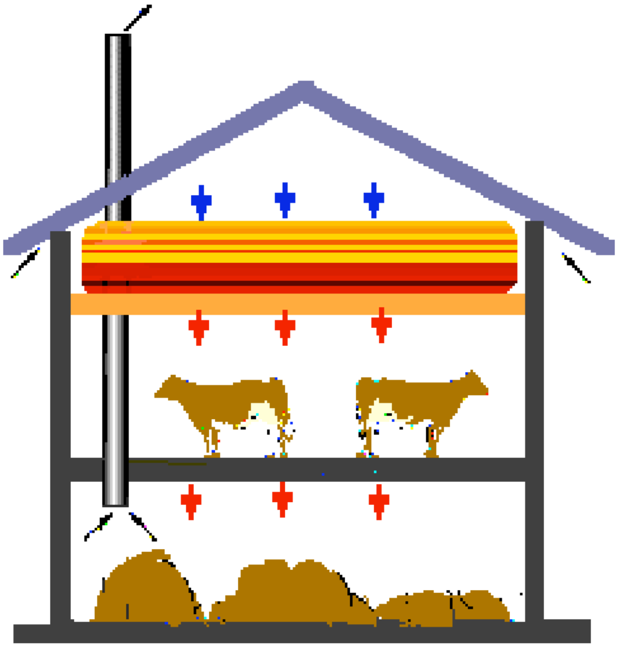


Figure 2.43: Conceptual diagram of dynamic insulation in ceiling compartment in farm building developed by Trygve Græe (Halliday, 2000)

In the 1980s, Thoren – a Swedish researcher, published a work concerned with the effects of the air exchange and transmission of heat by convection and radiation on dynamic insulation surfaces. While in Austria within the same period, Batussek and Hausleitner studied the physics of air movement through materials and developed a concept called Solpor System. This system introduced the pre-heating mechanism to the incoming air intake. Through a series of tests using a test cell and physical model of two private houses, they found that this system could reduce energy consumption without loss of comfort (Halliday, 2000).

In the 1990s, the dynamic insulation concept was widely accepted to be implemented in non-agricultural buildings. This includes a sports hall project in Rykkinnhallen, Norway that was completed in 1992. The basketball hall that has a 35-metres span of a curved roof, has applied the concept in its ceiling compartment and combined with roof-mounted fans to create pressurised-roof. The air that enters the hall is preheated through a 200 mm thick fibre insulation layer held by open-weave matting. The air is exhausted using grilles at 2.5 metres above floor level and then, the heat is collected using air-to-water heat pump for feeding the underfloor heating system (Figure 2.44). This technique has improved the indoor air quality and reduced the energy consumption of the building, where 50% of energy reduction is recorded over conventional buildings.

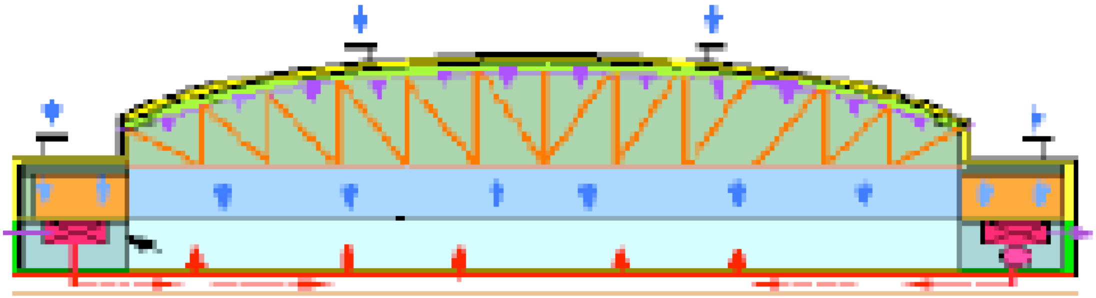


Figure 2.44: Theoretical diagram of dynamic insulation application in Rykkinnhallen Sports Hall (Halliday, 2000)

Baerum Nursing Home is another project located in Norway using the same principles as Rykkinnhallen but on a much smaller scale of an existing building. The building has a porous membrane located between the ceiling surface and pressurised loft compartment. Grilles are used to distribute the filtered air. This project uses the extraction point from the en-suite bathroom (directional airflow) – controlling and removing the moisture-laden air from the last point (Halliday, 2000). A heat pump is used to recover heat from the extract air (Figure 2.45). This method has produced a subjective sense of freshness which is unusual in healthcare facilities and supports the theory of contaminant diffusion in the air.

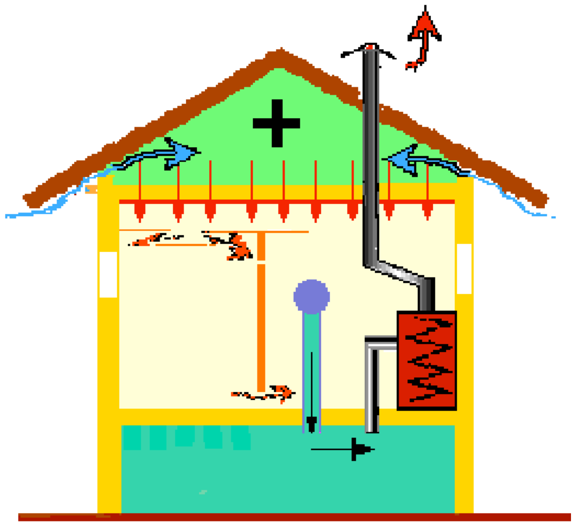


Figure 2.45: Theoretical diagram of dynamic insulation application in Baerum Nursing Home (Halliday, 2000)

Another project that implements dynamic insulation approach is Gullhaug Sheltered Housing in Baerum province in Norway. This project does not only apply the approach in loft compartment but also on the walls (Figure 2.46). Due to the unavailability of the ceiling compartment in the ground floor, this principle draws the air down from the upper floor to the ground floor through the cavity in the external walls. The air is preheated using a coil below the window sill and pre-cleaned using the insulation membrane before entering the habitable spaces. Similar to Baerum Nursing Home, the exhaust air is sucked out via the wet areas in the house such as kitchen and bathrooms and through an air-to-water heat pump. After three decades, the use of dynamic insulation in residential buildings and healthcare facilities in Scandinavia countries becomes common.

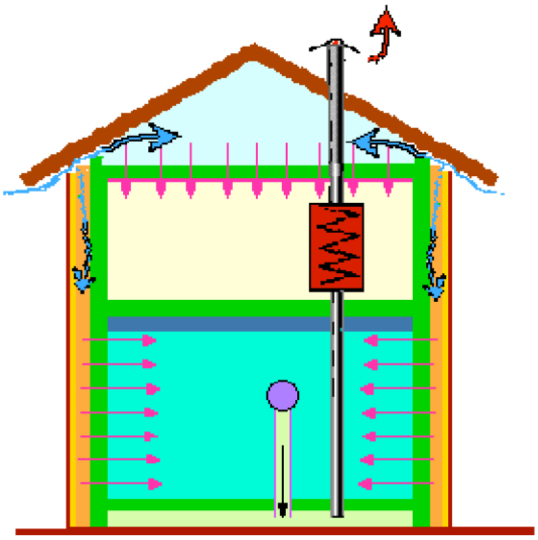


Figure 2.46: Theoretical diagram of dynamic insulation application in Gullhaug Sheltered Housing (Halliday, 2000)

As discussed earlier, the conventional dynamic insulation concept used a fan to suck the fresh air into the room and using the porous insulation, the fresh air will be warmed. Similar concept will be used in tropical climate but instead of warming the air, the new concept will cool the air as well as reduce moisture and airborne particles.

While in the UK, the first major building that uses this technique is the McLaren Community Leisure Centre (MCLC) – completed in 1998. The aim was to investigate the performance of the dynamic insulation in wet-side (swimming pool) and dry-side (bowling hall) environments of the sports complex. With the total area of approximately 3,591 sqm, this building introduces air into the swimming pool, wet changing, sports hall, squash courts and bowling areas using pressurised ceiling voids and through a dynamic insulation membrane. This layer consists of cellulose fibre, a layer of punctured ethylene and a visible layer of Heraklith ceiling tiles for the pool and bowling hall, while timber slats are used to replace Heraklith for the sports hall and squash courts (Halliday, 2000).

The main aim of the MCLC was to provide an energy-efficient and healthy building. Thus, for energy efficiency, a few strategies have been designed and implemented in the building. This includes a compact form and fabric of the building that integrates dynamic insulation to achieve the required temperatures, especially in high spaces. In terms of heating, all pools will get the benefit from the heat that recovers from extracted air and the ventilation rates at the minimum requirement and consistent for satisfactory indoor environment. Among other strategies that have been applied for achieving energy efficiency are low heating systems with lead condensing boilers, efficient domestic hot water delivery and well control lighting.

In terms of health aspects, this building implements minimum use of ductwork that is consistent with adequate air for ventilation, use of materials that do not produce negative effect to the indoor environment, use of downward ventilation for keeping the high humidity from the pool at lower level, and use of highly efficient filtration at air inlets and hygroscopic materials to reduce microbiological activity (Halliday, 2000). Among the factors that led to the incorporation of the dynamic insulation in this building were; structural soundness – where the pressurised ventilation was introduced to create dry roof space for reducing fabric maintenance requirements for long term benefits; healthy indoor climate – was achieved by implementing downward air distribution which could well-filter and well-distribute the air and at the same time reduce relative humidity levels especially in the pool areas; capital and running cost benefits – through the efficiency of ventilation rates, fan power demands could be reduced and consequently reached energy efficiencies (Halliday, 2000).

Figure 2.47 shows the conceptual diagram of the dynamic insulation system in the MCLC building where the system was designed for winter conditions of -5°C temperature and 100% RH. For the swimming pool hall, this area is ventilated by air supplied through the dynamic insulated ceiling. This technique was intended to supply the required fresh air at the velocity of 0.003 m/s (10 m/h) during winter and 0.007 m/s (25 m/h) during summer with a differential pressure of up to 35 Pa. When the air was drawn through the ceiling and dynamic insulation membrane, approximately 10°C to 13°C of heat (from the room’s internal design temperature of 30°C) was predicted to be added to achieve air temperature of 23°C to 26°C (Figure 2.47). Using humidistats, the pool hall humidity was controlled at 55-60%RH (Halliday, 2000).

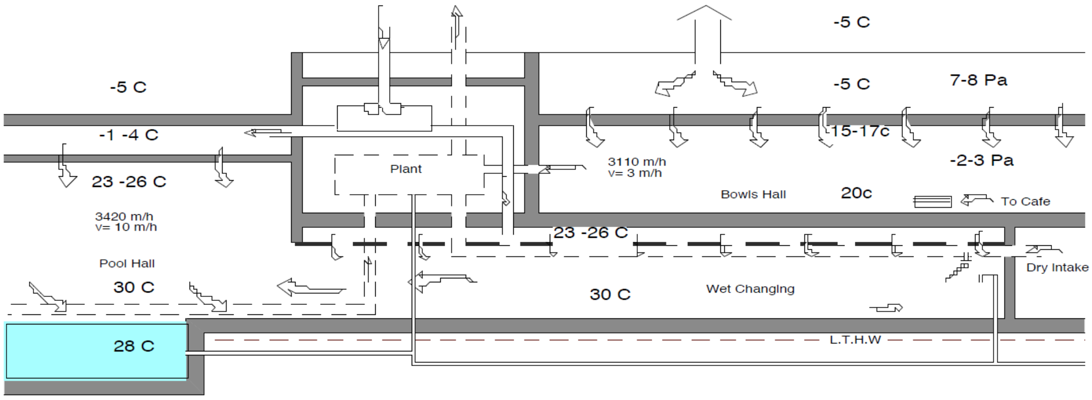


Figure 2.47: Conceptual diagram of dynamic insulation system in MCLC building (Halliday, 2000)

For the bowls hall, the filtered and unheated air is supplied into the loft of the hall at 0.8 m/s (3,110 m/h) and creating a pressure difference of about 10 Pa as well as providing an airspeed of 0.0008 m/s (3 m/h) through the ceiling. This was designed to achieve air temperature of 15°C to 17°C by the thermal exchange in the dynamic insulation membrane and with hot air at the upper part of the room (Figure 2.29). Using radiators, the temperature at occupancy height was set to be 20°C (Halliday, 2000).

Two years of on-site monitoring exercise (from 1998 to 2000) was conducted on this building to investigate the energy, health, buildability and cost issues related to dynamic insulation. The Gaia Architects – the designer of dynamically insulated buildings in Scotland, has produced a report in 2000 with inputs from a number of collaborators. This exercise also has contributed to understanding the performance of dynamic insulation in detail. Among the key strengths and weaknesses of the application of dynamic insulation in MCLC building are:

a. The required airflow rates through dynamic insulation membrane are achieved as designed, however, major rotary air movements were observed in the swimming pool and sports hall due to downdraughts from cold external walls and windows and up-draughts from radiators;
b. Rotary airflow was formed in the sports hall that gives advantage for reducing condensation risk, however, the strong drift velocity (between 0.2-0.25 m/s) below the ceiling also occurred;
c. The moisture levels recorded were low suggesting that the backflow of water vapour and moist air occurred in the pool areas, however, different humidity

levels were recorded at the condensation-prone perimeter (lower humidity) than at the extract points (higher humidity);

d. The dynamic insulation was found effective in transferring heat and preheating the air, however, overheating in the sports hall occurred during summertime and switching off supply fans is recommended;
e. Positive pressures in the swimming pool areas were significantly recorded leading to exfiltration of warm moist air from the pool to adjacent spaces – less extraction ventilation capacity was the main reason;

The report has also mentioned that the dynamic insulation system has made a significant contribution to the cost and operation of the building. However, the air quality investigation that was intended to be conducted (Halliday, 2000) is not executed until the moment this writing is completed. Above all, this project has contributed to significant information about dynamic insulation in detail in terms of its performance, strengths and weaknesses. The Gaia Architects in their report has also suggested several recommendations for future consideration on using this dynamic insulation system. Based on their experience from MCLC building, they concluded that if the system is applied correctly, the dynamic insulation has the potential to reduce insulation requirement, reduce fan power and reduce energy consumption. This system that provides filtered air is also believed can provide a clean internal environment. The main issues of this system are the buildability aspects that need to be met. The aspects – based on MCLC building, are:

a. Fully wind-proof outer skin to protect the porous surface from pressure fluctuations.
b. Closing the air leakage along joists is mandatory to force the supply air through the insulation and to avoid the risk of condensation.
c. Loft airtightness is absolutely compulsory. This aspect is the most important as pre-heated loft could sufficiently heat-up the habitable spaces.
d. Air leakage in the building fabric will short circuit the airflow.
e. The pressure differential of around 10 Pa is highly recommended as it would not cause problems with the door opening and shutting.
f. Another important aspect is the extract outlet should not be near light fittings as this will affect the downwards flow of the extract air.

All of the buildability aspects above, if not emphasised, will reduce the performance of dynamic insulation and create a pro-flux airflow which later will also create interstitial condensation. It is necessary to emphasise here that these findings are for the application of dynamic insulation in buildings located in cold and temperate climate where the heating demand is more than the cooling demand. It could be deduced that airtightness in the ceiling compartment and indoor spaces is mandatory. In addition, negative pressure condition in indoor spaces should also be achieved at all times for extraction of air efficiency.

2.5.4 Recent Application: Cleanrooms

In advance application using directional airflow, dynamic insulation has been implemented in healthcare and electronic facilities known as ‘cleanrooms’. As defined in the International Organization for Standardization (ISO) 14644-1: Cleanrooms and Associated Controlled Environments – Part 1, a cleanroom is defined as a ‘room in which the concentration of airborne particles is controlled, and which is constructed and used in a manner to minimise the introduction, generation, and retention of particles inside the room’ and in which other relevant parameters, e.g. temperature, humidity, pressure, vibration and electrostatic are controlled as necessary (ISO, 2015).

In the industry, these rooms are provided in the manufacturing of electronic hardware and in biotechnology and medicine, these rooms are used when it is necessary to ensure an environment that is free from bacteria, viruses, or other pathogens (Bhatia, 2012b). The basic rules for cleanrooms are:

1) Contaminants must not be introduced into the controlled rooms,
2) The materials or equipment within the controlled rooms must not generate contaminants,
3) Contaminants must not be allowed to accumulate in the controlled rooms,
4) Existing contaminants must be eliminated from the controlled rooms.

However, the integrity of the cleanrooms is totally created by the heating, ventilation and air-conditioning (HVAC) system which controls the required limits of contaminants (Bhatia, 2012b). This HVAC system requires:

1) Supplying airflow in sufficient volume and cleanliness,

2) Introducing constant air movement to prevent stagnant areas,

3) Filtering the outside air across high-efficiency particulate air (HEPA) filter,

4) Conditioning the air to meet the required temperature and humidity limits,

5) Ensuring enough air to maintain positive pressurisation.

On the other hand, the cleanroom HVAC system is more or less similar to the conventional HVAC system except three main differences that differentiate these two systems (Bhatia, 2012b) as follows:

1) Increased air supply – a normal HVAC system requires 2-10 air change rate/hour (ach), while a typical cleanroom would require 20-60 ach.
2) The use of high-efficiency filters – the use of HEPA filters in ceiling area is a key element of cleanrooms. This filter can eliminate 99.9% of particles and in most cases provide 100% ceiling coverage.
3) Room pressurisation – cleanrooms are positively pressurised. It is done by supplying more air and extracting less air from the controlled rooms.

In principle, cleanrooms apply three basic elements in its design – a blower or supply fan, a high-efficiency air filter and a plenum or space (Bhatia, 2012b). With the same basics, larger space requires more fans and filters. Typically, three airflow options are usually used in cleanrooms – unidirectional flow or laminar flow, non-unidirectional flow or turbulent flow, and mixed flow. The selection of the cleanroom criteria has to first identify the level of cleanliness as stated in Table 2.10. It shows the maximum permitted concentration of particles for each considered particle size. Unidirectional flow is typically assigned to ISO 4 and ISO 5 classes of cleanrooms that need stringent control of environment. For intermediate and less stringent environments, non-unidirectional flow or mixed flow are preferred (Table 2.10).

For example, cleanrooms with classes 10 (ISO 4) to 100 (ISO 5) will use unidirectional flow and cleanrooms classes more than 1,000 (ISO 6) to 100,000 (ISO 8) will use a non-unidirectional flow or mixed flow (Starke, 2012). The cleanrooms with classes of 10 to 100 require high air velocity and air change rate between 50 fpm to 110 fpm and 300 ach to 600 ach respectively (Starke, 2012), whereas the cleanrooms with classes of 1,000 to 100,000 require lower air velocity and ach between 10 fpm to 90 fpm and 10 ach to 250 ach respectively (Starke, 2012) (Table 2.11).

Table 2.10: ISO classes of air cleanliness by particle concentration (ISO, 2015)

ISO Class number (*N*)	Maximum allowable concentrations (particles/m³) for particles equal to and greater than the considered sizes, shown below[a]					
	0,1 µm	0,2 µm	0,3 µm	0,5 µm	1 µm	5 µm
1	*10*[b]	d	d	d	d	e
2	100	*24*[b]	*10*[b]	d	d	e
3	1 000	237	102	*35*[b]	d	e
4	10 000	2 370	1 020	352	*83*[b]	e
5	100 000	23 700	10 200	3 520	832	d, e, f
6	1 000 000	237 000	102 000	35 200	8 320	293
7	c	c	c	352 000	83 200	2 930
8	c	c	c	3 520 000	832 000	29 300
9[g]	c	c	c	35 200 000	8 320 000	293 000

a All concentrations in the table are cumulative, e.g. for ISO Class 5, the 10 200 particles shown at 0,3 µm include all particles equal to and greater than this size.

b These concentrations will lead to large air sample volumes for classification. Sequential sampling procedure may be applied; see Annex D.

c Concentration limits are not applicable in this region of the table due to very high particle concentration.

d Sampling and statistical limitations for particles in low concentrations make classification inappropriate.

e Sample collection limitations for both particles in low concentrations and sizes greater than 1 µm make classification at this particle size inappropriate, due to potential particle losses in the sampling system.

f In order to specify this particle size in association with ISO Class 5, the macroparticle descriptor M may be adapted and used in conjunction with at least one other particle size. (See C.7.)

g This class is only applicable for the in-operation state.

Table 2.11: Cleanroom design criteria (Bhatia, 2012a; ISO, 2015)

Cleanroom Design Criteria					
Criteria	**Class Limits**				
	10 (ISO 4)	**100 (ISO 5)**	**1,000 (ISO 6)**	**10,000 (ISO 7)**	**100,000 (ISO 8)**
Air Change Rate (ach)	300-600	300-480	150-250	60-120	10-40
HEPA Filter Coverage (%)	100	70-100	30-60	10-30	5-10
CFM per Sq.Ft.	90	65-36	32-18	16-9	8-5
Typical Filter Efficiency	99.9997	99.997	99.997	99.997	99.97
Typical Filter Velocity (fpm)	60-110	50-90	40-90	25-40	10-30
Airflow Type	Unidirectional	Unidirectional	Non-unidirectional / mixed	Non-unidirectional / mixed	Non-unidirectional / mixed
Return Air System	Raised Floor	Low Wall	Low Wall	Low Wall or Ceiling	Low Wall or Ceiling
Controls	Stringent	Stringent	Intermediate	Intermediate	Less Stringent

The unidirectional flow pattern where air moves vertically downward from the ceiling to a return air plenum on a raised floor or wall. To ensure its efficiency, 100% of ceiling or wall coverage is recommended (Figure 2.48). It is designed for air velocity of 60 fpm to 90 fpm to keep the contaminants directed downward or sideward before they settle onto surfaces (Bhatia, 2012a).

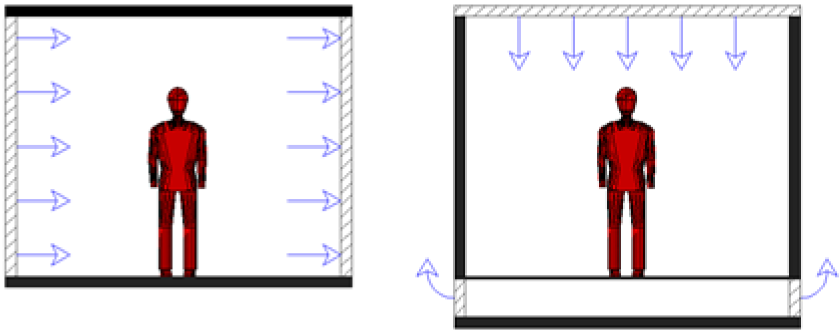


Figure 2.48: Unidirectional flow pattern in a cleanroom (MECHON, ND)

The method of non-unidirectional flow is often used in cleanrooms with the classification of 1,000 and above where intermediate control environment is needed. Due to the random pattern of air streamlines, pockets of air with high particle concentrations will occur. However, these pockets could only persist for a short period of time before disappearing through the random nature of the downward airflow (Bhatia, 2012b). Typically, sidewall return arrangement is used with non-unidirectional flow (Figure 2.49).

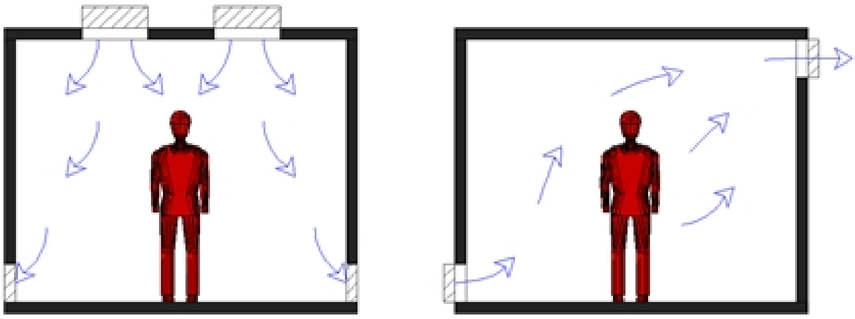


Figure 2.49: Non-unidirectional flow pattern in a cleanroom (MECHON, ND)

The mixed flow technique is used when there are critical and non-critical processes in the same space. These activities are divided by creating different zones in the space (Figure 2.50). More filters are installed in the ceiling of the zone that needs stringent control. For less stringent zone, fewer filters are installed. Return air arrangements are adjusted by locating sidewall grilles. For more effective results, raised floor could be used (Bhatia, 2012b).

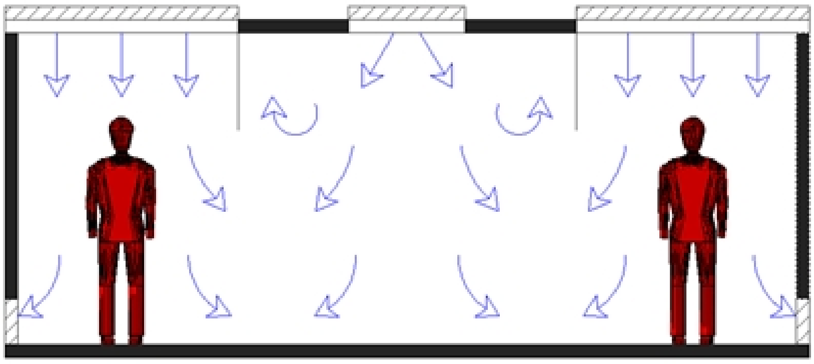


Figure 2.50: Mixed flow pattern in a cleanroom (MECHON, ND)

In a normal application, cleanrooms require air temperature and humidity conditions to be set at 20°C and 45% to 50% RH respectively (Bhatia, 2012b). Thus, to achieve these conditions constantly, cleanrooms are usually associated with HVAC systems (Bhatia, 2012a). With these stringent conditions, the concept of dynamic insulation in cleanrooms demands high energy consumption (Bhatia, 2012b) to condition the air with the right air change rate, air temperature (20°C) and humidity (45% to 50% RH). Undoubtedly, the combination of cleanrooms and HVAC system is highly energy-intensive, and the use of efficient HVAC have largely been ignored by the large profit companies. Considering that this system could control indoor spaces to be in good thermal and air quality environments, it is a necessary to re-evaluate the basic methods of cleanrooms and re-consider it in domestic buildings. As the application of these kind of systems in residential buildings are still undiscovered (which remains a mystery), this research will investigate the potential of dynamic insulation using cleanroom rules in providing health and comfort in high-rise social residential buildings in hot-humid climate.

In order to design an optimum dynamic insulation system in high-rise social housing in Kuala Lumpur, the actual thermal and air quality conditions of Kuala Lumpur need to be evaluated in the first place. Two fieldwork campaigns were conducted and explained in detail in Chapter 3. The first fieldwork was conducted in the dry season (July 2017) and measured the indoor thermal comfort parameters, including air temperature, operative temperature, relative humidity and airspeeds. The second fieldwork in the wet season (December 2017) measured both thermal comfort and indoor air quality parameters: PM_{10}, $PM_{2.5}$, CO_2 and CO. Only by establishing these conditions, the right design of dynamic insulation system using cleanrooms design rules that also taking into accounts of energy efficiency, could be determined.

This chapter has considered the application of dynamic insulation concept that mostly has been implemented in temperate climate countries. The potentials of the technique that can improve indoor comfort are really much appropriate to be implemented in tropical climate conditions. Therefore, in the next chapter the research investigates the actual indoor comfort conditions in high-rise social housing in Kuala Lumpur through fieldwork studies and computer simulation. These campaigns are crucial to determine the suitability of the concept in addressing the indoor comfort issues in the city.

3. CHAPTER 3: Actual Indoor Comfort in High-Rise Social Housing in Kuala Lumpur: Fieldwork and Computer Simulation

3.1 Identifying the Case Studies: People's Housing Program (PPR)

As discussed in Chapter 2, the Malaysian building regulations set the requirements for the key design of ventilation elements such as openings, atriums and light-wells in high-rise residential buildings (Lucon et al., 2014; Mohd Sahabuddin & Gonzalez-Longo, 2017; UBBL, 2013). Therefore, it is important to assess the suitability and effectiveness of this approach in providing comfort and health to the occupants.

The People's Housing Programme (PPR) in Malaysia is a government initiative to relocate the squatters and solve the housing woes of low-income groups in urban areas (Ministry of Urban Wellbeing, 2015). Kuala Lumpur – the capital city of Malaysia, has accommodated approximately 47% of the total PPR units so far and all of them are in high-rise buildings (JPN, 2016; MAMPU, 2016a). Two generations of PPR were produced by the Ministry of Urban Wellbeing Malaysia with two different designs: the first one used an open plan concept with atriums and the second, with a compact design with light-wells (Figure 3.1).

This change was also intended for improvements on shared facilities (multi-purpose halls, chaplaincy, child nurseries, playgrounds and open areas) (BERNAMA, 2013), but without considering the improvement on its indoor comfort. Thermal comfort and health issues which are crucial for the quality of life of the occupants (Ismail et al., 2015; Samad et al., 2016; N. Zaid & Graham, 2011), were not looked at and consequently, the occupants have to add individual air conditioning units shortly after occupying the buildings to address this indoor discomfort.

A few probabilities of thermal and air quality conditions in PPR buildings were suggested in Chapter 2, where the air temperature and air pollution are predicted to be low at a high level than the lower level. This is due to the stratification of air velocity according to building height. It was also predicted that the lower part of the buildings will be in high-risk condition: high temperature, high pollution and low air movement.

To investigate the actual thermal comfort and air quality conditions in these PPR buildings, two fieldwork campaigns were conducted. The first fieldwork was conducted in the dry season (July 2017) and measured the indoor thermal comfort parameters, including air temperature, operative temperature, relative humidity and airspeeds. The second fieldwork was in the wet season (December 2017) measured the air quality parameters: PM_{10}, $PM_{2.5}$, CO_2 and CO.

Two case studies representing the first and second generation of PPR located in Kuala Lumpur were selected to carry out the fieldwork in order to gather the necessary data. The first case study for the first generation was PPR Beringin, and PPR Seri Aman for the second generation. These two PPR complexes are located at the Northern part of Kuala Lumpur with only 500-metres (0.31 mile) distance between them.

The Department of Environment Malaysia (DOE) has also placed two stations to measure the air quality in Kuala Lumpur which are in Batu Muda and Cheras. The Batu Muda station and the Cheras station are just 6.08 km (3.78 miles) and 14.64 km (9.10 miles) away from the fieldwork sites respectively (Figure 3.2). Due to the similar geographic location, the surrounding environment and the locations of the DOE's air quality stations, these two PPRs are the most suitable to be used for these fieldwork studies.

Figure 3.1: PPR first generation (left) and PPR second-generation (right) of PPR in Kuala Lumpur

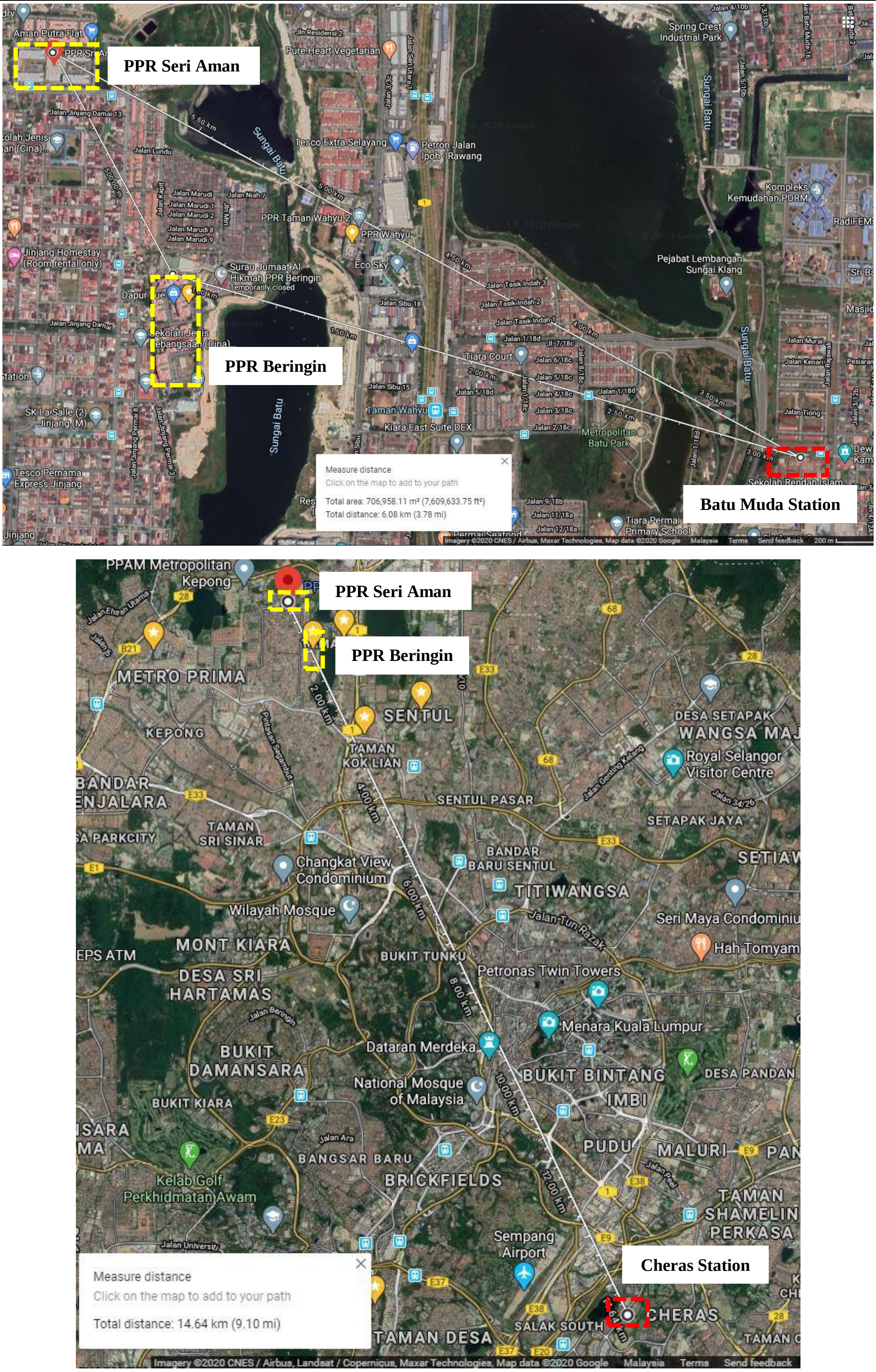


Figure 3.2: The location and distance of the Batu Muda Station and Cheras Station from the case studies (Source: Google Maps)

3.2 Methodology for Evaluating Thermal Comfort and Air Quality

The methodology used for evaluating thermal comfort in the case studies consisting of two campaigns of fieldwork and a computational simulation model. The fieldwork studies were conducted in two main seasons (dry and wet) in Malaysia, hence, they are not representing the whole year thermal comfort data of Kuala Lumpur. Therefore, simulation modelling using Integrated Environmental Solutions (IES) was also conducted to evaluate the full-year data of the thermal comfort of the city.

IES is chosen because of its high reputation and reliability as one of the most commonly used simulation software by many researchers (Marko Jarić, Nikola Budimir, Milica Pejanović, & Svetel, 2013). The software is suitable for simulating naturally ventilated buildings through its ‘Macroflo’ (Crawley, Hand, Kurnmert, & Griffith, 2008) and ‘Apache’ for the detailing of the building systems, allowing their optimisation, taking into account the criteria such as comfort and energy (Sousa, 2012). Apart from its economic aspect, this software costs the least time for simulating and calculating the environmental conditions of a 3D model (Li, 2015). The results gathered from both methods then will be compared and adjusted to establish a thermal comfort background in Kuala Lumpur for further comparative purposes in this study.

For air quality, simulation software that could simulate the concentration of air pollution substances such as CO, SO_2, benzene and particulate matter, is very limited. CONTAM can measure IAQ but the contaminants are classified as trace and non-trace contaminants only. Thus, the fieldwork results (indoor and outdoor conditions) and the full-year data of air quality in Kuala Lumpur from a third party (outdoor conditions only) will be used for further comparative purposes in this research (Table 3.1).

Table 3.1: Methodology for evaluating thermal comfort and air quality

Parameters	Fieldwork	IES Simulation	Third-Party
Thermal Comfort	Seasonal Data	Full Year Data	-
Air Quality	Seasonal Data	-	Full Year Data

3.2.1 Selection of Locations for Data Capture

The fieldwork was carried out between 11th and 29th July 2017, when the Southwest Monsoon was active. This Monsoon runs from May to September every year and provokes relatively dry weather, with an average prevailing wind speed (coming from the Southwest), usually below 15 knots (7.7 m/s) (MET, 2017b).

Carrying out the necessary fieldwork during this dry season is highly recommended due to the highest temperatures that usually occur in this period every year (MET, 2017b).

According to ASHRAE 55, the location of the instruments wherein an occupied zone should be located at the spot where the occupants are known to spend most of their time. For the unoccupied spaces, the location of the instrument should be at the centre of the room or space. In the cases of the PPR units, bedrooms are the best data gathering locations for occupied and unoccupied units since the majority of the occupants work during the day and spend most of their remaining time resting and sleeping.

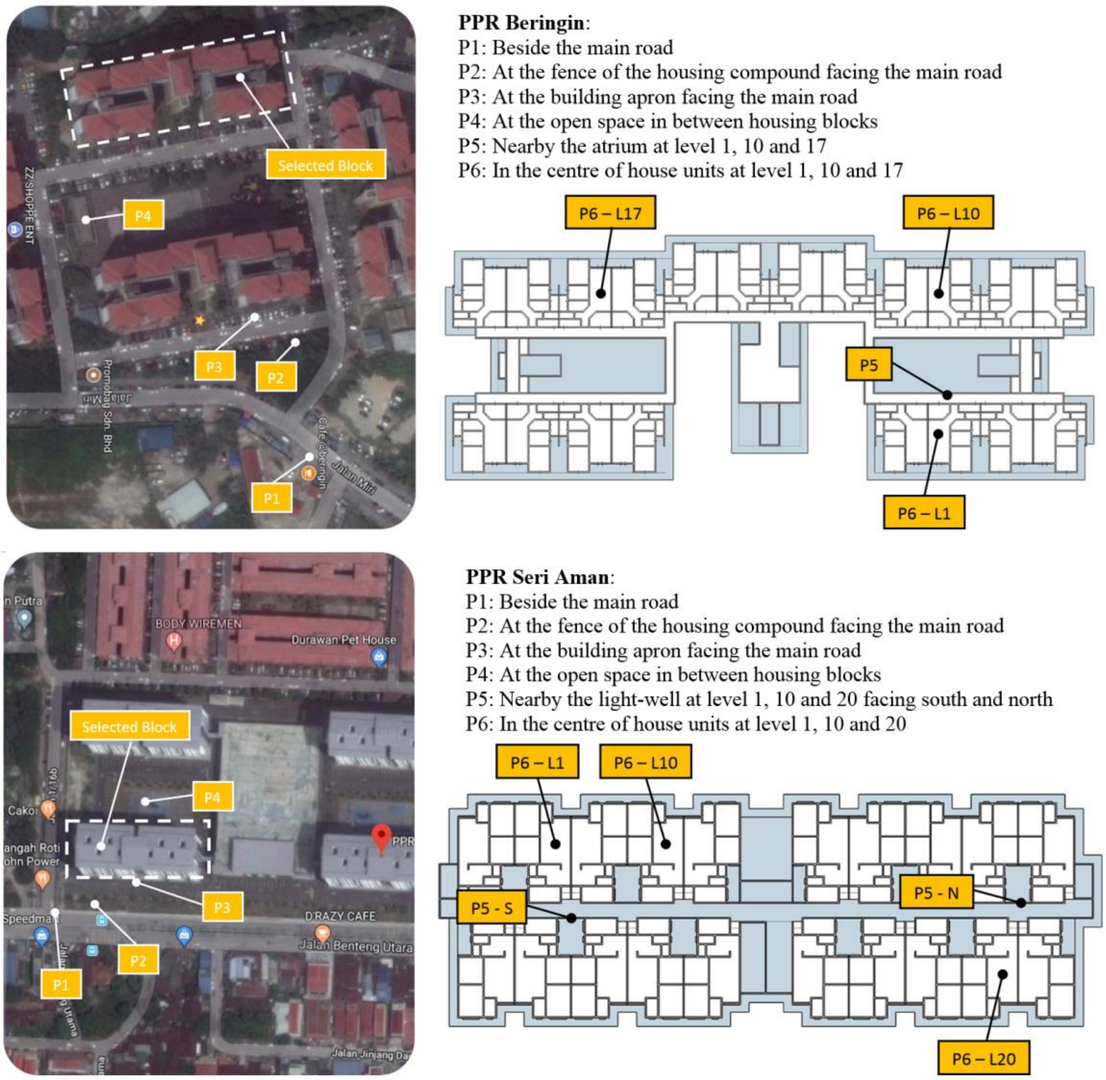


Figure 3.3: Locations of outdoor, semi-outdoor and indoor measurement points in PPR Beringin and PPR Seri Aman

For these fieldwork studies, two types of sampling location were used, located at the outdoor and indoor areas. Four outdoor locations were determined which are beside the main road (P1), at the fence of the housing compound or buffer zone (P2), at the sample block's apron (P3) and at the open space in between the blocks (P4). For indoor and semi-indoor locations, two points were selected which are near the atrium areas (P5) and in the centre of the house units (P6). Figure 3.3 shows the indoor and outdoor locations of measurement for both PPRs.

Similar to what happens in all the PPR buildings, the bedrooms were initially designed to be naturally ventilated. However, during the fieldwork study, a bedroom facing the atrium at level 10 of PPR first generation was using the air-conditioning system for several hours at night. All of these bedrooms were also supposed to have single-sided ventilation but the occupants have installed curtains and blinds and thus, making the interior susceptible to external influences. Ceiling fans, in most cases, were periodically switched-on to provide air movement in these rooms. These changes are among regular additions and modifications made by the occupants after the occupation.

3.2.2 Method of Assessment

Following a review of the different standards, the evaluation of thermal environment in ASHRAE Standard 55 – 'Thermal Environmental Conditions for Human Occupancy' was found to be the most suitable for this study as it is an internationally recognised standard which has been updated on a regular basis since its formulation back in 1966 (ASHRAE, 2013). As mentioned before in Chapter 2, the standard defines indoor comfort by addressing six primary criteria which have been segmented in two groups of factors: environmental factors (air temperature, radiant temperature, airspeed and relative humidity) and human factors (metabolic rate and clothing insulation) (ASHRAE, 2013). The methodology to be used in assessing comfort in indoor environments is as recommended in ASHRAE 55-2013 (Table 3.2).

According to ASHRAE 55 recommendations; 0.6 m and 1.1 m height from the floor level could be the best height of measurements for seated activities in evaluating the operative temperature, airspeed and humidity respectively (ASHRAE, 2013). However, this standard indicates only the measuring period for operative temperature and airspeed, which is three minutes as the most minimum time. There are only two measuring conditions suggested in this regard. These could be identified during the heating periods (winter conditions) and cooling periods (summer conditions). For this study, the measuring conditions during the cooling period were preferred due to the local hot and humid climatic conditions.

Table 3.2: Evaluation of thermal environment in accordance with ASHRAE 55 (Thermal Environmental Conditions for Human Occupancy)

Parameters	**ASHRAE 55 Recommendations**
Measuring Device Criteria	Meet the requirements in ASHRAE Standard 70 or Standard 113 or ISO 7726
Measurement Positions	Location of Measurements: a. In occupied zones - where the occupants are known to spend their time, OR b. In unoccupied rooms – an estimate of the most significant future occupant locations within the room, OR c. If occupancy distribution cannot be estimated – in the centre of the room Height Above Floor of Measurements: a. Operative temperature – at the 0.6 m level for seated occupants and 1.1 m level for standing occupants b. Airspeed – 0.1, 0.6 and 1.1 m levels for sedentary occupants c. Humidity – shall be measured at 0.6 m high from floor level for seated occupants
Measuring Periods	a. Temperature – minimum 3 minutes to 15 minutes to average cyclic fluctuations b. AirSpeed – for determining the average airspeed at any location shall be three (3) minutes
Measuring Conditions	a. Test during the cooling period (summer conditions)

For air quality, the methods for monitoring the indoor air quality (IAQ) set by WHO was referred for this fieldwork study. Table 3.3 shows the relevant specifications of sampling parameters for air quality measurement. According to the organisation, the two main types of samplers are gases and particles (WHO, 2011). The minimum duration of air quality sampling is 48 hours and therefore, this study will take the measurement for 54 hours consisting of three days in the weekend and weekdays. The sampling period was only from 6 am to 12 am (18 hours) a day. After midnight, the period (12 am to 6 am) was not suitable to measure due to safety factors and privacy reasons of the occupants.

Table 3.3: Specific considerations of sampling parameters for air quality measurement

Parameters	**WHO – Methods for Monitoring IAQ**
Type of samplers	IAQ parameters (PM_{10}, $PM_{2.5}$, CO_2 and CO)
Duration of sampling	54 hours (weekend and weekdays)
Sampling time	Every 3 hours (from 6 am to 12 am)
Outdoor air sampling	4 points (at various distance from the main road)
Indoor air sampling locations	2 points (indoor and semi-indoor) at lower, intermediate and higher levels of the sample block
Potential sources of emission activities	The peak period of vehicular movement (source of outdoor combustion), The peak period of human activities (source of indoor combustion)

3.2.3 Equipment and Instruments

For the on-site data gathering, four types of equipment were used to measure the thermal comfort parameters (air temperature, operative temperature, relative humidity and airspeed) and two equipment for IAQ parameters (PM_{10}, $PM_{2.5}$, CO_2 and CO). The best practice was to use the equipment and instruments that have the data logging functions, but due to financial and time constraints (including the unavailability of the suitable equipment from the university sources), the authors had to purchase several instruments while a few others were borrowed from a third party (person or organisation). This constraint resulted in the equipment obtained need to be used manually. This means that the data was logged manually by the authors according to the time and period that had been planned. Even though several of the equipment and instruments are manually operated, the accuracy of the data recorded is reliable as claimed by several researchers (Moreno-Rangel, Sharpe, Musau, & McGill, 2018).

The instruments used for thermal comfort evaluation in the first fieldwork were Tiny Tag Ultra 2, Kimo AMI 310 and Aercus Instruments WS1093 (Figure 3.4). The measuring ranges, accuracy values and recording methods for each of the thermal comfort equipment are demonstrated in Table 3.4. The TinyTag Ultra 2 can monitor the temperature and humidity with the ranges between -25°C to 85°C with accuracy of ±0.4%; while for RH, 0% to 95% RH with accuracy of ±3.0% RH. For internal and incoming airspeeds, the Kimo AMI 310 and Aercus WS1093 measure the airspeeds at the range of 0 m/s to 44 m/s with accuracy of ±3% for reading ±0.1m/s.

Table 3.4: Measuring ranges and recording method for thermal comfort

Equipment	Parameter(s)	Ranges	Accuracy	Recording Method
TinyTag Ultra 2	Air temperature	-25°C to +85°C	±0.4% at 25°C	10-min log intervals
	Relative Humidity	0% to 95% RH	±3.0% RH at 25°C	10-min log intervals
Kimo AMI 310	Internal airspeed	0 to 3 m/s	±3% of	10-min log intervals
Aercus WS1093	Incoming airspeed	0 to 44 m/s	±0.1m/s	10-min log intervals

Figure 3.4: The thermal comfort instrument

This research used two types of direct-reading instrument for IAQ evaluation. The first instrument, Fluke 975 Airmeter, was used to measure the CO_2 and CO and the other tool, HoldPeak SD-5800D, was used to monitor PM_{10} and $PM_{2.5}$. Table 3.5 lists the measuring ranges, accuracy values and display resolution for all equipment in this second fieldwork. The Fluke 975 Airmeter can monitor the gases with the ranges between 0 ppm to 5000 ppm and accuracy of 2.75% + 75 ppm for CO_2 and 0 ppm to 500 ppm with accuracy of ± 5% or ± 3ppm for CO. For the PM_{10} and $PM_{2.5}$ monitoring tool, the concentration ranges for both substances are similar between 0 µg/m^3 to 999.9

μg/m³ with accuracy of ±20% or ±15 μg/m³ (maximum). All equipment used were set to manufacturer calibration data.

Table 3.5: Measuring ranges and recording method for air quality

Equipment	Parameters	Ranges	Accuracy	Display Resolution
Fluke 975	CO_2	0 to 5000 ppm	2.75% + 75ppm	1 ppm
Airmeter	CO	0 to 500 ppm	± 5% or ± 3ppm	1 ppm
HoldPeak	PM_{10}	0~999.9 μg/m³	±20% or ±15	0.1ug/m³
SD-5800D	$PM_{2.5}$	0~999.9 μg/m³	μg/m³ (max.)	0.1ug/m³

Figure 3.5: The air quality instrument

3.2.4 Parameters, Ranges and Limits

In July 2017, when the fieldwork was carried out, Kuala Lumpur received an average monthly outdoor air temperature of 29°C (MET, 2017b) and the daily mean outdoor temperature for a year in Kuala Lumpur was 24°C (Milne, 2016). As mentioned in Chapter 2, considering the monthly outdoor temperature and two equations, the lower margin of the comfort temperature in Kuala Lumpur is 24.7°C and the upper margin is 28.7°C (CIBSE, 2015). Even though the formula was developed using the data collected primarily in European office buildings, the indoor operative temperature suggested is in line with several previous studies done in Malaysia (Gagge, Stolwijk, & Hardy, 1967; Mohd Sahabuddin & Gonzalez-Longo, 2015; Zain et al., 2007). For relative humidity and airspeed, the ranges provided by the standard are 40% to 70% RH and 0.15 m/s to 0.50 m/s respectively (Table 3.3).

As discussed in Chapter 2, ASHRAE 55 has set different figures for the comfort conditions in Kuala Lumpur. For an acceptable operative temperature in naturally conditioned spaces, the suggested temperature range according to Kuala Lumpur's outdoor mean temperature is between 24.0°C and 28.4°C (ASHRAE, 2013). For the relative humidity and airspeed, the standard set below 65% RH and between 0.15 m/s to 0.80 m/s respectively (ASHRAE, 2013) (Table 3.6).

In Malaysia, the standard that set the indoor design conditions for air temperature, relative humidity and airspeed is MS1525. Unlike CIBSE and ASHRAE standards, these design conditions are for air-conditioned spaces only. Figure 3.6 shows the comfort zone (green area) for Kuala Lumpur on a psychrometric chart according to ASHRAE 55, CIBSE Guide A and MS1525. This zone will be the benchmark for the study and will be used for future comparison in this research.

Table 3.6: Parameters, ranges and limits for fieldwork study

Parameters	**CIBSE Guide A (2015)**	**ASHRAE 55 (2013)**	**MS1525 (2014)**
Recommended Thermal Comfort Criteria			
Operative Temperature	24.7 – 28.7ºC	24.0°C – 28.4ºC	24°C – 26ºC
Relative Humidity	40 – 70 %RH	<65 %RH	50 – 70 %RH
Air Speed	0.15 – 0.50 m/s	0.15–0.80 m/s	0.15 – 0.50 m/s

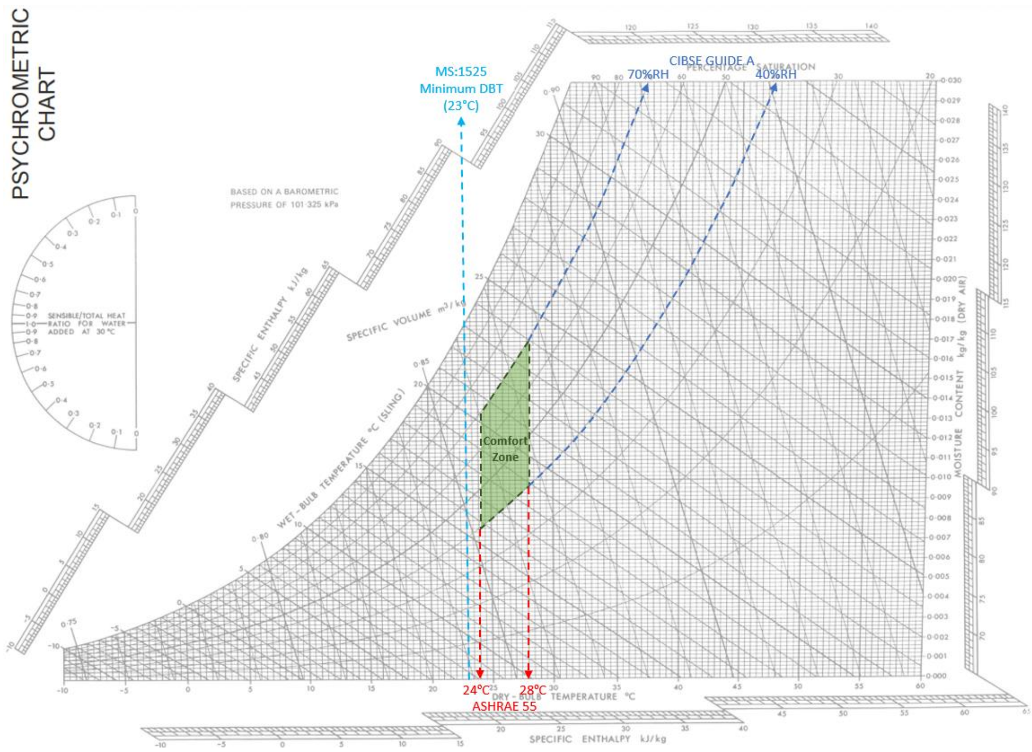


Figure 3.6: Kuala Lumpur's comfort zone on the psychrometric chart

As a major issue worldwide, which needs to be addressed, many organisations have produced guidelines and recommendations to measure and monitor the limits for various types of airborne pollutants. WHO, through its ambient air quality guidelines, has set the PM_{10} and $PM_{2.5}$ limits at 20 µg/m^3 and 10 µg/m^3 respectively (WHO, 2006) and DOE has set 40 µg/m^3 and 15 µg/m^3 for the substances (DOE, 2013), while CIBSE and ASHRAE have proposed 50 µg/m^3 and 15 µg/m^3 for the PM_{10} and $PM_{2.5}$ limits (Table 3.7). The values are for the annual mean concentrations.

CO_2 is one of the parameters measured and the limits for the gas according to CIBSE KS17 and DOE are 5000 ppm and 1000 ppm respectively. The DOE's limit is to indicate the adequacy of ventilation in any particular room. Hence, readings above this limit show an indication of inadequate ventilation (DOSH, 2010). CO, another gas measured in this study, has different limits set by CIBSE, ASHRAE and DOE which are 26 ppm, 35 ppm and 30 ppm respectively (Table 3.7).

Table 3.7: Parameters and limits of several guidelines

Parameters	**WHO [1]**		**CIBSE KS17 [2]**		**ASHRAE 62.1 [3]**		**DOE Malaysia [4]**	
	1 year	24hours	1 year	24 hours	1 year	24 hours	1 year	24 hours
	µg/m^3		µg/m^3		µg/m^3		µg/m^3	
PM_{10}	20	50	50	150	50	150	40	100
$PM_{2.5}$	10	25	-	-	15	65	15	35
	ppm		ppm		ppm		ppm	
CO_2	-	-	-	5000	-	-	-	1000
CO	-	-	-	26	9	35	10	30

Notes: [1] WHO Ambient Air Quality Guidelines
[2] Indicated exposure limits for selected airborne pollutants
[3] The concentration of interest for selected contaminants
[4] New Malaysia Ambient Air Quality Standard (Department of Environment Malaysia)

3.3 Case Studies

3.3.1 PPR Beringin (First Generation)

The PPR Beringin, first occupied in 2004, consists of six blocks of 18-storey and 15-storey height, with 1,896 units in total (316 units per block). The design of each block includes two large open atriums in each block to provide natural lighting and ventilation into inward rooms and a row of residential units abutting to a corridor (Figure 3.7). The windows are composed by single-glazed glass louvres. Three units in block C located at level 1, level 10 and level 17 were selected, representing the lower, intermediate and upper parts of the block and the different conditions of obstructions (Figure 3.8).

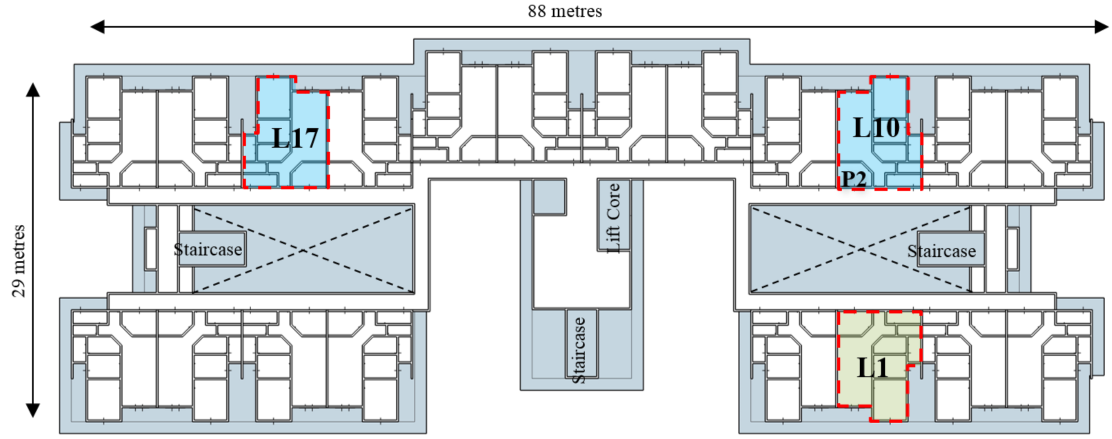


Figure 3.7: Typical floor plan of PPR Beringin (First Generation)

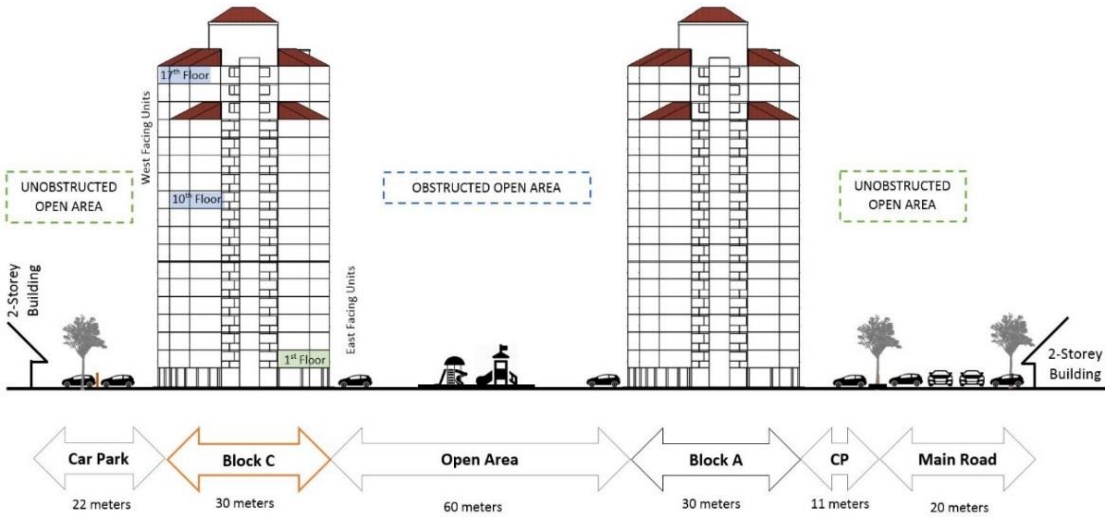


Figure 3.8: Site section of PPR Beringin

3.3.2 PPR Seri Aman (Second Generation)

The PPR Seri Aman, the second generation of PPR, was completed in March 2017 and currently accommodates approximately 1,560 units in four blocks of 20-storey and 19-storey height. This second generation PPR consists of two rows of residential units abutting to a corridor, with an enclosure setting environment compared to the previous design. In contrast to PPR Beringin, light-wells are the main source of natural lighting and ventilation for the bedrooms, kitchens and bathrooms facing towards the corridor (Figure 3.9). Single-glazed casement windows are installed in this PPR second generation instead of the glass louvres in the previous design. Six house units were selected in block A to represent the block's lower, intermediate and upper zones. Three of the units are facing an unobstructed open areas and three other are facing an obstructed open area (Figure 3.10).

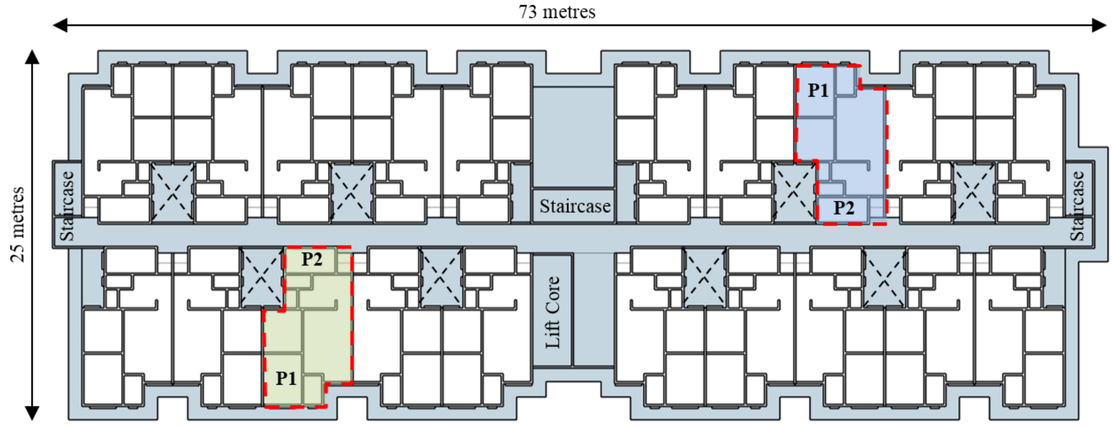


Figure 3.9: Typical floor plan of PPR Seri Aman (Second Generation)

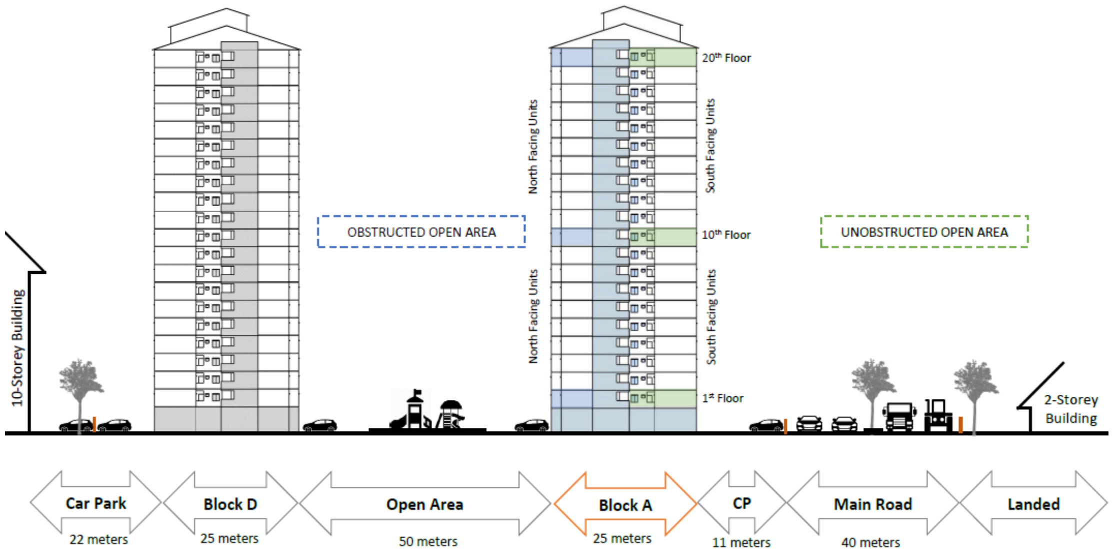


Figure 3.10: Site section of PPR Seri Aman

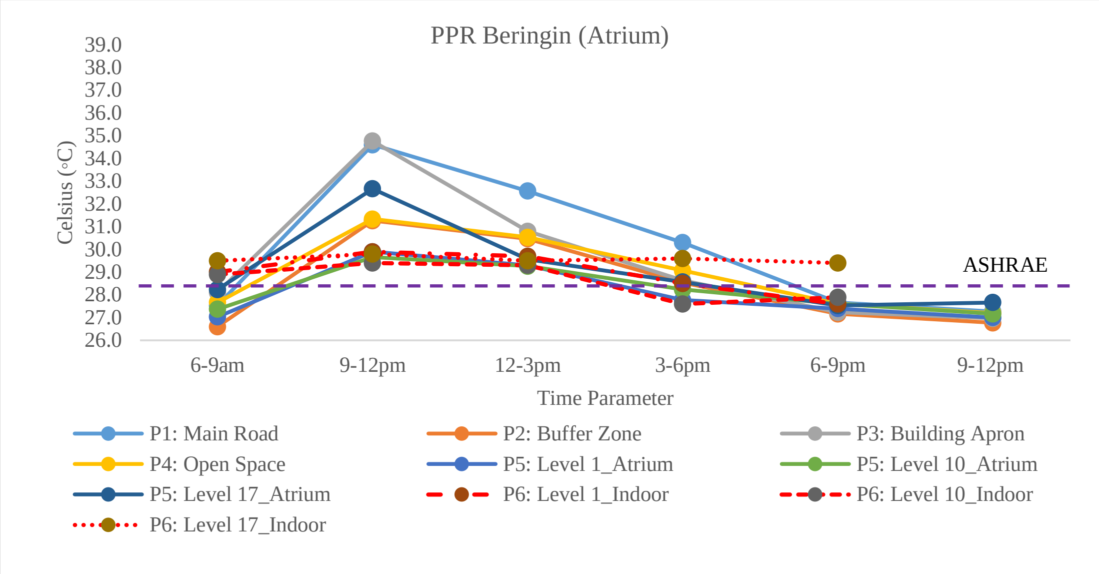
3.4 Fieldwork 1: Results and Analysis

3.4.1 Thermal Comfort

<u>Air Temperature</u>

The average air temperatures at all points in PPR Beringin (atrium) from 9 am to 6 pm have generally exceeded the 28.0°C limit set by ASHRAE 55 and CIBSE Guide A. The average operative temperatures for indoor spaces in three house samples were recorded between 27.5°C to 30°C from 6 am to 9 pm. The operative temperature at level 17 was recorded with a constant pattern between 29°C to 30°C from 6 am to 9 pm (Figure 3.11). This scenario formulates that indoor spaces in PPR Beringin were generally in an uncomfortable situation during the daytime.

For PPR Seri Aman (light-well), all the outdoor points (P1 – P4) had recorded a very high air temperature range of 29°C to 38°C. The average operative temperature (indoor) at P5 (near to light-well) and P6 (in the centre of house unit) were between 28°C to 31°C which mostly surpassed the CIBSE limit (Figure 3.11). This larger margin shows that the indoor spaces in PPR Seri Aman were more uncomfortable than in PPR Beringin.



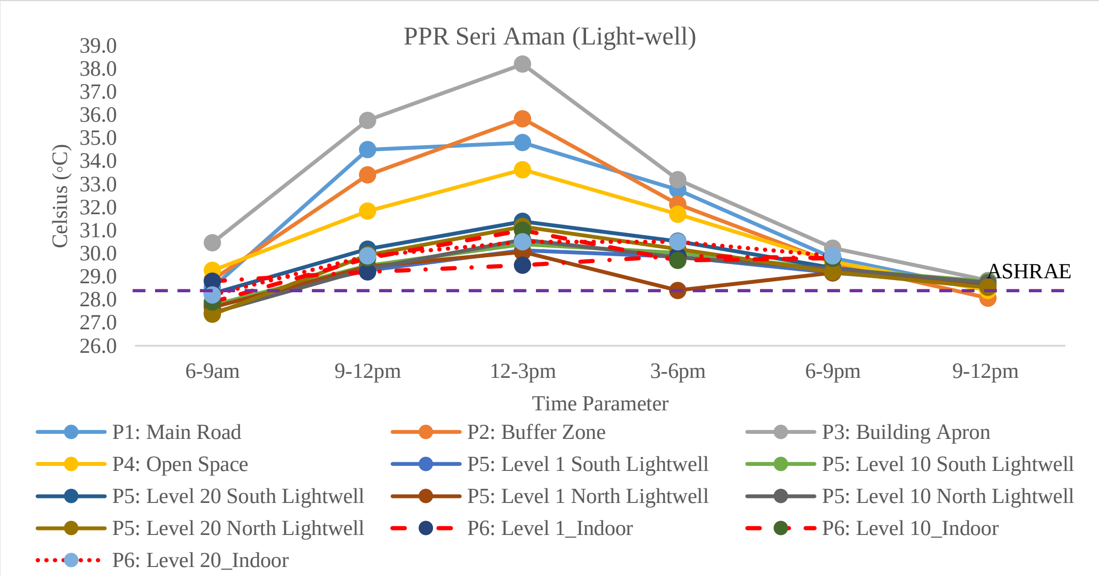
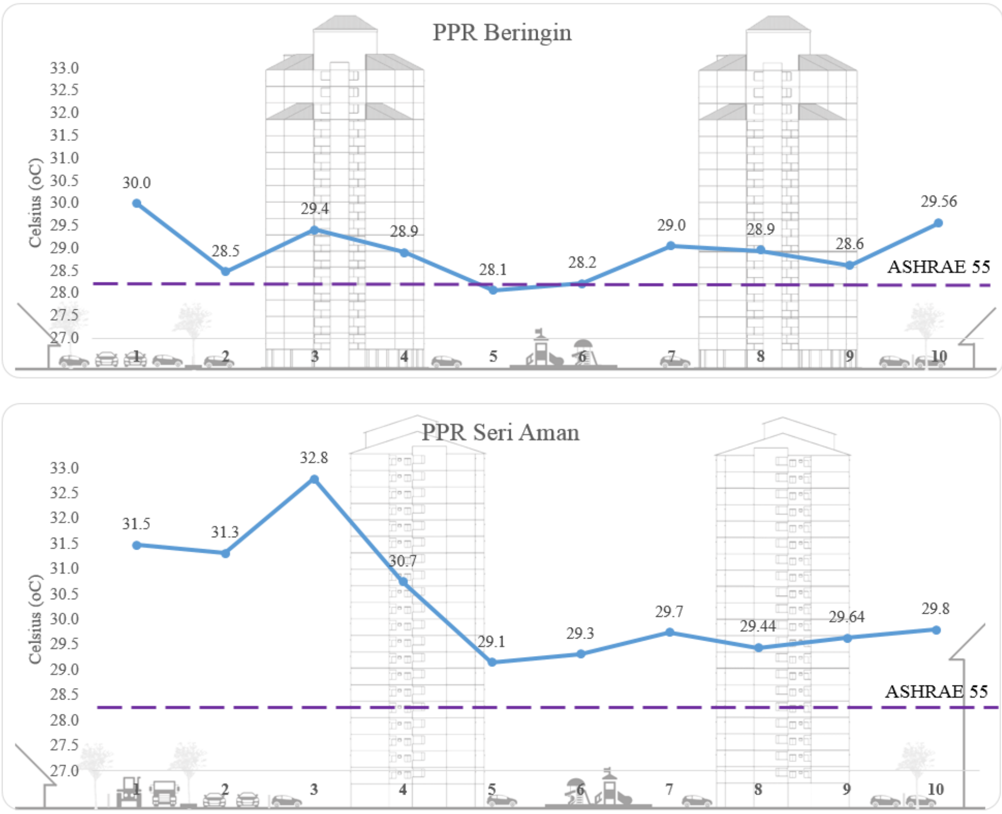


Figure 3.11: Air temperature and operative temperature readings in PPR Beringin and PPR Seri Aman

In PPR Beringin, the operative temperature (P6) was ranged from 28.6°C to 29.6°C. Whereas in PPR Seri Aman, the average operative temperatures (P6) were recorded between 29.4°C to 29.8°C (Figure 3.12). High average operative temperatures recorded at the topmost floors in both PPRs. The average operative temperatures in indoor units adjacent to light-wells were higher almost 1°C than the indoor units adjacent to the atriums. It could be deduced that the average air temperature and the operative temperature in PPR using light-well entirely exceeded the CIBSE limit while in PPR using atrium, the average temperatures were partly below the limit (level 1 and level 10).

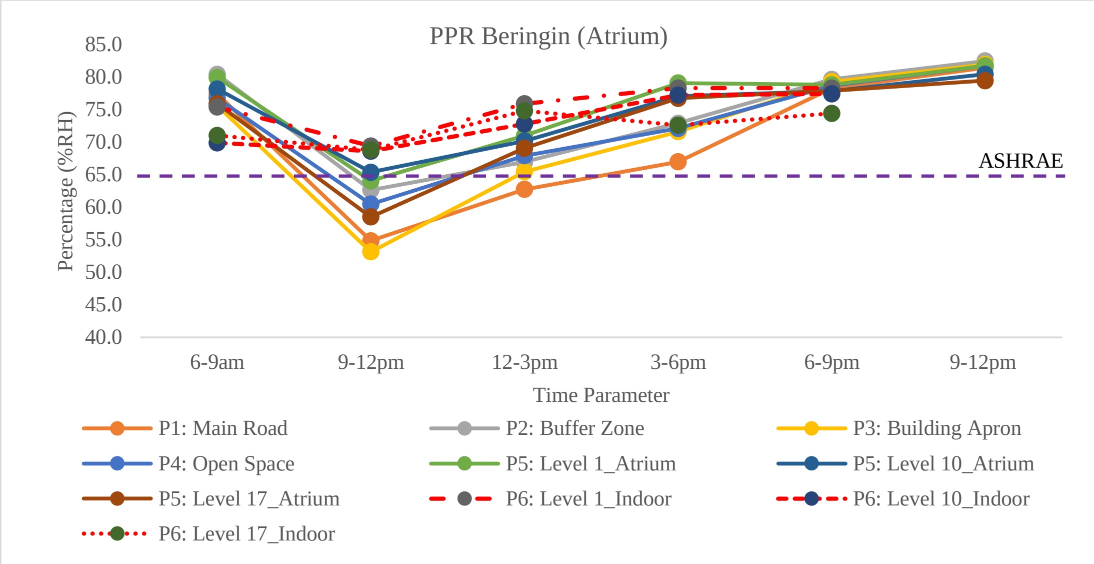


Note: 1) P1 – Main Road; 2) P2 – Buffer Zone; 3)P3 – Building Apron; 4) P4 – Open Space; 5) P5_L1 – Atrium Level 1; 6) P5_L10 – Atrium Level 10; 7) P5_L17/L20 – Atrium Level 17/20; 8) P6_L1 – Indoor Level 1; 9) P6_L10 – Indoor Level 10; 10) P6_L17/20 – Indoor Level 17/20

Figure 3.12: Average air temperature and operative temperature in three days at each point in PPR Beringin and PPR Seri Aman

<u>Relative Humidity</u>

In PPR Beringin, the average indoor humidity in all indoor samples was consistently surpassed the ASHRAE 55 limit of 65% RH. At the atrium area, the average humidity recorded at level 1 was the highest and level 17 was the lowest. Figure 3.13 shows the humidity levels that were always high in indoor spaces compared to outdoor spaces during daytime. For PPR Seri Aman, the average humidity levels in indoor space at level 1 were consistently high followed by spaces at level 10 and level 17. The average humidity levels in indoor spaces at level 1, 10 and 20 were recorded below ASHRAE 55 limit from 9 am to 6 pm. Most of the time, the average humidity in PPR Seri Aman was between the ASHRAE's limit except from 9 pm to 9 am (Figure 3.13).



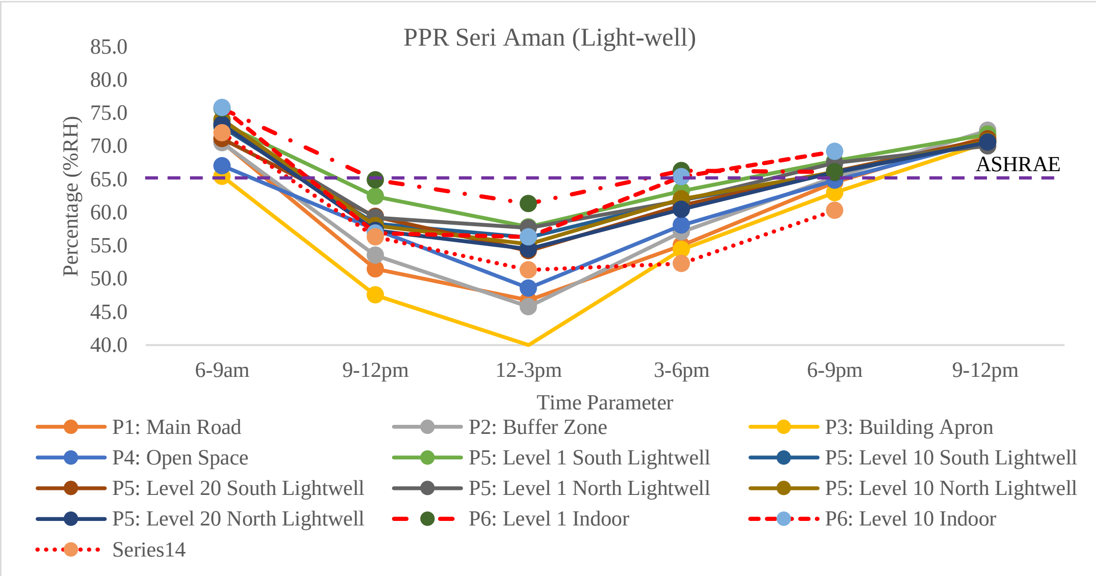
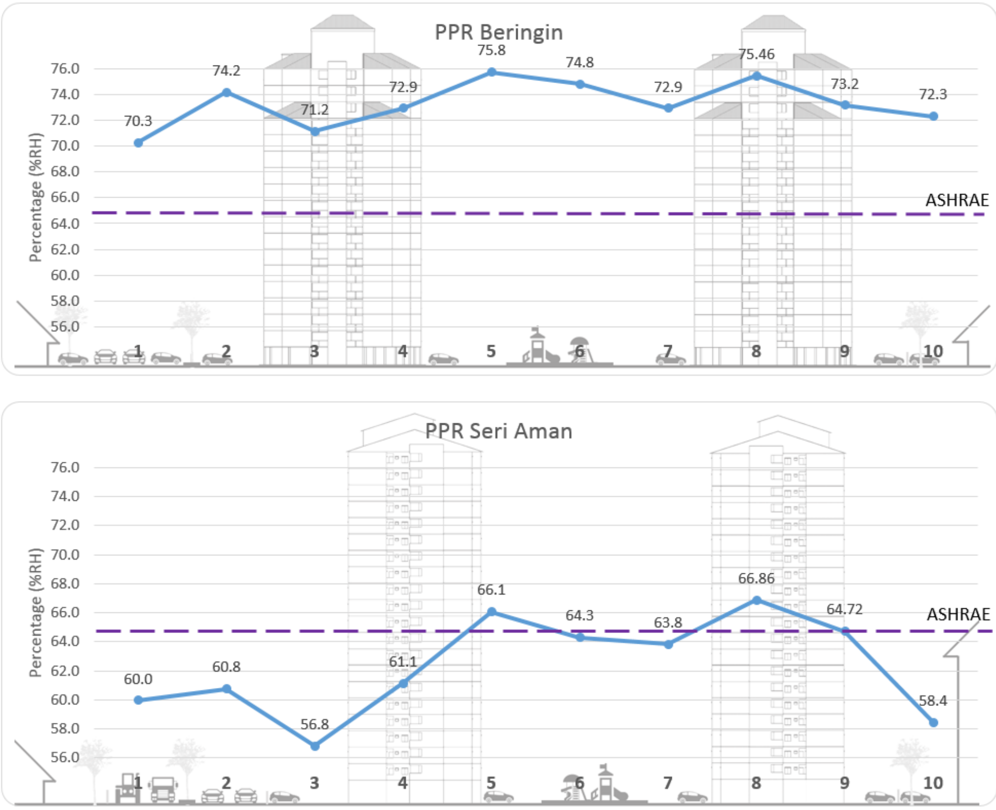


Figure 3.13: Relative humidity levels in PPR Beringin and PPR Seri Aman

For outdoor locations (P1 – P4), the relative humidity levels around PPR using atrium were 9% to 15% higher than in PPR using light-well due to more landscape and plants around the PPR Beringin compound. In the semi-indoor environment, PPR Seri Aman had recorded lower readings of relative humidity with the range between 9% to 11% (Figure 3.14). This scenario occurred due to the enclosure environment set-up in

PPR Seri Aman. For indoor units, the humidity readings in PPR using atrium were recorded higher approximately 22% than in PPR using light-well. The relative humidity levels at PPR using atrium entirely exceeded the ASHRAE limit and partly exceeded for PPR using light-well.



Note: 1) P1 – Main Road; 2) P2 – Buffer Zone; 3)P3 – Building Apron; 4) P4 – Open Space; 5) P5_L1 – Atrium Level 1; 6) P5_L10 – Atrium Level 10; 7) P5_L17/L20 – Atrium Level 17/20; 8) P6_L1 – Indoor Level 1; 9) P6_L10 – Indoor Level 10; 10) P6_L17/20 – Indoor Level 17/20

Figure 3.14: Average relative humidity in three days at each point in PPR Beringin and PPR Seri Aman

Incoming Air Speed and Internal Air Speed

As mentioned in the operative temperature results, external wind movement is the main factor for the temperature and humidity profiles. It also affects the maximum incoming air movement as shown in Figure 3.15. The gradient wind profile in the urban areas makes the maximum airspeeds for the rooms facing unobstructed open area (south façade) were gradually increasing from level 1 to level 20. In PPR Seri Aman, for the rooms facing the obstructed open area (north façade), the highest air movement was at level 10 due to eddies and re-circulation regions of wind formed at the windward section of the sample block.

For the rooms facing enclosed light-well, the airspeed recorded at level 1 was the lowest due to weaker stack effect at the intermediate part of the light-well (Figure 3.15). As a result, the average internal air movement has only recorded 0.0 m/s in all cases which is insufficient to meet the recommendations set by several established standards (ASHRAE 55, CIBSE Guide A and MS1525). The recommended range set by ASHRAE 55 is 0.15 m/s to 0.80 m/s. It can be deduced that natural ventilation is inconsistent and unreliable in these high-rise social housing buildings.

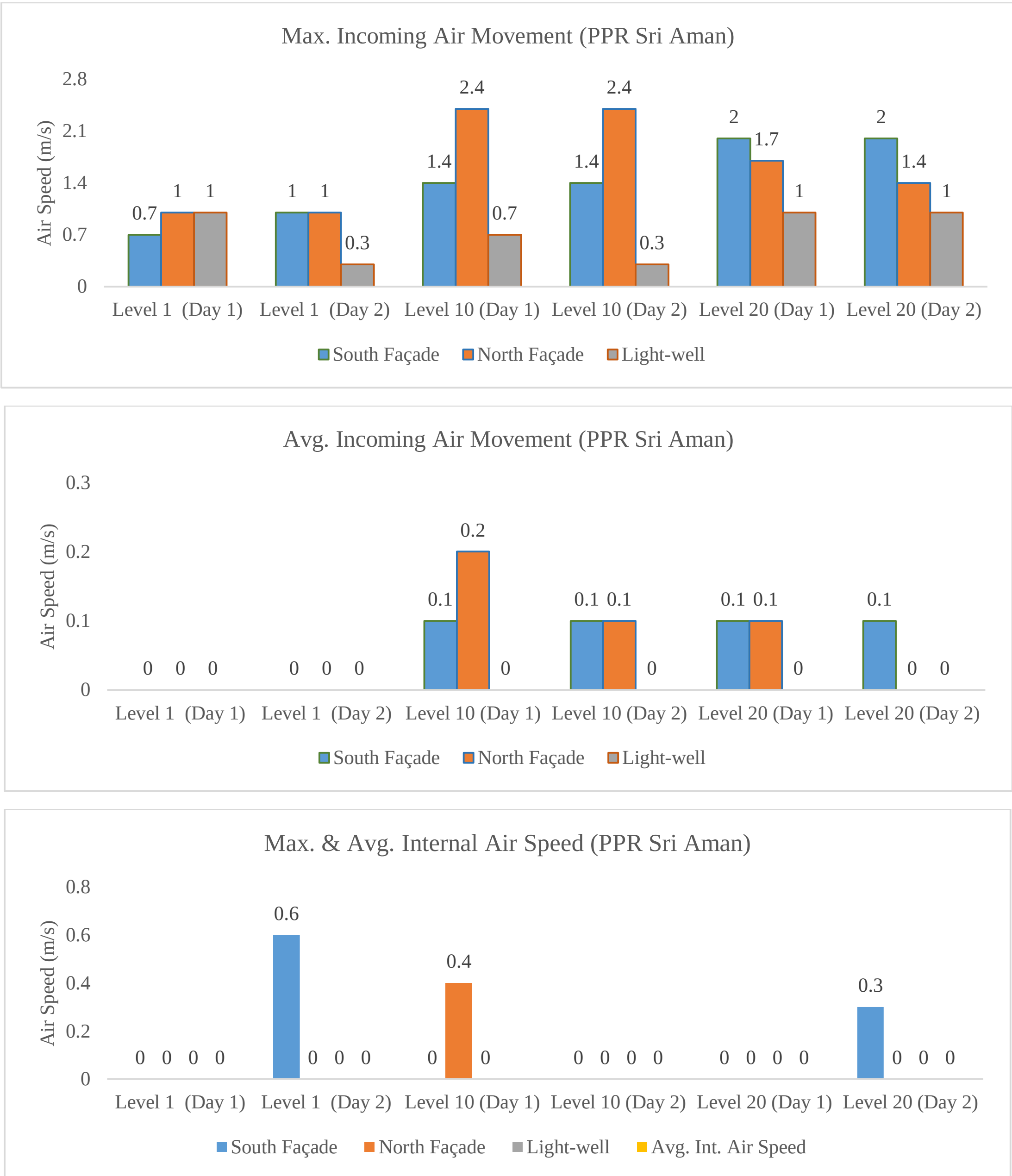


Figure 3.15: The maximum and average incoming airspeed in PPR Seri Aman

3.5 Fieldwork 2: Results and Analysis

3.5.1 Indoor and Outdoor Air Quality

<u>PM_{10} Concentrations</u>

In PPR Beringin, from 6 am to 12 am, almost all the average PM_{10} readings exceeded the WHO limits especially from 6 pm to 12 am due to human activities (religious ritual – joss stick burning, thin stick that burns with a smell of incense). Hence, the PM_{10} concentrations are considered at a high level in this building. For PPR Seri Aman, the average PM_{10} level in the indoor space at level 1 was the highest among other indoor spaces at level 10 and 20. In general, the average PM_{10} levels at all points were above the WHO limit at all times (6 am – 12 am), significantly surpassed the limit during night time due to human activities (Figure 3.16).

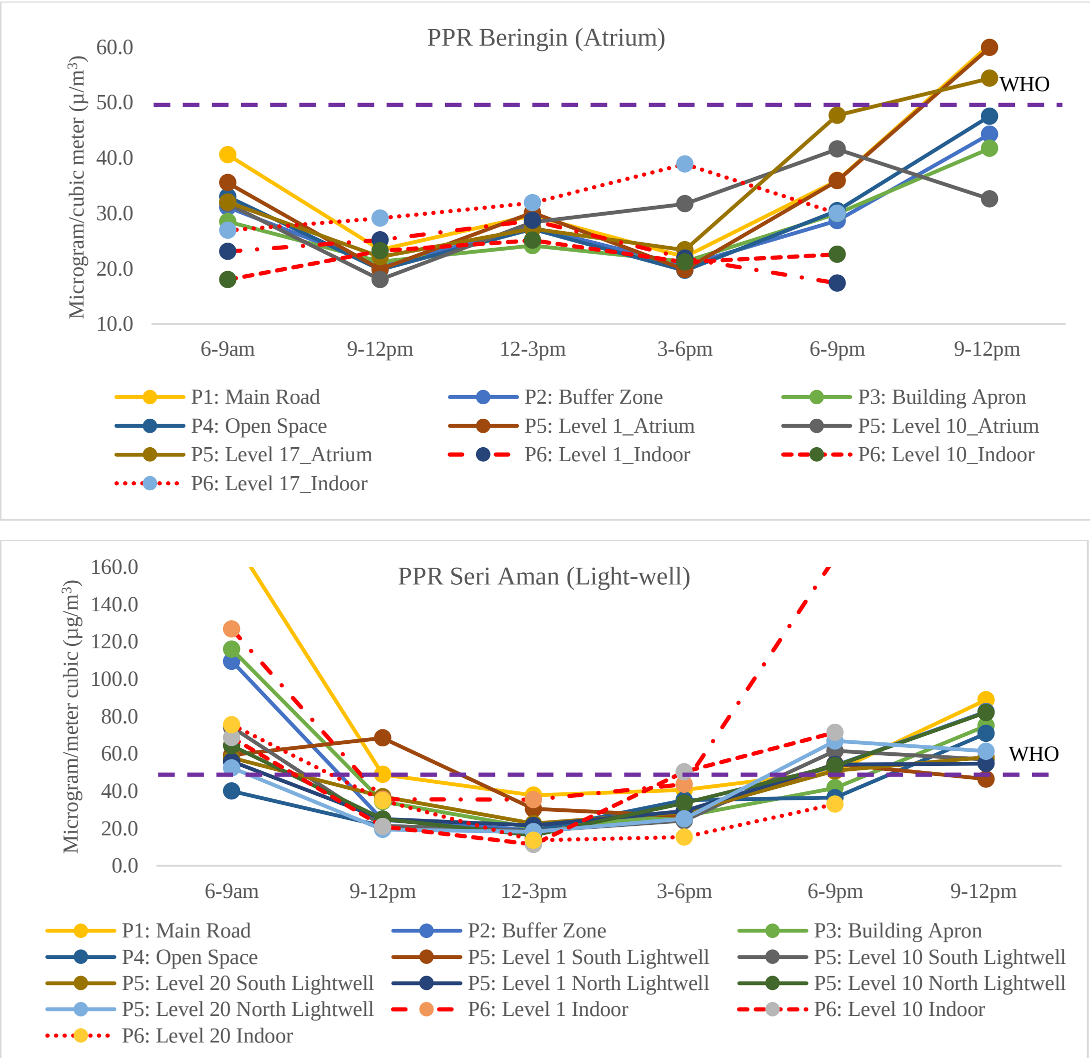
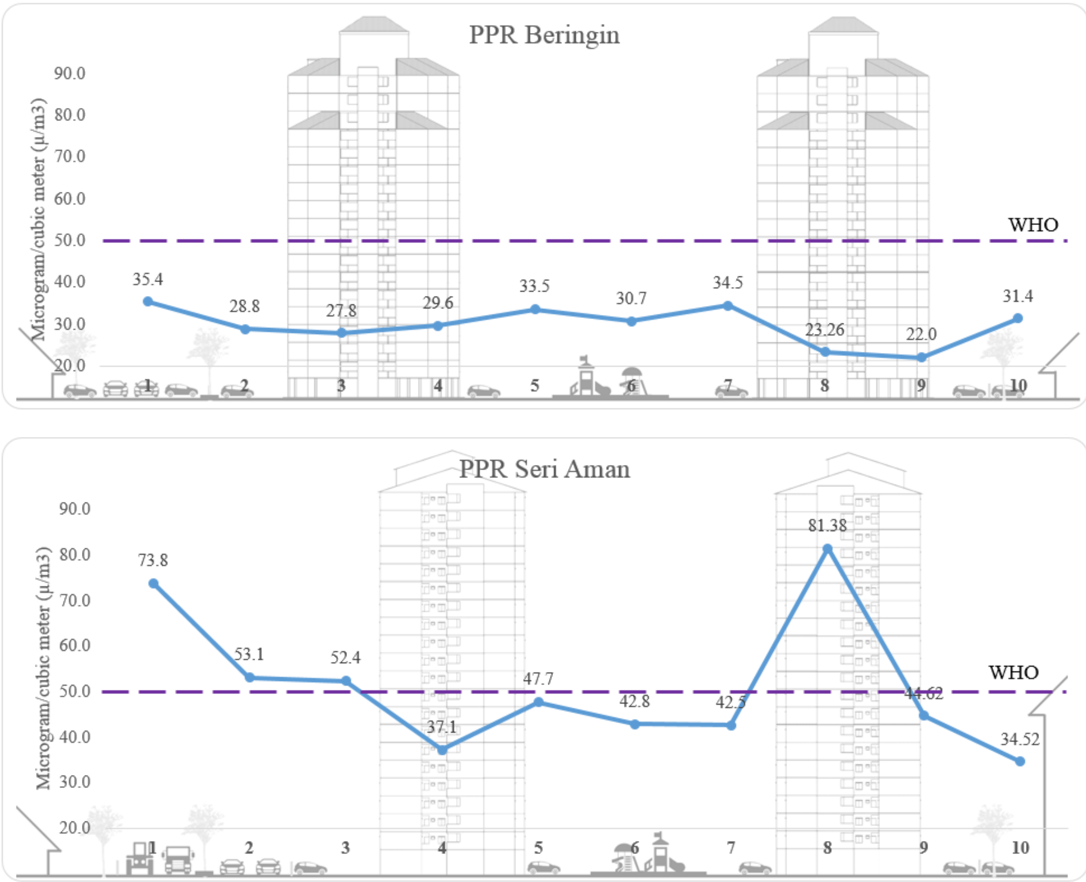


Figure 3.16: PM_{10} average concentration in PPR Beringin and PPR Seri Aman

As a comparison, the PM_{10} level in PPR using light-well was 15 µg/m^3 higher than in PPR using atrium. The enclosure environment in PPR Beringin has decreased the air movement in semi-indoor and indoor spaces. For indoor units, the highest PM_{10} average level was recorded at level 1 in this building. Meanwhile, the PM_{10} concentration level in PPR using light-well was recorded significantly high especially for level 1 due to joss stick burning. The PM_{10} concentrations in PPR using atrium were entirely below the WHO limit. However, in PPR using light-well, the average values were significantly exceeded especially during early morning and evening (high traffic/ human activities) in the locations near the main road and level 1 (Figure 3.17).

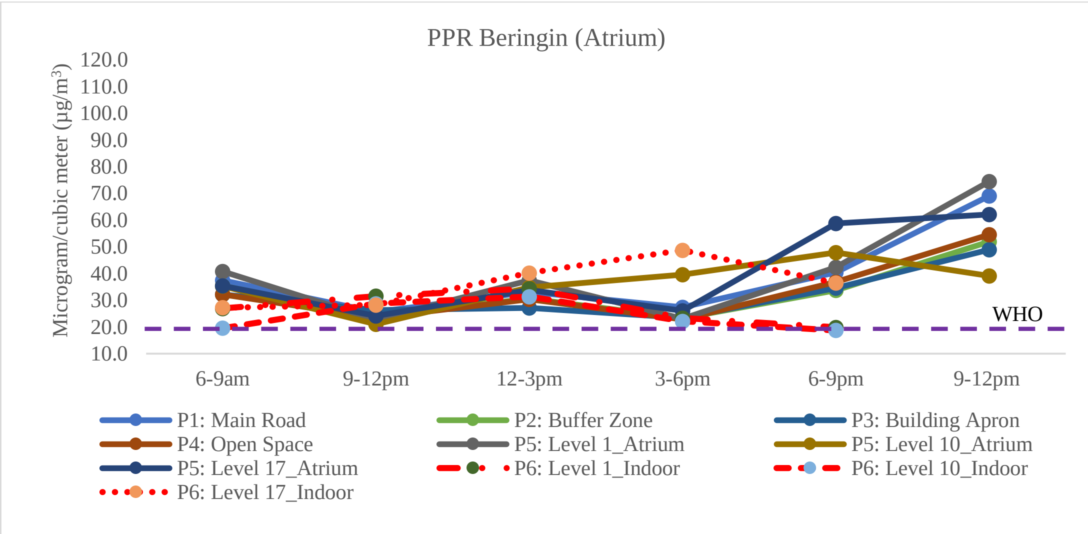


Note: 1) P1 – Main Road; 2) P2 – Buffer Zone; 3)P3 – Building Apron; 4) P4 – Open Space; 5) P5_L1 – Atrium Level 1; 6) P5_L10 – Atrium Level 10; 7) P5_L17/L20 – Atrium Level 17/20; 8) P6_L1 – Indoor Level 1; 9) P6_L10 – Indoor Level 10; 10) P6_L17/20 – Indoor Level 17/20

Figure 3.17: Average PM_{10} concentration in three days at each point in PPR Beringin and PPR Seri Aman

<u>$PM_{2.5}$ Concentrations</u>

The average $PM_{2.5}$ levels in PPR Beringin at most outdoor points exceeded the WHO limit at all times (Figure 3.18). Suggesting that the $PM_{2.5}$ particles are the main cause of air pollution in these sites due to these fine particles that are so small and light, which can stay longer in the air than heavier particles (Payus et al., 2013). In PPR Seri Aman, the average $PM_{2.5}$ levels at outdoor and semi-outdoor points (P1 – P5) exceeded the WHO limit and also most of the time in indoor points (P6) except from 9 am to 6 pm in indoor spaces at level 10 and 20 (Figure 3.18). This shows that $PM_{2.5}$ is the main substance of air pollution at low level near the ground level, especially during morning and evening due to human activities (i.e. high traffic and joss stick burning).



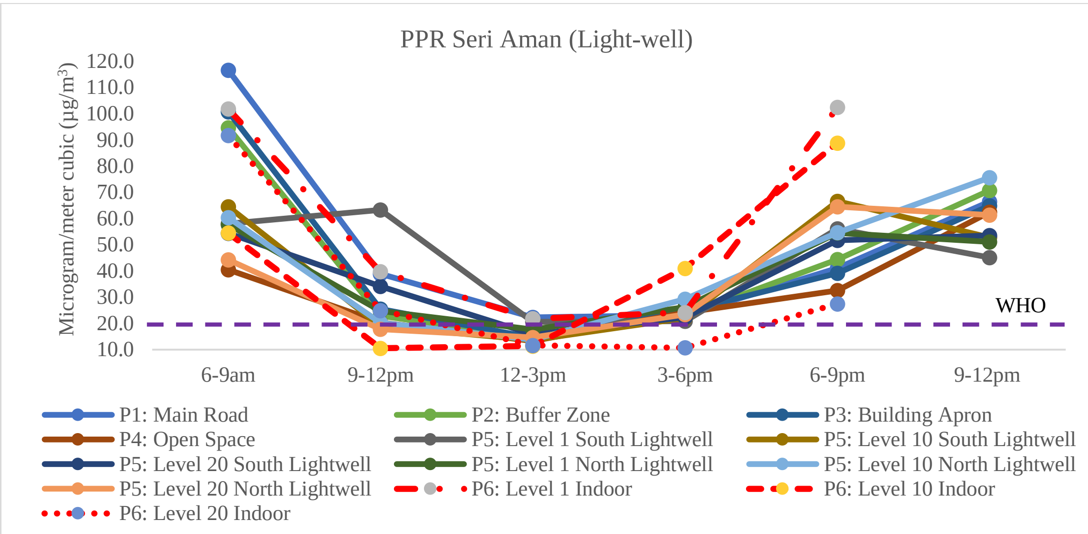
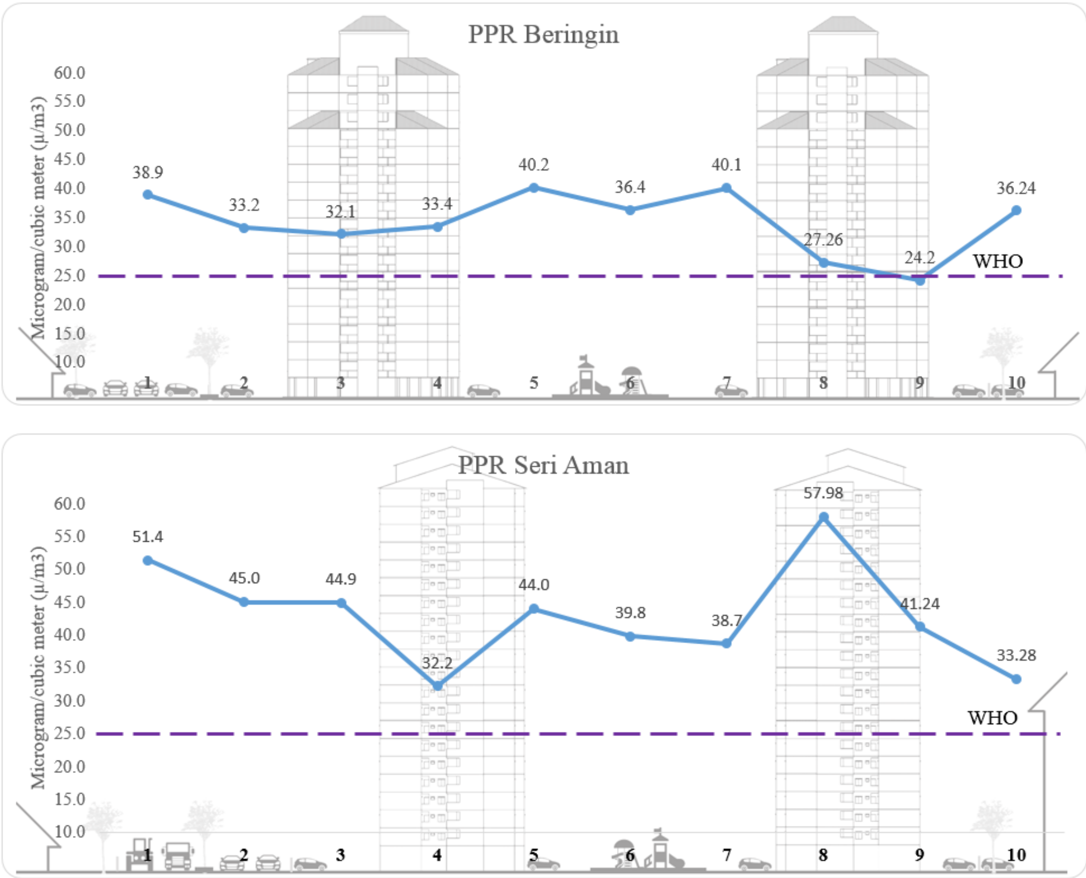


Figure 3.18: $PM_{2.5}$ average concentration in PPR Beringin and PPR Seri Aman

The outdoor $PM_{2.5}$ concentration levels in PPR using light-well were generally higher than in PPR using atrium. Similar to PM_{10} concentration, the $PM_{2.5}$ level in PPR using light-well was significantly high especially in the indoor unit at level 1. Both

PPRs have recorded significantly high $PM_{2.5}$ concentration levels which surpassed the WHO daily limit of 25 µg/m^3 (Figure 3.19).

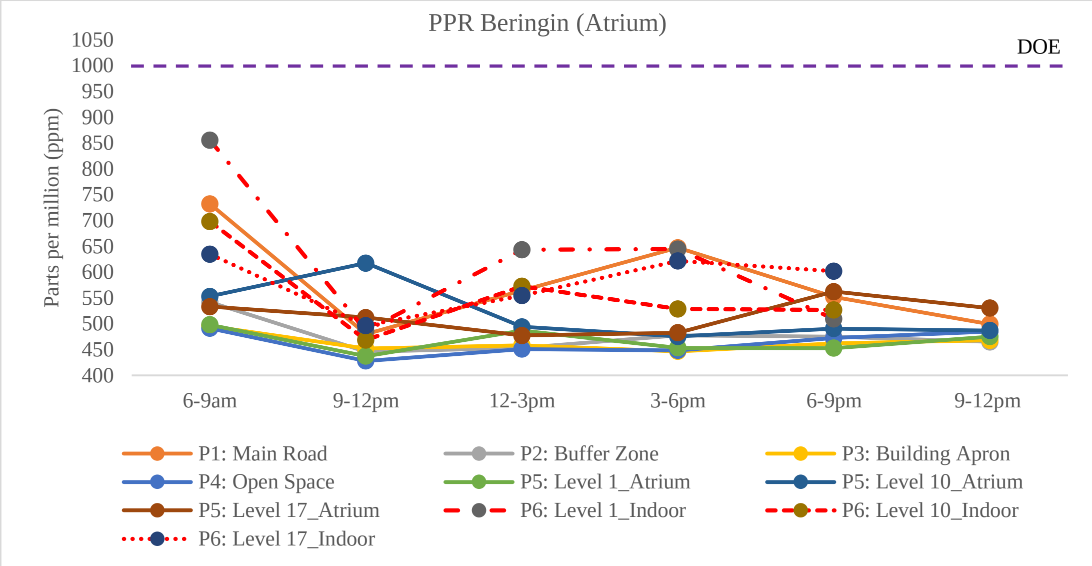


Note: 1) P1 – Main Road; 2) P2 – Buffer Zone; 3)P3 – Building Apron; 4) P4 – Open Space; 5) P5_L1 – Atrium Level 1; 6) P5_L10 – Atrium Level 10; 7) P5_L17/L20 – Atrium Level 17/20; 8) P6_L1 – Indoor Level 1; 9) P6_L10 – Indoor Level 10; 10) P6_L17/20 – Indoor Level 17/20

Figure 3.19: Average $PM_{2.5}$ concentration in three days at each point in PPR Beringin and PPR Seri Aman

<u>CO_2 Concentrations</u>

Figure 3.20 shows the average CO_2 levels recorded which were far below the limit set in the established standard, guideline and regulations. However, the CO_2 levels in indoor spaces were significantly higher than the outdoor environment due to human appearance and activities in PPR Beringin. For PPR Seri Aman, the average CO_2 levels in indoor space at level 1 were significantly higher than indoor spaces at level 10 and 17 (Figure 3.20). During daytime from 9 am to 6 pm, the CO_2 levels were generally lower than 500 ppm and it increased above 500 ppm at night due to human presence in indoor space and heavy traffic flow.



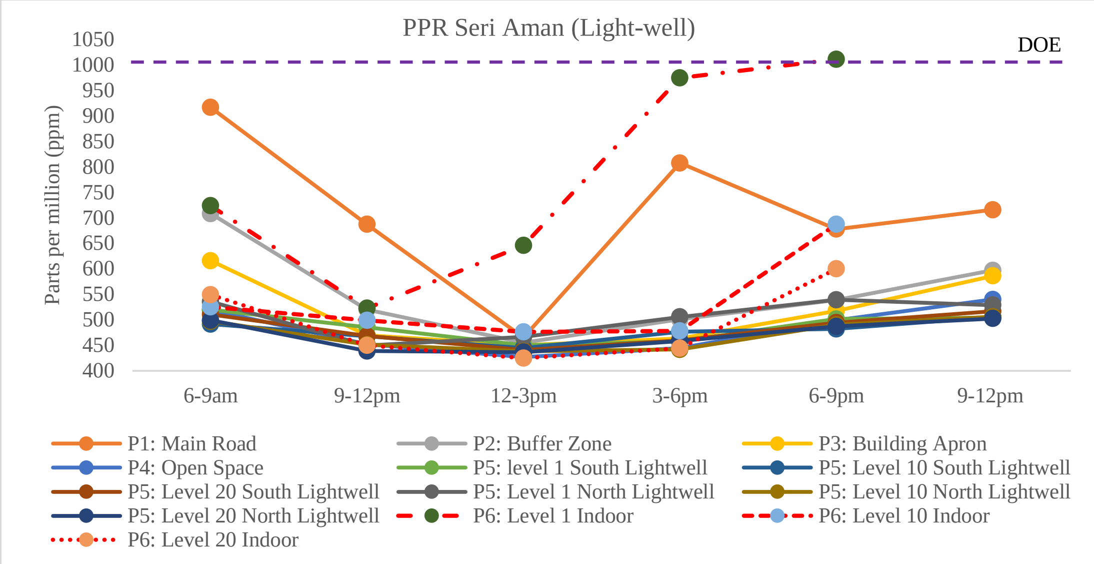
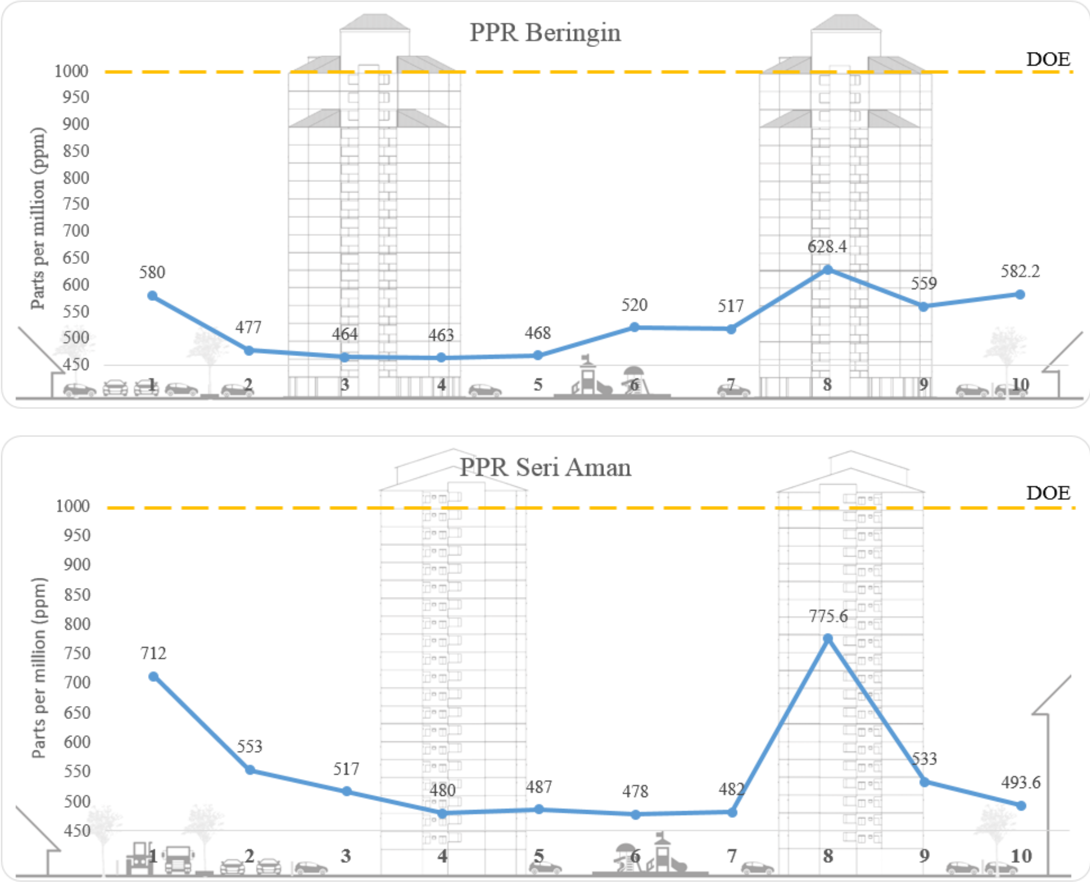


Figure 3.20: CO_2 Average in PPR Beringin and PPR Seri Aman

Generally, for outdoor locations, the CO_2 concentration levels were within similar levels in both PPRs. However, in indoor spaces (at level 1 in both PPRs) high CO_2 concentrations were recorded; among the highest average compared to the other levels in each block. Due to the closed environment set-up, the average CO_2 levels in indoor spaces in both PPRs were recorded higher than outdoor spaces (Figure 3.21). However, the readings recorded were much lower than the limit of 1,000 ppm set by the Department of Occupational Safety and Health (DOSH), suggesting that the CO_2 concentrations are still at the acceptable levels. The high CO_2 level recorded in indoor space at level 1 (775.6 ppm) was due to the human occupancy which at the time of measurement the unit was occupied with more people than any other units.



Note: 1) P1 – Main Road; 2) P2 – Buffer Zone; 3)P3 – Building Apron; 4) P4 – Open Space; 5) P5_L1 – Atrium Level 1; 6) P5_L10 – Atrium Level 10; 7) P5_L17/L20 – Atrium Level 17/20; 8) P6_L1 – Indoor Level 1; 9) P6_L10 – Indoor Level 10; 10) P6_L17/20 – Indoor Level 17/20

Figure 3.21: Average CO_2 concentration in PPR Beringin and PPR Seri Aman

<u>CO Concentrations</u>

The average CO levels in PPR Beringin (indoor and outdoor) recorded were low and intangible. The levels were far below from the NAAQS and DOE's limits of 9 ppm. Thus, CO was not the main substance for air pollution in this location. A similar situation occurred in PPR Seri Aman where the average CO levels in indoor spaces at level 1, 10 and 20 were considerably low and intangible. This condition suggested that CO has a very minimal impact on air pollution in Kuala Lumpur (Figure 3.22). These results were consistent with the results published by DOE in their air quality reports (DOE, 2016a, 2017). At the outdoor locations, the CO levels were low in both PPRs. The CO levels were also low in indoor spaces in both PPRs (Figure 3.23). Both PPRs recorded low CO level at all times and this suggests that CO was not affecting the indoor air quality in these locations.

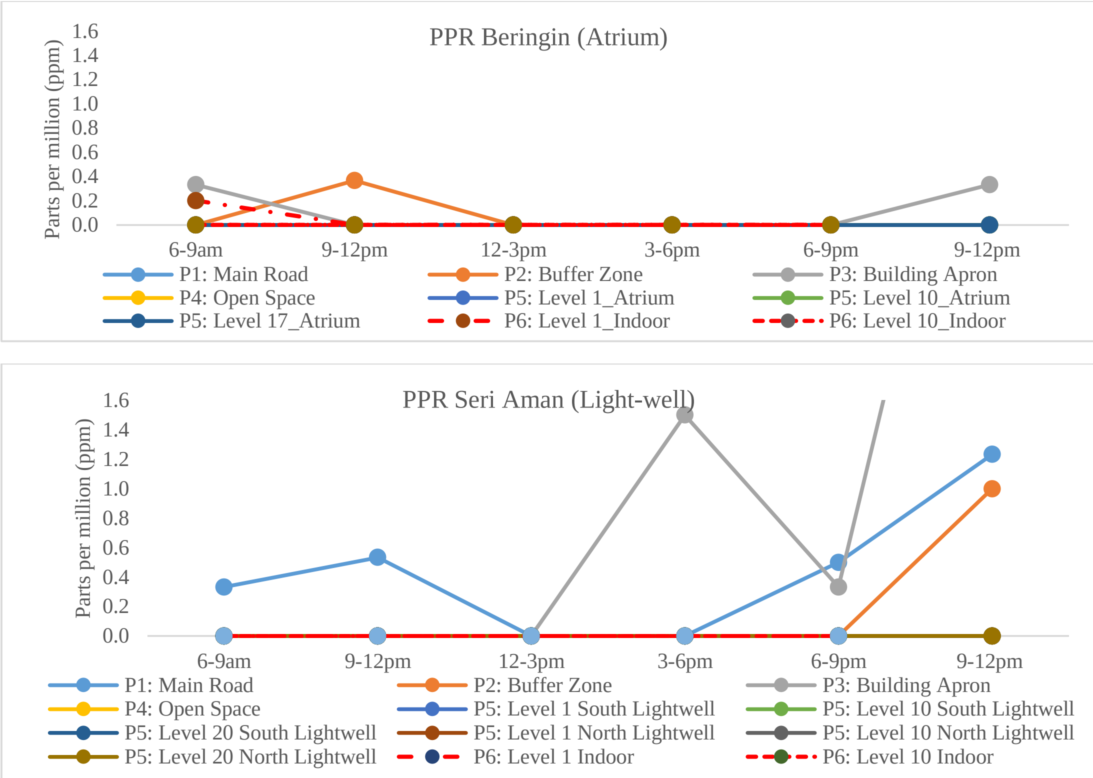
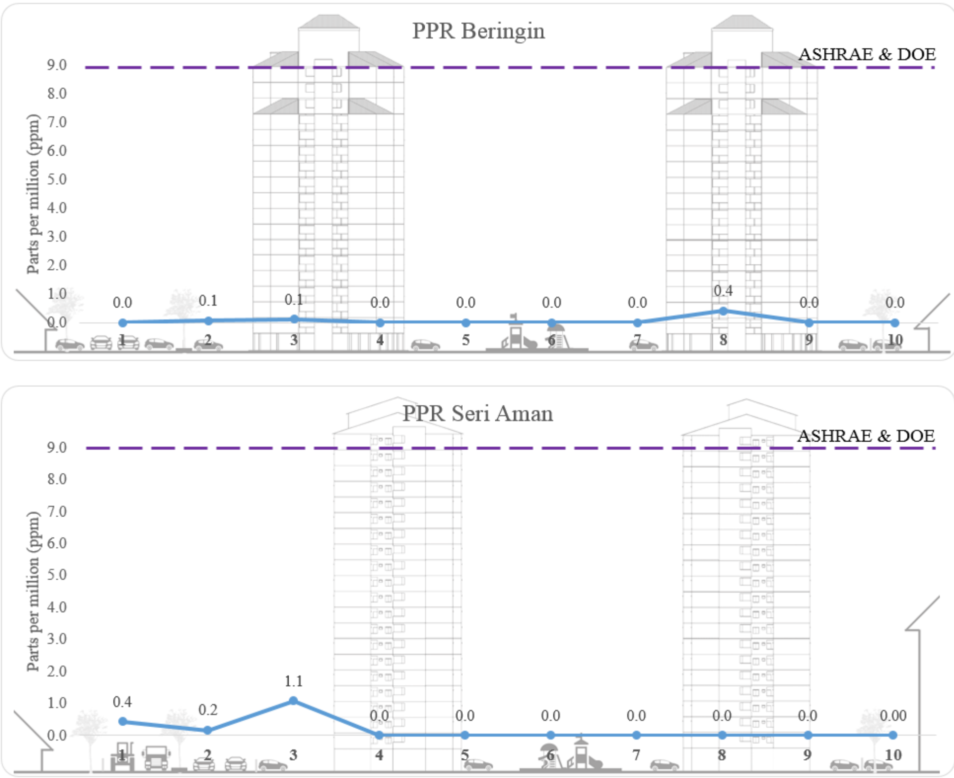


Figure 3.22: CO average concentration in PPR Beringin and PPR Seri Aman



Note: 1) P1 – Main Road; 2) P2 – Buffer Zone; 3)P3 – Building Apron; 4) P4 – Open Space; 5) P5_L1 – Atrium Level 1; 6) P5_L10 – Atrium Level 10; 7) P5_L17/L20 – Atrium Level 17/20; 8) P6_L1 – Indoor Level 1; 9) P6_L10 – Indoor Level 10; 10) P6_L17/20 – Indoor Level 17/20

Figure 3.23: Average CO concentration in PPR Beringin and PPR Seri Aman

3.6 Computer Simulation

Following the fieldwork study that had been conducted in evaluating indoor comfort conditions in two types of social housing in Kuala Lumpur; an environmental simulation using IES software had been carried out to validate the comfort conditions of the PPR second generation block for a full year in detail. The development of the PPR first generation has been terminated by the Malaysian government since 2008 (BERNAMA, 2013) and thus, this type of building will not be simulated in this research. The main objective of this simulation is to get a complete environmental condition dataset for the PPR second generation block and in conjunction with the results, the establishment of the average operative temperature (OT) and relative humidity (RH) of the block could be made. This simulation will also propose the percentages of OT and RH total comfort hours in a full year. For this simulation work, a 20-storey PPR second generation block was constructed using the software (Figure 3.24).

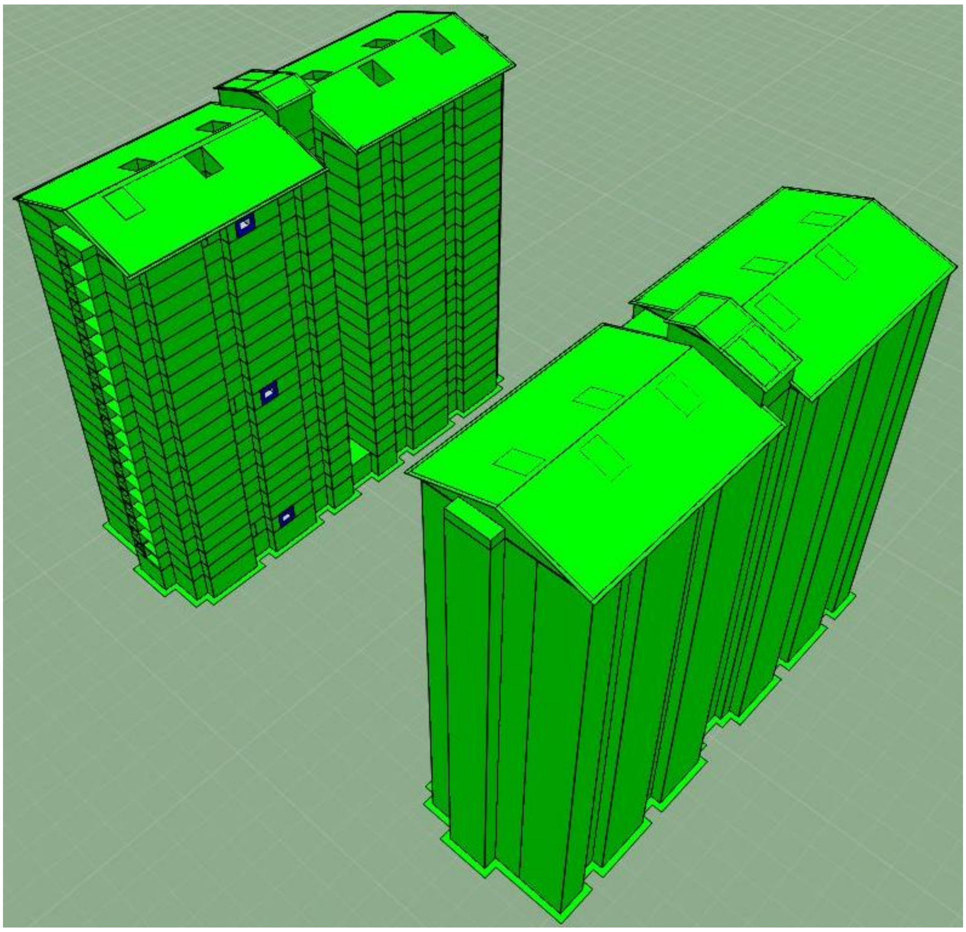


Figure 3.24: 3D Model of a PPR Block in IES

3.6.1 Weather Data and Site Location Preferences

Figure 3.25 shows the preferences for the ‘Location & Site Data’ and ‘Design Weather Data’. The weather data location selected for Kuala Lumpur is Subang, which is the nearest DOE’s weather station to the existing PPR buildings used in the fieldwork studies. The latitude is 3.12°N and longitude 101.55°E with the elevation of the model’s base from sea level at 22 metres. For this model, the ground reflectance index assigned is 0.2, which is for humid tropical localities throughout the year. The city terrain type is chosen and 420 ppm of external CO_2 concentration according to a study done by the authors (Mohd Sahabuddin & Gonzalez-Longo, 2018). Wind exposure setting is normal with reference to air density of 1,200 kg/m^3. For the design weather data, the values of dry-bulb and wet-bulb temperatures set by the Malaysian Standard 1525 are referred. The values are 33.3°C and 27.2°C for dry-bulb and wet-bulb temperatures respectively (MS1525, 2014).

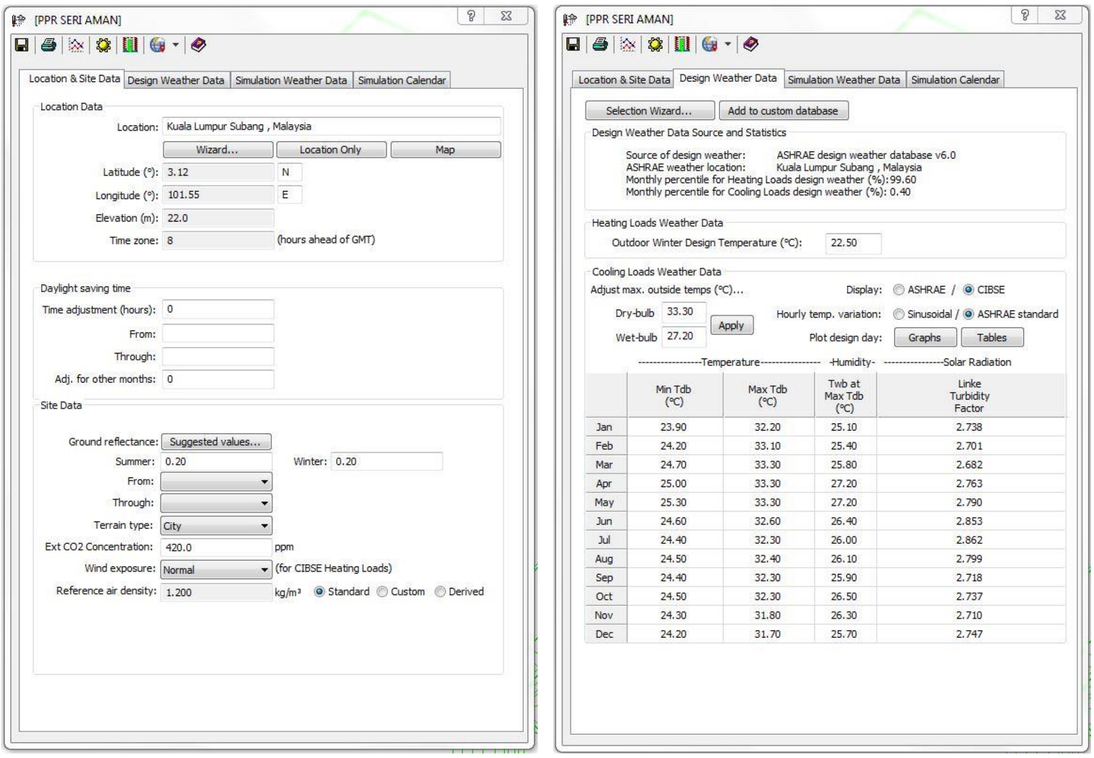


Figure 3.25: Simulation Model’s preferences

3.6.2 Modelling Samples

In accordance to the fieldwork studies, three levels (level 1, 10 and 20) were defined in the PPR Seri Aman (second generation) and therefore, in the simulation model, the same levels were used to represent the lower, intermediate and upper levels of the PPR block (Figure 3.26). At each level, two housing units were also selected, one faces the north (unobstructed open area) and another one faces the south (obstructed open area). According to ASHRAE 55, the best data gathering spots are where the occupants are known to spend most of their time. For this reason, two bedrooms (main bedroom and third bedroom) were selected and measured in each housing unit. This model used 12 simulation names derived from three criteria: 1) the level where the unit is located (level 1 or level 10 or level 20), 2) the unit's facing direction (north or south), and 3) type of bedroom (bedroom 1 or bedroom 3). For example, the main bedroom in a unit at level 1 that faces south will be named as L1S_P1. Table 3.8 shows the 12 simulation names derived from these criteria. The names had been assigned to the simulation model as shown in Figure 3.26.

Table 3.8: Configuration of Sample Names

No.	Level of the Unit	Facing Direction	Type of Bedroom	Simulation Names
1	Level 1	South	Bedroom 1	L1S_P1
2	Level 1	South	Bedroom 3	L1S_P2
3	Level 1	North	Bedroom 1	L1N_P1
4	Level 1	North	Bedroom 3	L1N_P2
5	Level 10	South	Bedroom 1	L10S_P1
6	Level 10	South	Bedroom 3	L10S_P2
7	Level 10	North	Bedroom 1	L10N_P1
8	Level 10	North	Bedroom 3	L10N_P2
9	Level 20	South	Bedroom 1	L20S_P1
10	Level 20	South	Bedroom 3	L20S_P2
11	Level 20	North	Bedroom 1	L20N_P1
12	Level 20	North	Bedroom 3	L20N_P2

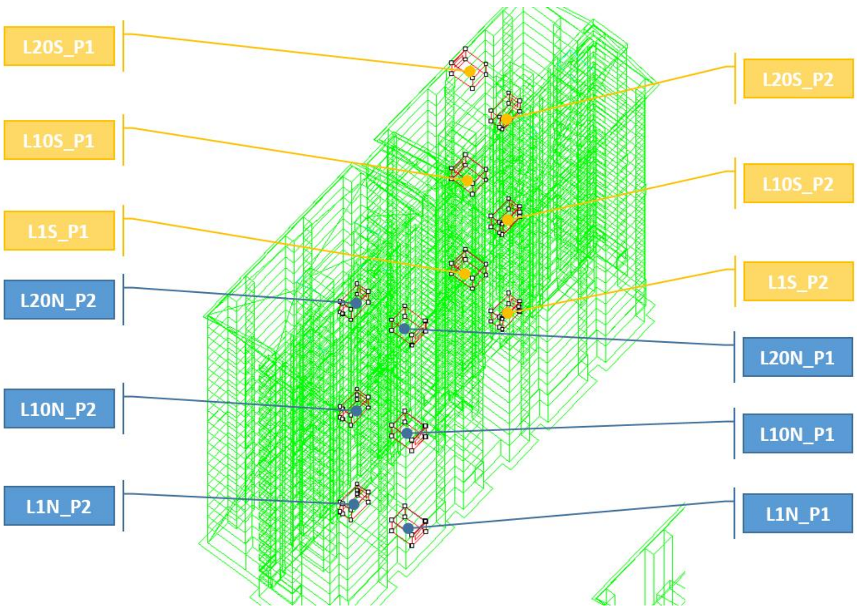


Figure 3.26: The levels selected in the 3D model

3.6.3 Model Attributes and Input Values

This simulation model is an imitation of the real PPR Seri Aman building and thereafter this computer model uses the same types of materials used in the actual building. Referring to the construction drawings supplied by the Ministry of Urban Wellbeing, Housing, and Local Government, the floor of every housing unit is made of the reinforced concrete slab (150 mm thick) with cement screed and tiles finishing. The walls are 110 mm thick brick with 20 mm thick cement plaster and paint finish on both sides. Windows are single-glazed with 6 mm thick glass. These materials and thickness have been assigned to the IES simulation model, as approximate as possible due to the software constraints as listed in Table 3.9.

Table 3.9 lists the details of materials selected for three building components (floors, walls and windows) in the simulation model. The materials assigned are the un-insulated concrete, brickwork single-leaf construction light plaster and single-glazed windows domestic, respectively. These materials are the most suitable and available in the software. They have similar properties with the actual materials on site. For the un-insulated concrete slab, the U-value, R-value, thickness and mass values are given as 1.5583 W/m^{2}K, 0.4913 m^{2}K/W, 200 mm and 330.3 kg/m^2 respectively. For brickwork single-leaf construction light plaster and single-glazed windows – domestic, the details of the U-value, R-value, thickness and mass are shown in Table 3.9.

Table 3.9: Details of Modelling Materials Assignment

Building Component	**Material Assigned**	**U-value (W/m^{2}K)**	**R-value (m^{2}K/W)**	**Thickness (mm)**	**Mass (kg/m^2)**
Floors	Un-insulated Concrete slab	1.558	0.491	200	330.3
Walls	Brickwork Single-Leaf Construction Light Plaster	1.949	0.343	120	381.8
Glass for windows	Single-Glazed Windows - Domestic	5.693	0.176	6	-

3.7 Baseline Simulation: Results and Analysis

3.7.1 Thermal Comfort

Operative Temperature (OT)

The operative temperature results for a year for the PPR second generation block were between 24°C and 34°C. The diurnal temperature range is 10°C. The highest temperatures were recorded on July 6th and June 24th; while the lowest was on April 6th (Table 3.10). There was no significant difference in OT according to the latitude of the housing unit. In general, the average OT for this block was between 28.7°C to 29.1°C.

Table 3.10: OT's Minimum, Maximum and Mean

Location	Min (°C)	Min. Time	Max (°C)	Max. Time	Mean (°C)
Level 1					
L1S_P2	24.25	11:15,06/Apr	33.41	17:15,06/Jul	28.74
L1N_P2	24.25	11:15,06/Apr	33.41	17:15,06/Jul	28.74
L1S_P1	24.37	10:45,06/Apr	33.87	17:15,06/Jul	29.11
L1N_P1	24.24	10:45,06/Apr	33.92	16:45,24/Jun	28.96
Level 10					
L10N_P1	24.28	10:45,06/Apr	33.95	16:45,24/Jun	28.99
L10S_P2	24.25	11:15,06/Apr	33.41	17:15,06/Jul	28.74
L10S_P1	24.37	10:45,06/Apr	33.87	17:15,06/Jul	29.11
L10N_P2	24.25	11:15,06/Apr	33.40	17:15,06/Jul	28.74
Level 20					
L20N_P1	24.37	10:45,06/Apr	33.95	16:45,24/Jun	29.05
L20S_P2	24.29	11:15,06/Apr	33.40	17:15,06/Jul	28.78
L20N_P2	24.26	11:15,06/Apr	33.38	16:45,24/Jun	28.74
L20S_P1	24.37	10:45,06/Apr	33.83	17:15,06/Jul	29.07

As suggested by ASHRAE 55, the acceptable OT range for naturally conditioned spaces is between 24.0°C to 28.4°C (ASHRAE, 2013; Mohd Sahabuddin & Gonzalez-Longo, 2018). Hence, Table 3.11 lists the percentages of hours in the range above 28°C, with the average total hours outside the comfort temperatures being 70%. It could be deduced that all of the master bedrooms (P1) facing outward the block (both north and south direction) recorded higher percentages of hours in the range above 28.0°C (above 70%) than third bedrooms (P2). All the P2 locations facing to the light-wells recorded 67.1% of total hours above 28°C. Among the P1 locations, all bedrooms facing the south direction recorded higher percentages than bedrooms facing the north direction. On 24th of June, the maximum OT was 33.5°C and the minimum was 26.5°C (Figure 3.27). The graph represent for daily distribution of OT and it suggests that the daily diurnal range follows the hourly variations in the measured data.

Table 3.11: Percentages of hours in the range above 28°C

Location	% hours in range > 28 °C
L1S_P2	67.1
L1N_P2	67.1
L1S_P1	73.9
L1N_P1	70.9
L10N_P1	71.6
L10S_P2	67.1
L10S_P1	73.8
L10N_P2	67.1
L20N_P1	72.7
L20S_P2	67.7
L20N_P2	67.1
L20S_P1	73.2
Total hours (% of sum)	**69.9**

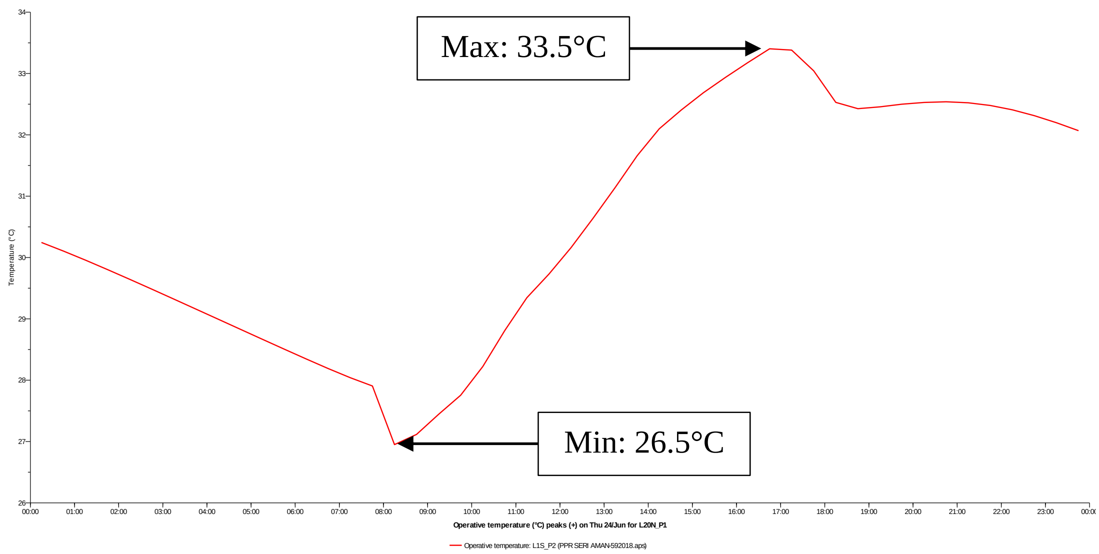
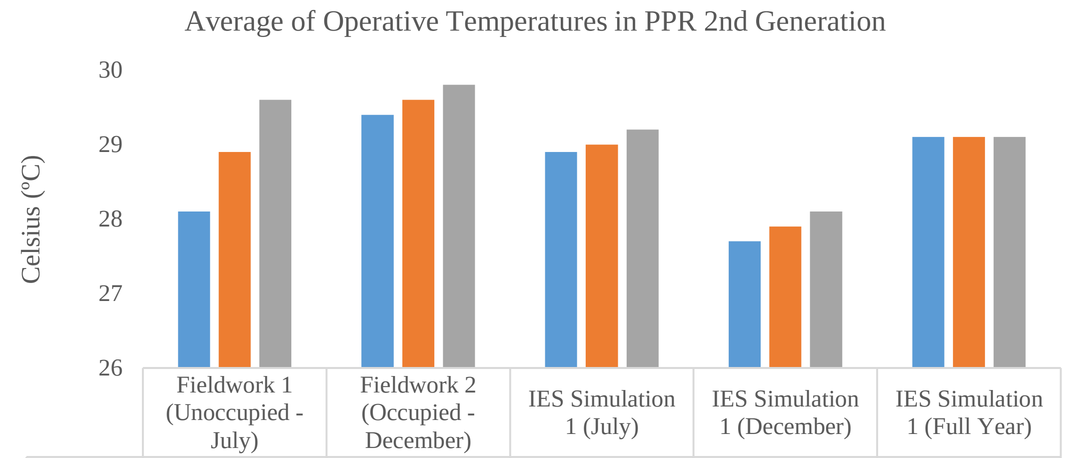


Figure 3.27: Daily distribution of OT on 24th June

The trends of all OT results gathered from the simulation model and fieldwork studies showed an increasing pattern from level 1 to level 20 (Figure 3.28). In July 2017, the PPR second generation building was still unoccupied, thus, fieldwork 1 recorded the average OT results from 28.1°C to 29.6°C. However, when the building was occupied in December of the same year, the fieldwork 2 recorded higher OT from 29.4°C to 29.8°C (Figure 3.28). This temperature increment was caused by the common modifications applied by the occupants after occupancy by putting curtains, blinds and shutting windows for privacy reasons. For IES simulation in July, the average OT results were from 28.9°C to 29.2°C and in December, from 27.7°C to 28.1°C (Figure 3.28). It could be deduced that the full year average temperature for this PPR block is 29.1°C and this value is equivalent to the results recorded in the fieldwork studies and IES simulation.



	Fieldwork 1 (Unoccupied - July)	Fieldwork 2 (Occupied - December)	IES Simulation 1 (July)	IES Simulation 1 (December)	IES Simulation 1 (Full Year)
Level 1	28.1	29.4	28.9	27.7	29.1
Level 10	28.9	29.6	29.0	27.9	29.1
Level 20	29.6	29.8	29.2	28.1	29.1

Figure 3.28: Comparison of OT Results with Fieldwork Studies

Relative Humidity (RH)

The relative humidity in the PPR second generation was between 38% RH to 100% RH. The difference was 62% RH. The highest readings (100%) were recorded on August 8th and December 31st; while the lowest readings (38.5% to 39.2%) were recorded on July 3rd (Table 3.12). Conversely, from OT, the RH average readings had a slight difference among different levels. The highest average RH reading was at level 1 and the lowest was at level 20. In general, the average RH for this block was between 72% RH to 74% RH. As suggested by ASHRAE 55, the acceptable RH limit for naturally conditioned spaces should be below 65% RH (ASHRAE, 2013). Therefore, Table 3.13 lists the percentages of hours in the range above 65% RH, with the average total hours of 85%, which was outside the comfort humidity.

Table 3.12: RH's Minimum, Maximum and Mean

Location	Min (%)	Min. Time	Max (%)	Max. Time	Mean (%)
Level 1					
L1S_P2	39.19	17:15,03/Jul	100	04:45,08/Aug	74.10
L1N_P2	39.19	17:15,03/Jul	100	04:45,08/Aug	74.10
L1S_P1	38.67	17:15,03/Jul	100	05:15,08/Aug	72.71
L1N_P1	38.63	17:15,03/Jul	100	13:45,31/Dec	73.29
Level 10					
L10N_P1	38.59	17:15,03/Jul	100	05:15,08/Aug	73.16
L10S_P2	39.19	17:15,03/Jul	100	04:45,08/Aug	74.10
L10S_P1	38.67	17:15,03/Jul	100	05:15,08/Aug	72.71
L10N_P2	39.19	17:15,03/Jul	100	04:45,08/Aug	74.10
Level 20					
L20N_P1	38.56	17:15,03/Jul	100	05:15,08/Aug	72.96
L20S_P2	39.17	17:15,03/Jul	100	04:45,08/Aug	73.96
L20N_P2	39.20	17:15,03/Jul	100	04:45,08/Aug	74.10
L20S_P1	38.71	17:15,03/Jul	100	05:15,08/Aug	72.87

Table 3.13: Percentages of hours in the range above 65%RH

Location	% hours in range > 65%RH
L1S_P2	86.7
L1N_P2	86.7
L1S_P1	82.7
L1N_P1	84.1
L10N_P1	83.7
L10S_P2	86.7
L10S_P1	82.7
L10N_P2	86.7
L20N_P1	83.3
L20S_P2	86.5
L20N_P2	86.8
L20S_P1	83.2
Total hours (% of sum)	**85.0**

For RH, the pattern of percentages hours above 65% RH was different compared to the OT results. All of the master bedrooms (P1) facing outward the block (south and north direction) recorded lower percentage of hours in the range above 65% RH (below 84%) than all the third bedrooms (P2). On 8th of August, the maximum RH was 100%RH and the minimum was 65%RH (Figure 3.29), suggesting that the diurnal range is slightly higher (10-15%) than the hourly variations in the measured data over a day.

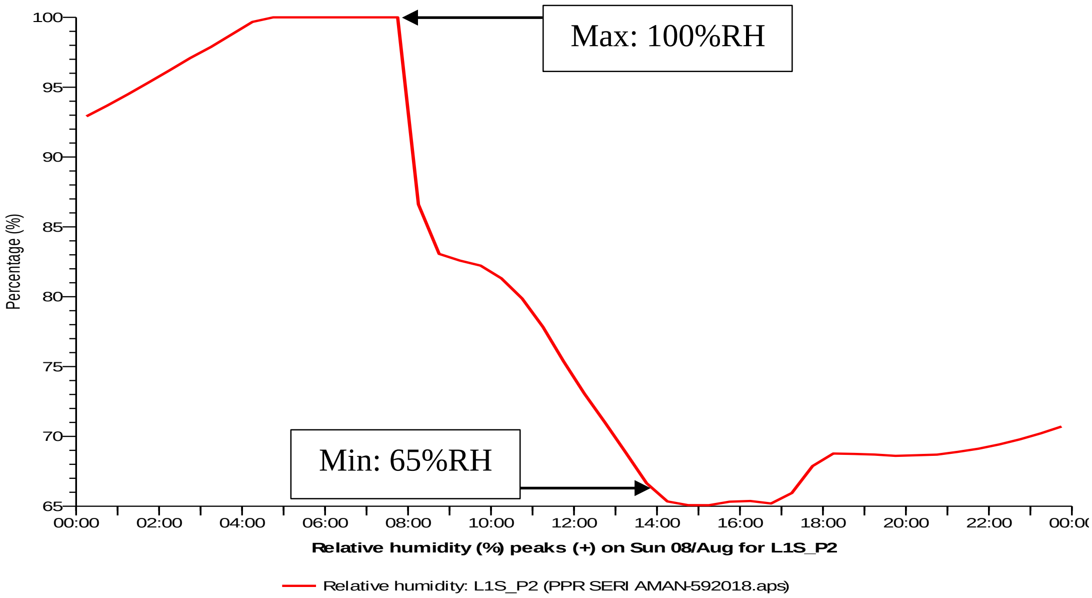
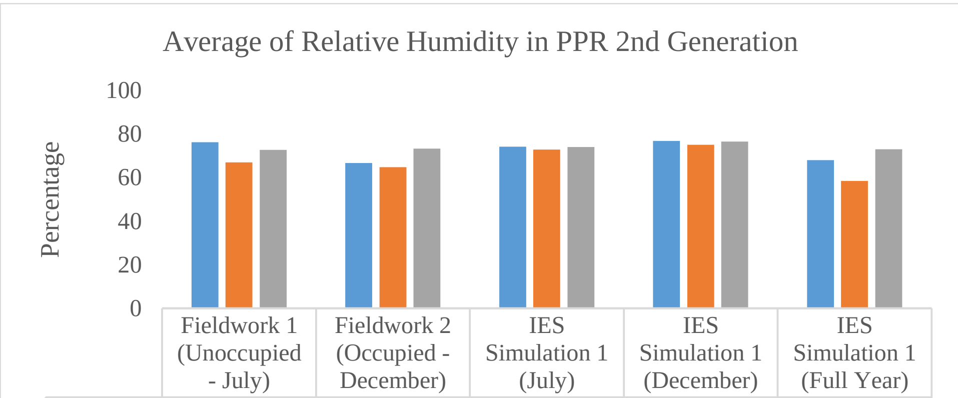


Figure 3.29: Daily distribution of RH on 8th August

The trends of RH results from the simulation modelling and fieldwork studies are shown in Figure 3.30. In general, the up-down-up pattern of RH from level 1 to level 20 is similar in all the results. Fieldwork 1 recorded the average RH results from 66.9% RH to 76.2% RH and fieldwork 2 resulted from 64.7% RH to 73.2% RH. For IES simulation, the average RH results in July were from 72.8% RH to 74.1% RH and in December were from 75.0% RH to 76.7% RH. It could be deduced that the average humidity for the full year for this PPR block was between 58.0% RH to 72.9% RH. For comparison purposes in future research, this study would use 66.4% RH as its humidity benchmark.



	Fieldwork 1 (Unoccupied - July)	Fieldwork 2 (Occupied - December)	IES Simulation 1 (July)	IES Simulation 1 (December)	IES Simulation 1 (Full Year)
Level 1	76.2	66.6	74.1	76.7	68.0
Level 10	66.9	64.7	72.8	75.0	58.4
Level 20	72.7	73.2	74.0	76.5	72.9

Figure 3.30: Comparison of RH Results with Fieldwork Studies

3.8 Comparison of Fieldwork and Baseline Simulation Outcomes

3.8.1 Thermal Comfort

As discussed previously, the fieldwork study found three different zones for indoor comfort and air quality in PPR Seri Aman (second generation) which were the 'unobstructed facing zone', 'obstructed facing zone' and 'enclosed facing zone' (Figure 3.31). The study also found that a uniform zone was created in PPR Beringin (first generation) after the house units were being occupied. The environmental conditions of the PPR first generation such as operative temperature and relative humidity showed similar trends, which were uniform and similar regardless of levels and locations of the rooms (Figure 3.31). This was due to the closed-environment set-up created by the occupants using curtains and blinds. These accessories reduced the performance of natural ventilation and inhibited air exchange, resulting later in heat (created from solar radiation and human activities) accumulated and trapped within indoor spaces.

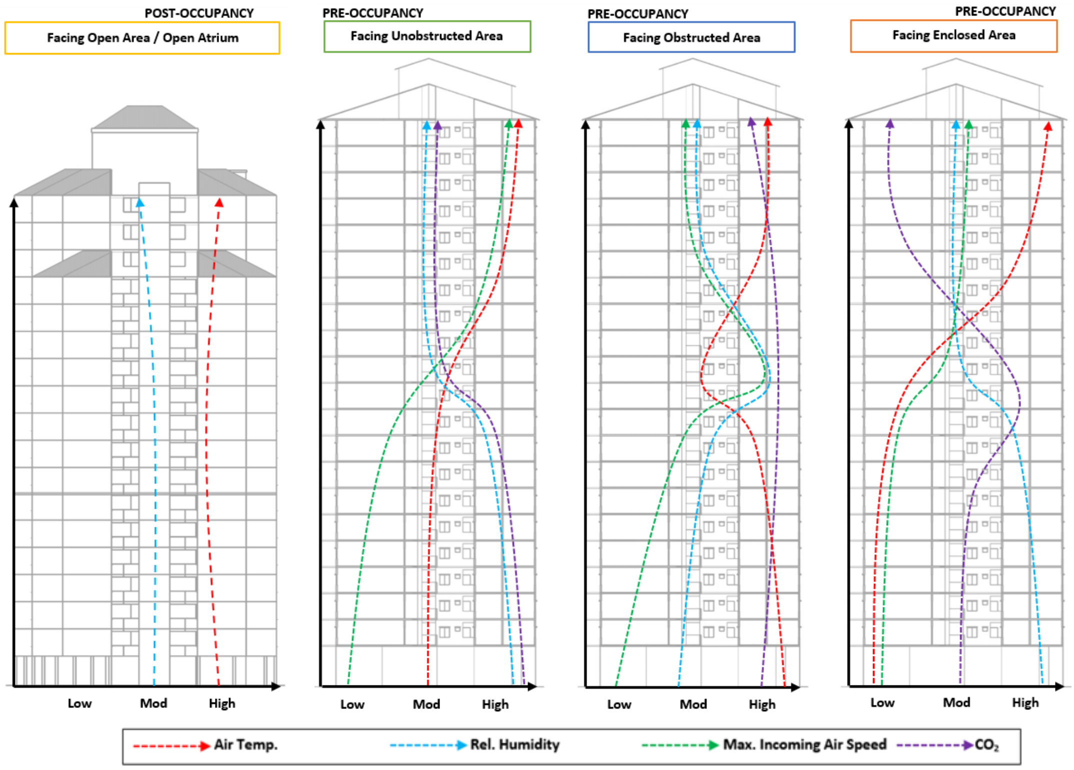


Figure 3.31: The identified four different environmental conditions zones in PPR Seri Aman and PPR Beringin (Appendix 1D).

It could also be deduced that the gradually increasing operative temperature profile for the unobstructed facing zone was resulted from the gradient wind profile in the urban areas (Energy, 2016). The eddies and recirculation regions of the wind movement (Tominaga, Akabayashi, Kitahara, & Arinami, 2015) at the obstructed facing zone had reduced the operative temperature in level 10 and the weaker stack effect (Prajongsan, 2014) in the light-wells (enclosed facing zone) decreased the operative temperature in level 20.

Light-wells, a compulsory element in PPR second generation for provisioning daylight and ventilation (Mohd Sahabuddin & Gonzalez-Longo, 2017; UBBL, 2013), were typically designed as passive cores that served the adjacent rooms through stack effect ventilation. However, as explained before, the passive stack effect in the case studies was ineffective for ventilation purposes. It could be deduced that different airspeed profiles were the main factors contributing to the variety of operative temperature, relative humidity and airspeed values in these zones (Figure 3.31).

The locations that received more heat in the block were the outward-facing spaces – the spaces facing direct unobstructed open environment. This was due to the direct solar radiation that penetrated into indoor spaces through exposed walls. These walls needed to be insulated and covered to minimise the radiation. For relative humidity, even though the humidity levels were very high throughout the block, the inward-facing spaces (facing light-wells) recorded a higher percentage of moisture compared to the outward-facing spaces (facing open areas). This was due to the enclosed-type of the environment in which the spaces faced.

This study also proved that the typical openings and designs of windows in the case studies, which were another compulsory element in providing views and ventilation for the occupants, did not provide healthy and adequate ventilation for the occupants of the buildings at the moment. The resulting three different environmental zones in the PPR second generation, made the required clean, cool and constant air circulation almost impossible to achieve.

Furthermore, through simulation modelling, the actual weather condition in Kuala Lumpur was not able to create the right comfort conditions by natural means in indoor and outdoor spaces as required by the established standards. Approximately 70% of hours in a year for operative temperature in indoor spaces in PPR second generation block was above 28°C. Whereas, for relative humidity, 85% of hours in a year were above 65% RH. In addition, the simulation also verified that the humidity percentages in inward-facing rooms and light-wells were high especially at level 1 and level 20. These facts suggested that the comfort conditions in the PPR block were critical and could not fulfil the occupant comfort needs.

The simulation results also had confirmed that a weaker stack effect was in place inside the light-wells. A strategy should be implemented to improve the air movement inside the light-wells. This simulation by referring to the fieldwork studies had validated that the average operative temperature and relative humidity in PPR second generation block were 29.1°C and 66.4 % RH respectively (Table 3.14). These values surpassed the required ASHRAE and CIBSE requirements. According to the facts mentioned before, it was recommended that an energy-efficient strategy could be used to reduce the air temperature, and passive air filtering technique also could reduce the excessive humidity and particles in the air.

Table 3.14: Fieldwork studies and IES 1 results for PPR Second Generation

PPR Second-Generation	Mean OT (°C)	Mean RH (%RH)
Ranges	24.0 – 28.4[1]	<65[1] / 40.0 – 70.0[2]
Fieldwork Studies (1 & 2)	29.3	70.1
IES Simulation 1 (Full Year)	29.1	66.4

Note: [1] ASHRAE 55,
[2] CIBSE Guide A

The fieldwork studies and IES simulation results as tabulated on a psychrometric (Figure 3.32) clearly showed that the ambient outdoor thermal environment in Kuala Lumpur could not provide the minimum requirement of indoor comfort for the city’s population. Knowing this condition was crucial for this study which would give an insight that indoor comfort by natural means in urban areas in Kuala Lumpur was impossible to achieve. Thus, a new mechanism of strategies should be implemented in buildings for assisting and providing indoor comfort in residential units in Kuala Lumpur urban areas, especially in high-rise buildings.

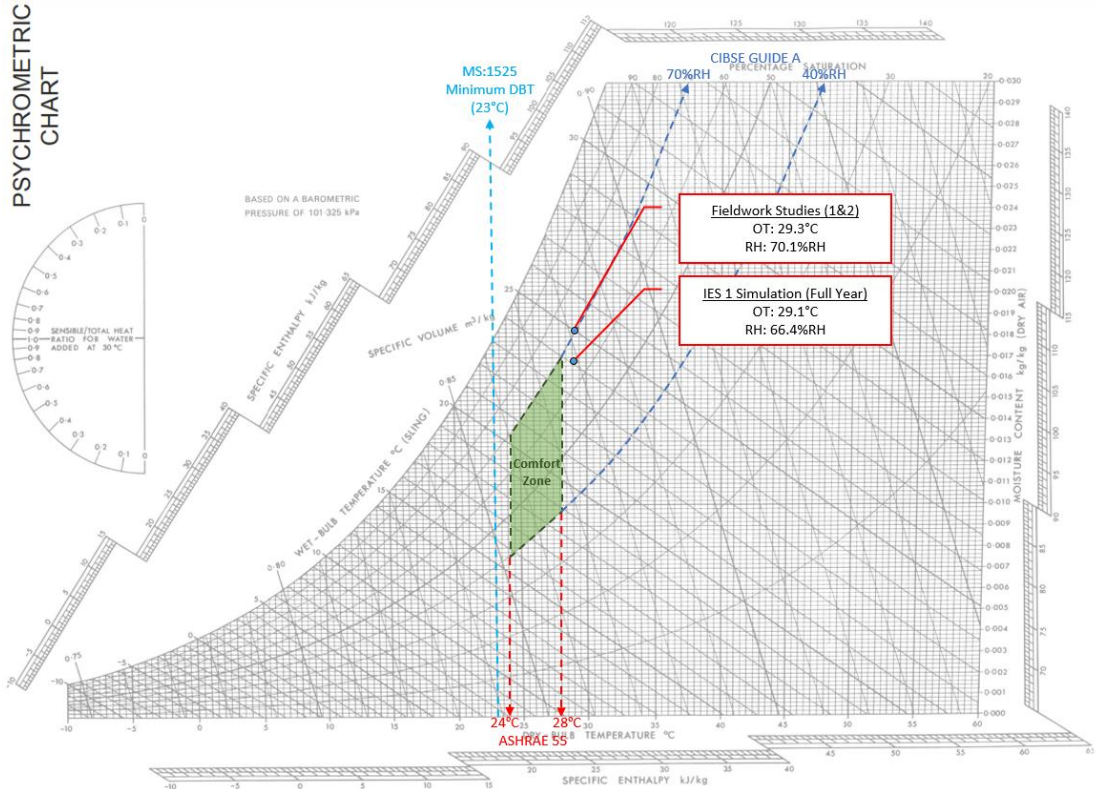


Figure 3.32: The location of the fieldwork studies and IES simulation results on the psychrometric chart

3.8.2 Air Quality

As previously discussed, through the fieldwork studies, the two major substances contributed to the poor air quality in indoor and outdoor spaces in Kuala Lumpur were PM_{10} and $PM_{2.5}$. One of the main factors contributed to high PM_{10} and $PM_{2.5}$ levels in both PPRs was from the religious ritual (joss stick burning, thin stick that burns with a smell of incense) which usually happens especially after working hours (6 pm onwards). Surrounding factors also contributed to high PM_{10} and $PM_{2.5}$, among the factors were the construction works nearby the fieldwork sites, and heavy traffic flow in the morning and evening that spread the dust particles to the lower atmosphere.

However, there was a significant difference in the concentration of PM_{10} and $PM_{2.5}$ in buildings with atrium and light-well. The concentrations of PM_{10} and $PM_{2.5}$ in buildings with atriums were towards ascending trends where the highest floor recorded high concentration, contrary with the buildings with light-wells which the concentrations were decreasing from higher floors to lower floors (Table 3.15). This suggested that passive strategies like atrium and light-well had different concentration profiles for PM_{10} and $PM_{2.5}$.

Table 3.15: Summary of the fieldwork study 2 results

Parameter	PPR Beringin			PPR Seri Aman		
	Outdoor	P5: Atrium	P6: Indoor	Outdoor	P5: Lightwell	P6: Indoor
PM_{10}						
Level 1	P1: Moderate	Moderate	Low	P1: High	Moderate	High
Level 10	P2: Low	Moderate	Low	P2: Moderate	Moderate	Moderate
Level 17/20	P3: Low	Moderate	Moderate	P3: Moderate	Moderate	Moderate
-	P4: Low	-	-	P4: Moderate	-	-
$PM_{2.5}$						
Level 1	P1: High	High	High	P1: High	High	High
Level 10	P2: High	High	High	P2: High	High	High
Level 17/20	P3: High	High	High	P3: High	High	High
-	P4: High	-	-	P4: High	-	-
CO_2						
Level 1	P1: Moderate	Low	Moderate	P1: Moderate	Low	Moderate
Level 10	P2: Low	Moderate	Moderate	P2: Moderate	Low	Moderate
Level 17/20	P3: Low	Moderate	Moderate	P3: Moderate	Low	Low
-	P4: Low	-	-	P4: Low	-	-
CO						
Level 1	P1: Low	Low	Low	P1: Low	Low	Low
Level 10	P2: Low	Low	Low	P2: Low	Low	Low
Level 17/20	P3: Low	Low	Low	P3: Low	Low	Low
-	P4: Low	-	-	P4: Low	-	-

Note 1:

PM_{10}	: Low (<30 $\mu g/m^3$)	Moderate (30-50 $\mu g/m^3$)	High (>50 $\mu g/m^3$)
$PM_{2.5}$	: Low (<10 $\mu g/m^3$)	Moderate (10-15 $\mu g/m^3$)	High (>15 $\mu g/m^3$)
CO_2	: Low (<499 ppm)	Moderate (500-999 ppm)	High (>1000 ppm)
CO	: Low (<5 ppm)	Moderate (5-9 ppm)	High (>9 ppm)

Note 2:
P1 – Main Road; P2 – Buffer Zone; P3 – Building Apron; P4 – Open Space; P5 – Atrium or Light-well; P6 – Indoor

This study also found that PM_{10} and $PM_{2.5}$ concentration at a lower level was more crucial in a high-rise building with light-wells due to high humidity. In general, buildings with atriums performed better than buildings with light-wells in terms of indoor comfort and health. Hence, a new mechanism should be implemented in the light-well design to increase its effectiveness in reducing PM_{10} and $PM_{2.5}$ concentrations. This contribution could also increase the air movement and reduce the air temperature in indoor spaces in high-rise residential buildings.

Based on a few studies (Mohamed Bin Yehmed, Abdullah, Zainal, Zawawi, & Elawad, 2016) and the DOE annual reports (DOE, 2015, 2016a, 2017), the substances such as SO_2, NO_2, CO_2 and CO were not considered as the main substances of air pollution in Kuala Lumpur. A fieldwork study by Leh et al. (2012) proved that CO and SO_2 were good in all sampling days and NO_2 recorded moderate levels (Leh et al., 2012). The results of this study revealed that $PM_{2.5}$ was the major substance in an indoor and outdoor environment in Kuala Lumpur (Leh et al., 2012) due to the particles that were lighter and could stay longer in the air than PM_{10} particles (Fuller, 2018). However, in a high humidity area such as at the lower part of a light-well, these particles became heavier and without adequate air movement, these particles could not release from the light-well space by itself.

Taken into consideration of this second fieldwork study conducted by the authors in December 2017, the average concentrations for PM_{10} and $PM_{2.5}$ in indoor spaces in PPR second-generation were 53.5 $\mu g/m^3$ and 44.2 $\mu g/m^3$ respectively. Both values surpassed the WHO limits with $PM_{2.5}$ recorded higher concentrations. Another long term (all year round) fieldwork by Rahman et al. (2015) from 2002 to 2011 found that the annual average for PM_{10} and $PM_{2.5}$ were 48.4 $\mu g/m^3$ and 26.1 $\mu g/m^3$ respectively (S. A. Rahman et al., 2015). Both values were consistent with the fieldwork studies by the authors and also surpassed the annual limit set by the WHO (Table 3.16).

Another monitoring works done by the DOE from 2000 to 2015, found that the annual average for PM_{10} from 2000 to 2015 in urban areas in Kuala Lumpur was 48.0 $\mu g/m^3$ (DOE, 2016a). Similarly, the value surpassed the WHO limits. It was undeniable that both PM_{10} and $PM_{2.5}$ concentrations in Kuala Lumpur, either in indoor or outdoor spaces – short or long term, were well above the WHO recommendations.

Table 3.16 Comparison of fieldwork studies in Kuala Lumpur

Parameters	**Duration**	**Fieldwork 2 (2017)**	**Rahman et al. (2002 – 2011)[1]**	**DOE Dataset (2000 – 2015)[2]**	**WHO Limits[3]**
Sampling Location		Indoor	Outdoor	Outdoor	
Mean PM_{10}	(24 hours)	53.5	-	-	50.0
($\mu g/m^3$)	(1 Year)	-	48.4	48.0	20.0
Mean $PM_{2.5}$	(24 hours)	44.2	-	-	25.0
($\mu g/m^3$)	(1 year)	-	26.1	-	10.0

Notes: [1]Rahman et al. (2015)
[2]Department of Environment (DOE), Malaysia (2016)
[3]WHO Ambient Air Quality Guidelines (2006)

3.8.3 Possible Strategies to Address the Issues Found

It could be deduced that buildings using atrium could perform better than buildings using light-well in terms of indoor comfort and air quality. It was found that large atriums that surrounded by corridors could allow adequate air movement. The existence of pilotis/columns improves air movement at ground level. Vacant areas at ground level has also prevented stagnant air in the atriums by allowing wind force to enter the building from any angle. Directly, improving indoor comfort of the housing units. The fieldwork studies found that only relative humidity in buildings using light-well produced better results. Having to take consideration of the scarcity of land in urban areas, a compact design using light-well would be the best option. That was the main reason for the evolution of PPR designs from the first generation to the second generation, which was to accommodate more people in a limited area.

Based on the fieldwork studies and IES simulation results, it was recommended that PPR buildings to undergo a significant transformation. Indoor environmental conditions should be taken into consideration upon designing the high-rise residential buildings so that they could achieve indoor comfort and air quality, as well as the subsequent reduction in consumption of energy and resources. Optimum different strategies and designs should be explored in order to provide an acceptable indoor comfort and air quality for the entire building regardless of altitude, plan layout and facing direction of the housing units.

A comfortable and healthy living environment could be achieved by architectural designs that could ensure constant air movement in indoor spaces, and at the same time filtering of external air pollution. Considering that natural ventilation strategies had some limitations such as allowing outdoor air pollution, an integrated strategy of passive and low energy consumption should be explored in greater detail. This integrated strategy should consider the design of openings and light-wells in more detail to cope with the problems of indoor comfort and health issues in the urban environment.

As explained in Chapter 2, dynamic insulation was known to have a great potential in solving the four issues arisen in this research: 1) high air temperature, 2) high humidity, 3) high air pollution, and 4) low air movement. The dynamic insulation term had been coined to describe the incoming air stream being delivered through an insulation matrix above an air-permeable ceiling (or wall) to act primarily as an energy efficiency technique, especially in temperate climates (Craig & Grinham, 2017; Halliday, 1997). This technique, however, had the additional advantage of providing a large volumetric filter membrane that can filter air pollution (B. Taylor & Imbabi, 1998) and heat and moisture at the same time (Craig & Grinham, 2017; Halliday, 1997, 2000).

Given the above facts, dynamic insulation was the only technique that could provide constant, clean and cool air which ultimately would solve the problems of indoor discomfort and air pollution in high-rise residential buildings in Kuala Lumpur. The application of this technique in Malaysia and its region was not yet identified. This technique also could be integrated with light-wells that usually were provided in high-rise buildings in Malaysia. According to the fieldwork studies and IES simulation, there were additional issues in PPR second generation block regarding passive light-wells which were the weaker stack effects that created short-circuit of air movement and high humidity that usually occurred in the light-wells' lower level. Significant improvement in the light-well strategy was very much demanded to cope with thermal comfort and air quality issues in the urban environment.

Further research would focus on this and involve a series of physical experiments using a reduced-scale model with different selections of filtering membrane including different approaches of activated carbon applications. At this stage, the ability of dynamic insulation technique would be fully tested using organic and toxicant contaminants.

4.CHAPTER 4: Dynamic-Hybrid Air Permeable Ceiling (DHAPC)

4.1 The Physical Model

Chapter 3 has explained in detail the actual thermal and air quality condition in high-rise social housing in Kuala Lumpur. From there, the four main issues (high air temperature, high humidity, high air pollution and low air movement) that need to be addressed were determined in order to achieve indoor comfort as well as the subsequent reduction in consumption of energy and carbon emissions. It means that high-rise social housing in Kuala Lumpur needs a significant transformation in terms of a ventilation strategy to ensure the constant air movement and filter the external heat, moisture and air pollution from entering its indoor spaces.

As explained in Chapter 2, dynamic insulation (DI) is known to have a great potential in solving the four main identified issues in this research. The use of DI allows for constant unidirectional airflow, mitigating the risk of airborne contaminants being released from a high-polluted area such as kitchen and bathroom (Jennette, 2014; Olmsted, 2008). At the moment, the use of unidirectional airflow concept in housing units is not sufficiently explored. This strategy has been widely implemented in 'cleanrooms' – especially in healthcare and electronic facilities (Bhatia, 2012b; Cho, Woo, & Kim, 2019).

This research tries to do this by re-designing the dynamic insulation strategy using 'cleanrooms' rules; this research calls this new system as 'Dynamic-Hybrid Air Permeable Ceiling' (DHAPC). This new strategy applies the 'cleanroom' rules (as described in Chapter 2) in high-rise residential buildings. In order to test the proposed system, a series of physical experiments have been carried out using a reduced-scale model with different types of filtering membrane including different methods of activated carbon applications. The filtering ability of DHAPC has been tested using organic smoke and toxic gases from petrol and diesel engines.

A reduced-scale model of the actual master bedroom in PPR second generation was built on a scale of 1:5. The model consists of three compartments reproducing the different environments and elements: the outdoor chamber, the DHAPC and the indoor space (Figure 4.1). The outdoor chamber compartment tries to reproduce the average outdoor thermal and air quality in Kuala Lumpur during daytime and night-time in the dry season. The condition ranges used were based on the first and second fieldwork studies done by the authors, as described in Chapter 3. The overall form of the test model was a straight duct equipped with a high-efficiency particulate air (HEPA) filter in the DHAPC compartment (Figure 4.1). Using straight duct and HEPA filters are recommended by ASHRAE 52.2 and EN779. Two instruments that can measure indoor comfort parameters were placed in the outdoor compartment and indoor space compartment during the test (Figure 4.2).

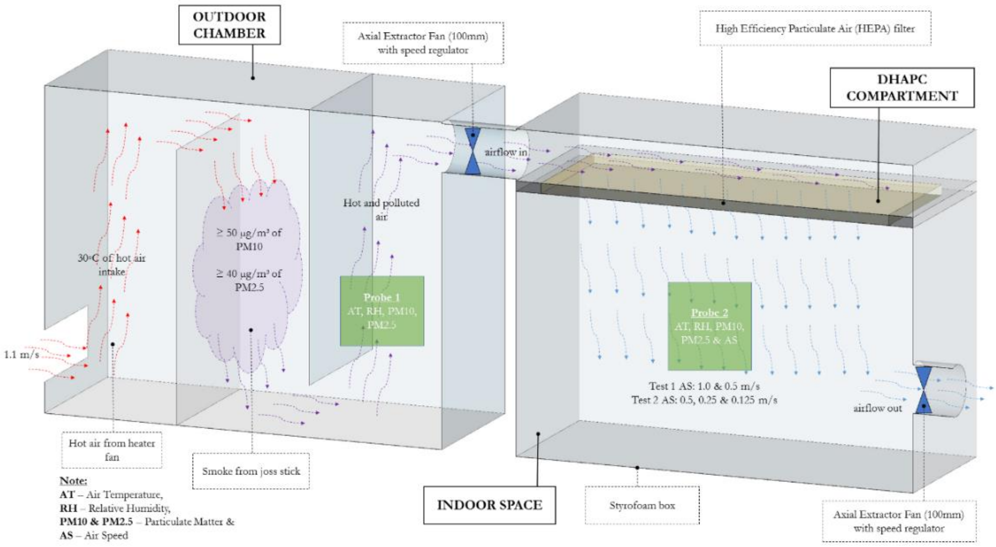


Figure 4.1: DHAPC theoretical model concept

The actual room dimension as built-in the PPR second generation is 4000 mm (L) x 3000 mm (W) x 3150 mm (H) and thus, the model is 800 mm (L) x 600 mm (W) x 630 mm (H) respectively (Table 4.1). It was built airtight and made of closed-cell extruded polystyrene foam due to its very low rate of thermal conductivity, keeping the indoor space condition at a stable temperature regardless of any external condition (AlQdah & AlGrafi, 2013). The selection of this material is appropriate because a 25 mm thick of polystyrene sheet has an equivalent of U-value (2.0 W/m^{2}k) with the U-value of a single layer of a brick wall (100 mm), which is the typical construction method in Malaysia. Two particle counter instruments were placed – one in the outdoor chamber and another in the indoor space compartment – to measure the concentration of particulate matter and toxic gases as well as the air temperature and humidity levels.

Figure 4.2: The actual physical model

Table 4.1: Reduced-scale model design in comparison with the actual room

Parameters	Units	Actual Room	Reduced-Scale Model
Length	mm	4000	800
Width	mm	3000	600
Height	mm	3150	630
Wall Material	-	Single-layer brick wall	Polystyrene
Wall Thickness	mm	100	25
U-value	W/m^2k	2.0	2.0

4.2 Testing

4.2.1 Methodology

The investigation using the physical model was carried out to address three aims in three tests (Figure 4.3). Using synthetic materials, the baseline thermal comfort and air quality performance were tested (Test 1) followed by improving the results obtained in Test 1 using recycled materials (Test 2). Then, it was continued with a refining test of the system using activated carbon techniques (Test 3). Test 1 was carried out to evaluate the performance of dynamic insulation and hybrid ventilation using synthetic insulations. This initial test was crucial to define the four fundamental criteria to be used in this research in order to fulfil the research objectives. The criteria are 1) to validate the reliability of the physical model, 2) to define the best ventilation protocol(s), 3) to determine the best airspeed value(s), and 4) to propose the best filter membrane to be used in the proposed system. Test 2, as a continuity from Test 1, was conducted to improve the performance of the DHAPC system using different configurations of ventilation protocol(s), types of insulations and airspeed value. These configurations were suggested from the findings obtained in Test 1.

Finally, Test 3 was conducted to add the value of the research which also enhanced the filtering performance of the DHAPC system with toxic gases from vehicles. This test used substances produced by petrol and diesel engines. This test was also crucial as it gave an added value to the research contribution in different perspectives, proposing that the system was tested in-depth using several types of pollution sources from organic smoke to toxic gases.

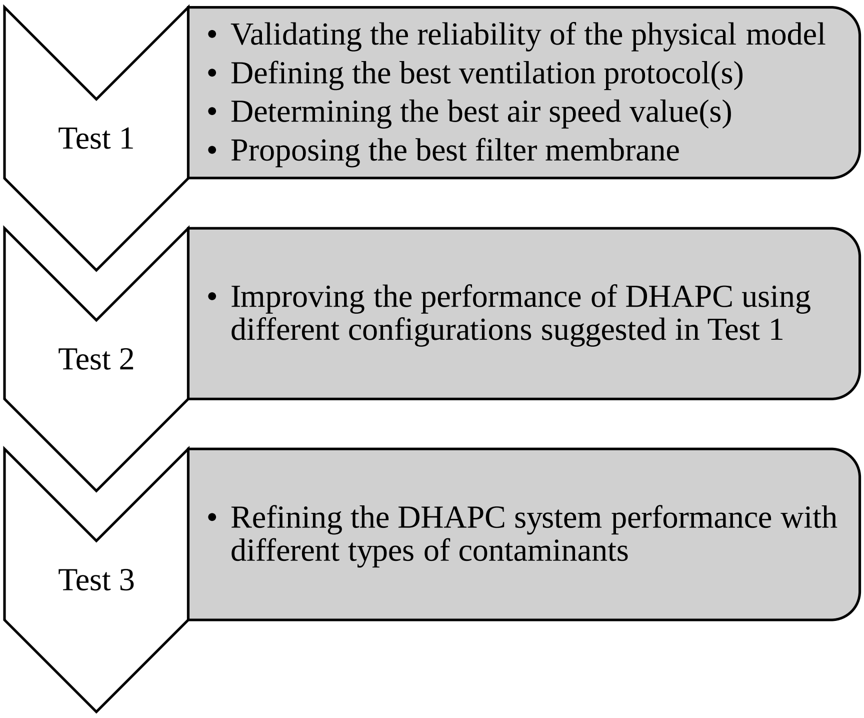


Figure 4.3: Method for assessing the physical model tests

4.2.2 Instruments

Table 4.2 shows the details of the instruments used in these tests. For Test 1 and 2, instrument ‘A’ was used. This instrument with ‘plant tower’ technology measured the air temperature, humidity and airborne particles from the range of 0°C to 50°C, 20% to 90% RH and 0 to 999 µg/m^3 respectively. Only for Test 3 that involved a few types of gases, instrument ‘B’, ‘C’ and ‘D’ were used (Figure 4.4). Instrument ‘B’ measured CO using a detection technique of ‘stabilised electrochemical gas-specific’ that has a test range from 0 to 1000 ppm. Instrument ‘C’, equipped with ‘semiconductor sensing technology’, was used to measure benzene and instrument ‘D’ for measuring SO_2 using aspirator that can detect the gas within the range of 0 to 20 ppm.

Table 4.2: The details of the instrument used in Test 3

Instrument	Substance(s) Measured	Test Range	Detection Technique	Density Unit
A) Home Monitoring Air Quality	PM_1,$PM_{2.5}$ & PM_{10} Air Temperature Relative Humidity	0 – 999 0 – 50 20 - 90	Plant Tower - ARM 32 Bit Processor	µg/m^3 °C %RH
B) Crowcon SO_2 Detector	CO	0 – 1000	Stabilised Electrochemical Gas-Specific (CO)	ppm
C) Formaldehyde Detector	Benzene	0 – 9.999	Semiconductor Sensing Technology	mg/m^3
D) Carbon Monoxide (CO) Tester	SO_2		Optional Manual Aspirator	ppm

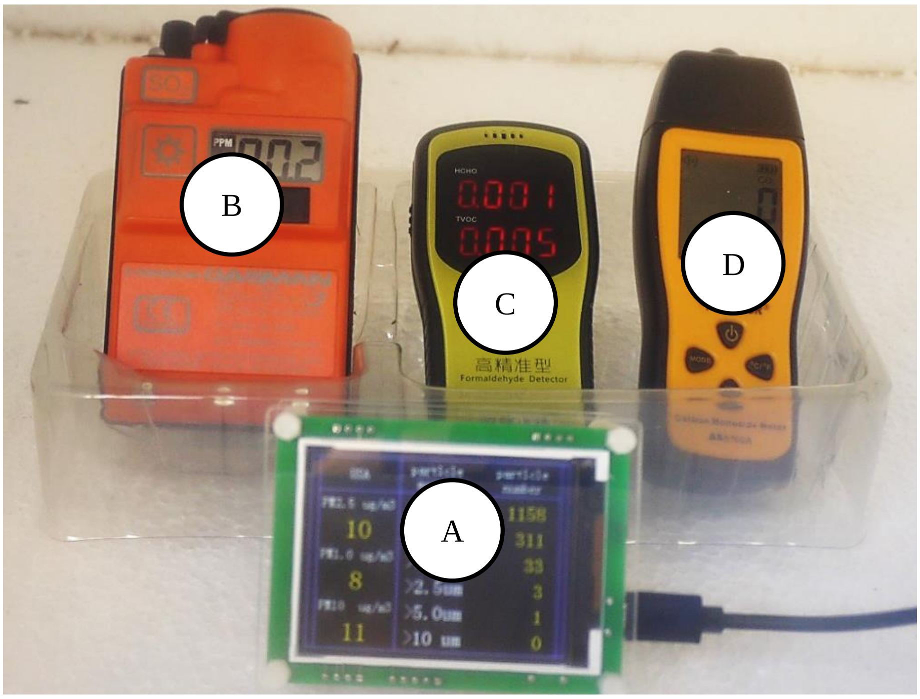


Figure 4.4: The instruments used in the test

A study suggested that these low-cost instruments are sufficiently accurate and have the potential to identify high pollutant exposures, providing high-density and reliable data (Moreno-Rangel et al., 2018). Another study found that low-cost instruments are accurate and reliable in detecting large sources that they appear suitable for measurement-based control to reduce exposures to $PM_{2.5}$ mass in homes (Singer & Delp, 2018).

4.2.3 Measurement Procedures

The tests 1 and 2 followed the recommendations outlined in the ASHRAE 52.2 – 'Method of testing general ventilation air-cleaning devices for removal efficiency by particle size' (ASHRAE, 2007) and the European Standard EN779 – 'Particle air filters for general ventilation-determination of filtration performance' (EN, 2012). The suggested ranges set by ASHRAE 52.2 and EN779 are between 0.3µm - 10µm and 0.2µm -3µm respectively (Figure 4.3). For these tests, and in accordance with the results of the second fieldwork, only two-particle sizes were counted – $PM_{2.5}$ and PM_{10}.

Table 4.3: Comparison of measurement procedures in ASHRAE 52.2, EN779 and DHAPC physical model

Parameters	ASHRAE 52.2	EN779	DHAPC Test 1 & 2
Particle Sizing Range	0.3~10µm	0.2~3µm	2.5~10µm
Sampling Instrument	Optical counter or Aerodynamic particle counter	Optical counter	Laser $PM_{2.5}$ sensor
Test Duct	Straight/U shape duct, HEPA filter installed	Straight duct, HEPA filter must be installed at the inlet	Straight duct, HEPA filter installed
Inlet Air	Indoor air or return air	Indoor air or outdoor air	Indoor air
Exhaust Air	Exhaust to the outside, indoor, or recirculated	Exhaust to the outside, indoor, or recirculated	Exhaust to the outside
Temperature	10°C~38°C	n/a	29°C~33°C
Relative Humidity	20%~65%	<75%	30%~55%
Pressure	Positive pressure	Positive pressure or negative pressure	Positive pressure or negative pressure
Air Flow Range	0.22~1.4 m^3/s	0.24~1.5 m^3/s	0.5 and 1.0 m^3/s

One of the main objectives of this test was to define the best ventilation protocol in solving the problems of indoor comfort and air quality in Kuala Lumpur urban areas. These tests have taken the four parameters into consideration – air temperature, relative humidity, $PM_{2.5}$ and PM_{10}, and assessed them using four different ventilation protocols (Figure 4.5), as follows:

1) Fully passive (B-B) – both DHAPC and indoor space compartment use wind buoyancy;
2) Hybrid-negative (B-F) – DHAPC uses wind buoyancy and indoor space compartment uses exhaust fan;
3) Hybrid-positive (F-B) – DHAPC uses supply fan and indoor space compartment uses wind buoyancy; and
4) Fully active (F-F) – both DHAPC and indoor space compartment use fans (supply and exhaust).

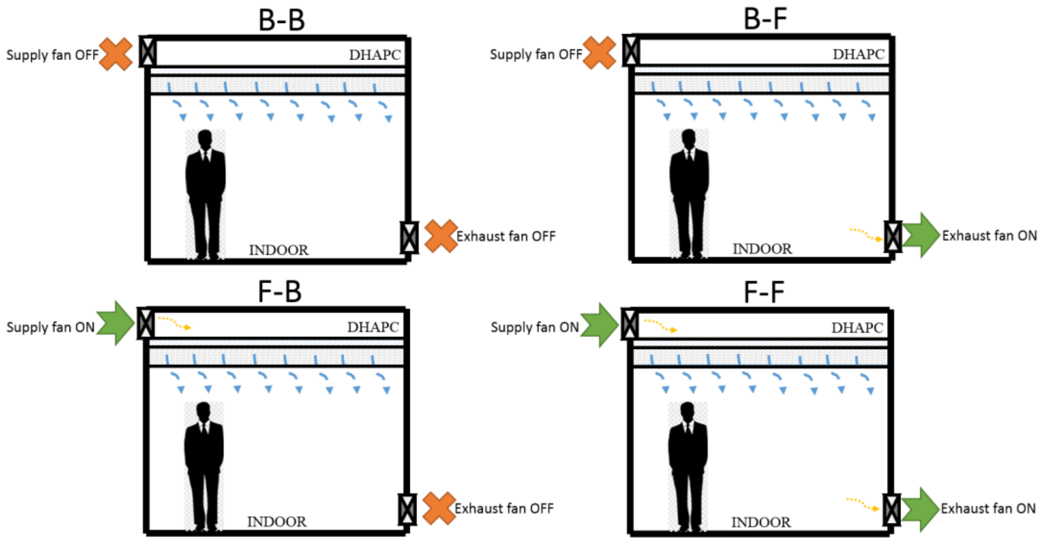


Figure 4.5: Four ventilation protocols used in the tests

In Test 1, these protocols were tested using three synthetic filters – polyester, polyethylene terephthalate also known as PET, and a combination filter of a carbon-charcoal filter with polyester and PET (Figure 4.6). These insulation materials used different thicknesses – 30 mm for polyester, 40 mm for PET and 50 mm for the combination filter. This test used three different time log intervals which were 5, 10 and 15 minutes and two different airspeeds – 1.0 m/s or 0.5 m/s as suggested in ASHRAE 52.2 and EN779. The analysis of results was based on the reduction rate; the more reduction rate achieved by any configuration, the better the result would be.

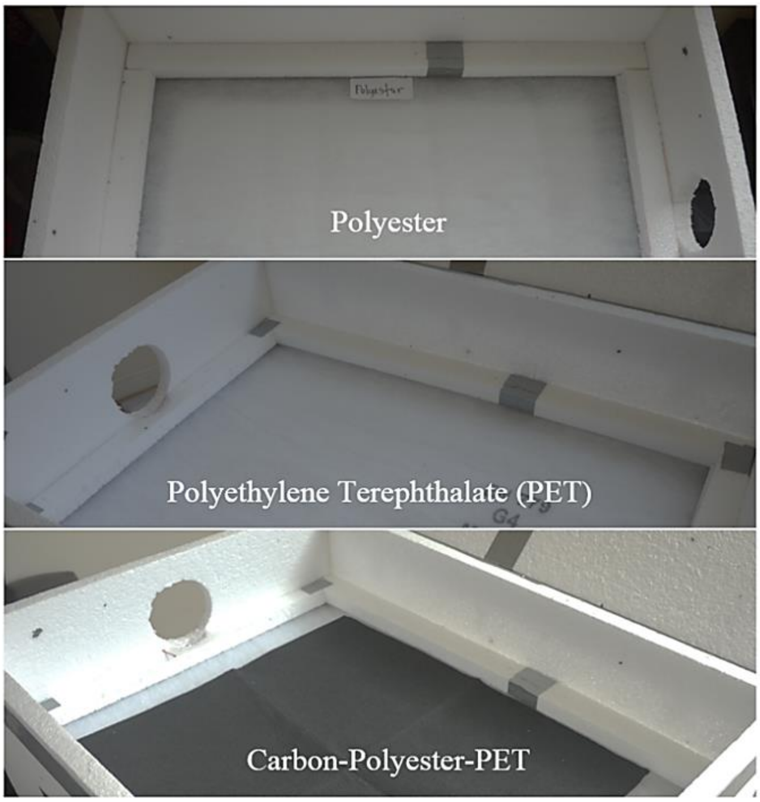


Figure 4.6: The synthetic materials used in Test 1

In Test 2, the protocols were tested by using three different loft insulations made from recycled materials such as recycled glass, recycled plastic and recycled wool (Figure 4.7). Each of the insulation will also be tested with a cartridge that consists of activated carbon (AC) granules. The insulation materials used in this test shared a similar thickness of 100 mm. Likewise in Test 1, this Test 2 used similar log time intervals (5 mins / 10mins / 15 mins) with three different airspeeds (0.5, 0.25 and 0.125 m/s) that were suggested from the Test 1 findings and the established standards.

Activated carbon (AC) that has undergone the additional processing to make it better in trapping gas molecules and usually effective for reducing 'volatile organic compounds' (VOCs) (Myers, 2018) was chosen to be studied in Tests 2 and 3. For Test 1, the AC was in cartridge form where the AC granules were filled in a box made from polystyrene (Figure 4.8). In Test 3, two types of AC applications were tested; the AC cartridge application, and the AC in a loose-fill application where the AC was flattened on the DHAPC membrane top surface (Figure 4.8). The first option had a compressed box while the second option had an uncompressed surface.

Figure 4.7: The recycled insulations used in Test 2

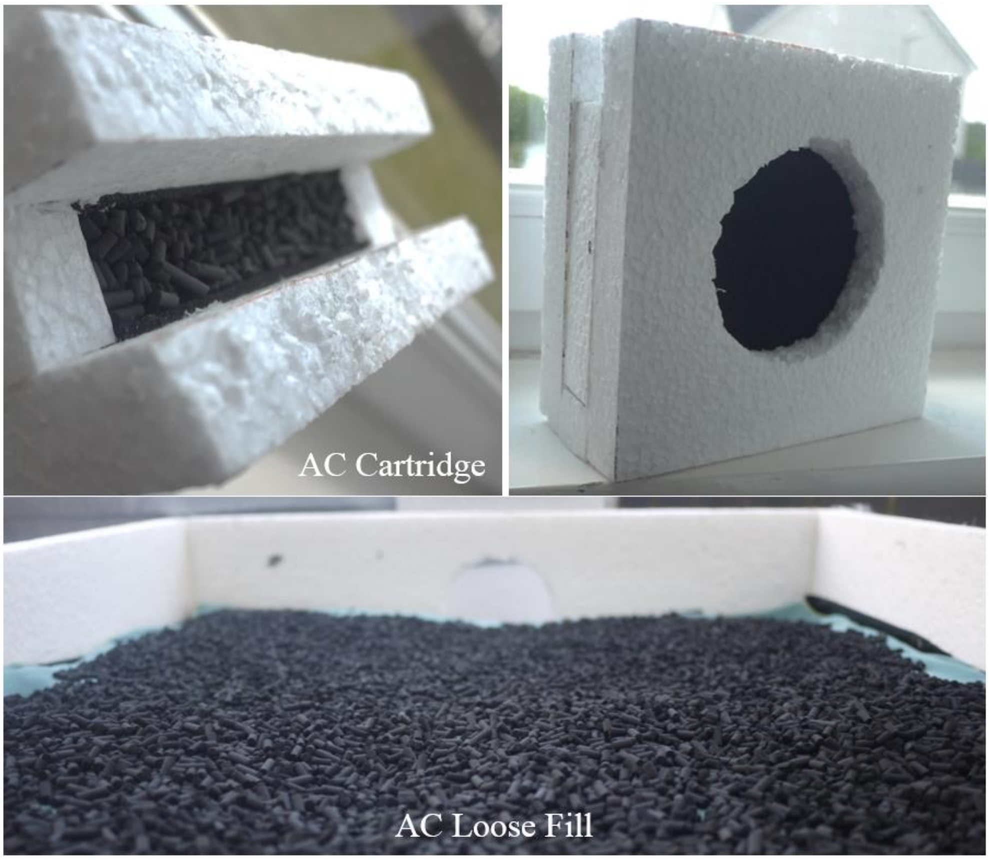


Figure 4.8: The AC cartridge (above) and AC loose-fill (below)

As a continuation from Tests 1 and 2, Test 3 was conducted to refine the performance of DHAPC in filtering the toxic gases and particles from petrol and diesel engines. Among the substances measured were CO, benzene, SO_2, PM_1, $PM_{2.5}$ and PM_{10}. The CO, benzene and SO_2 are categorised as gaseous-typed substances and the rest are airborne particles with different sizes. As determined in Test 1 and Test 2, two ventilation protocols (F-B and B-F) were applied in this Test 3 using 0.125 m/s of airspeed and recycled glass filter. The readings were taken three times every three minutes (Table 4.4).

Table 4.4: The test details

Ventilation Protocol		Test Air Speed	Test Membrane	Log Time
1	Hybrid-Positive (F-B)	0.125 m/s	Recycled Glass	Every 3 minutes
2	Hybrid-Negative (B-F)			

Figure 4.9 shows the placement of the test model with the car samples. The model's air inlet was located at the nearest distance from the car's exhaust pipe. This set-up allowed the maximum amount of substances from the cars to enter the outdoor chamber of the model. Each run assessed four filtering methods:

1) F-B with AC cartridge,
2) F-B with AC loose-fill,
3) B-F with AC cartridge, and
4) B-F with AC loose-fill.

Each filtering method consisted of three data-logging series (15 minutes duration). Figure 4.10 shows the timeline of the initial series. The engine was run until the CO sensor became saturated after approximately one minute. The engine was then deactivated until the CO level dropped to ambient, at which point the fans were activated delivering the exhaust gases into the chambers. After two minutes, the data was recorded. This delay was an attempt to provide more 'steady-state' conditions in accordance with the parameters of the sensors, however, fresh air infiltration did produce a diluting effect (Figure 4.10).

Figure 4.9: The placement of the test model with the petrol (above) and diesel (below) cars

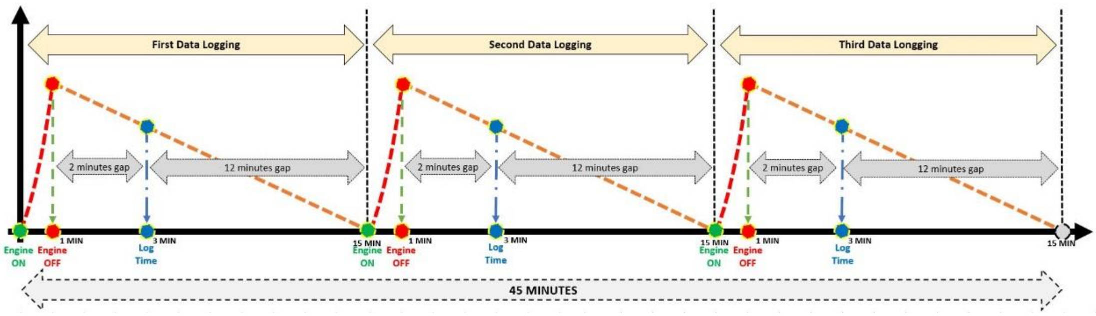


Figure 4.10: Measurement methods timeline (Appendix 1E)

In Test 3, two cars that represented the petrol and diesel engines were used. The petrol engine was made in 2004 and has a cylinder capacity of 1598 cc. This engine produced 180 g/km of CO_2. For diesel engine, a 2993 cc engine was chosen which contributed 164 g/km of CO_2 (Table 4.5). The diesel engine was equipped with a catalytic converter, was made in 2014. This converter is capable to convert an estimated 90% of the hydrocarbons, carbon monoxide, and nitrogen oxides produced into less harmful compounds (Colls, 1997). The different engine sizes, years of manufacture, CO_2 levels and the installation of the catalytic converter did not concern the test results because this test only analysed the reduction rates of the substances from the engines – regardless of the amount of the substances.

Table 4.5: Petrol and diesel engines details

Details	**Petrol**	**Diesel**
Year of Manufacture	2004	2014
Cylinder Capacity	1598 cc	2993 cc
CO_2 Emissions	180 g/km	164 g/km
Catalytic Converter	No	Yes

A baseline test reading was recorded which measured the reduction rates of recycled glass membrane without any AC techniques. Due to the catalytic converter that was installed in the diesel engine, this test only measured the baseline rates for petrol engine. This was because the catalytic converter will make the baseline readings for diesel engine seem intangible. Table 4.6 summarises all the set-ups used in Tests 1, 2 and 3. In the results and analysis section, the values will be shown in percentage reductions and not the absolute value differences. This was due to the absolute values that fluctuate within a very low and high ranges of data which do not represent the actual conditions. Furthermore, to determine the performance of the configurations, percentage reduction values are more appropriate to be used and compared.

Table 4.6: Scale model test set-up

Ventilation Protocols	**Pollution Source**	**Filtering Media**	**Airspeed Variables**	**Type of Pollution**
Test 1: B-B, B-F, F-B and F-F	Joss sticks	Synthetic insulation	1.0 and 0.5 m/s	PM_{10} and $PM_{2.5}$
Test 2: B-F and F-B	Joss sticks	Recycled insulation AC cartridge	0.5, 0.25 0.125 m/s	PM_{10} and $PM_{2.5}$
Test 3: B-F and F-B	Petrol diesel engines	Recycled glass AC cartridge/AC loose fill	0.125 m/s	PM_1, $PM_{2.5}$, PM_{10}, CO, Benzene, SO_2

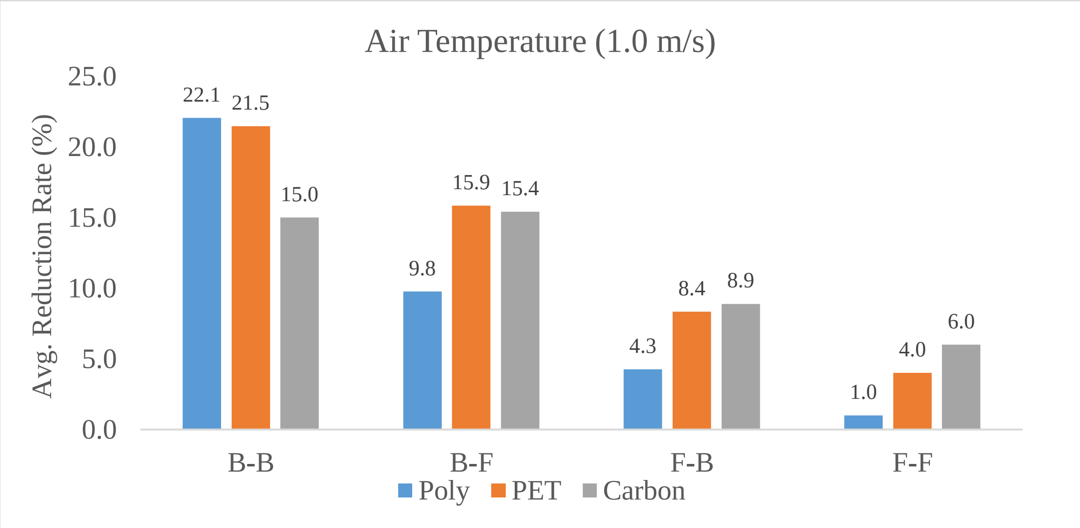
4.3 Test 1: Results and Analysis

4.3.1 Thermal Comfort

Air Temperature and Relative Humidity

The air temperature results show that the fully passive protocol (B-B) achieved the best result of reduction rate for all the filters. The reduction rates for B-B protocol when using 1.0 m/s of airspeed were between 15% to 22%, and when a lower airspeed of 0.5 m/s was applied, 14% to 25% of reduction rates were recorded. B-F protocol produced an outstanding performance of air temperature reduction rates of between 10% to 22%, followed by F-B protocol with slightly lower results between 4% to 21%. This test also found that the F-F protocol recorded the least result of reduction rate, which is between 1% to 15% only. It could be deduced that more reduction rate was achieved when lower airspeed being applied. In terms of material performance, the combination filter with the thickest depth gave better results (Figure 4.11).

The relative humidity results show a contradictory pattern of reduction rates. F-F protocol produced the highest reduction rate of humidity, up to 35%. The second-best performance was F-B protocol, followed by B-F and B-B protocols. The highest reduction rate recorded for the F-B protocol was 27% and 15% for B-F protocol. Meanwhile, only 12% of reduction rate was achieved by B-B protocol (Figure 4.12). These results suggested that humidity could be filtered efficiently when higher airspeed was set.



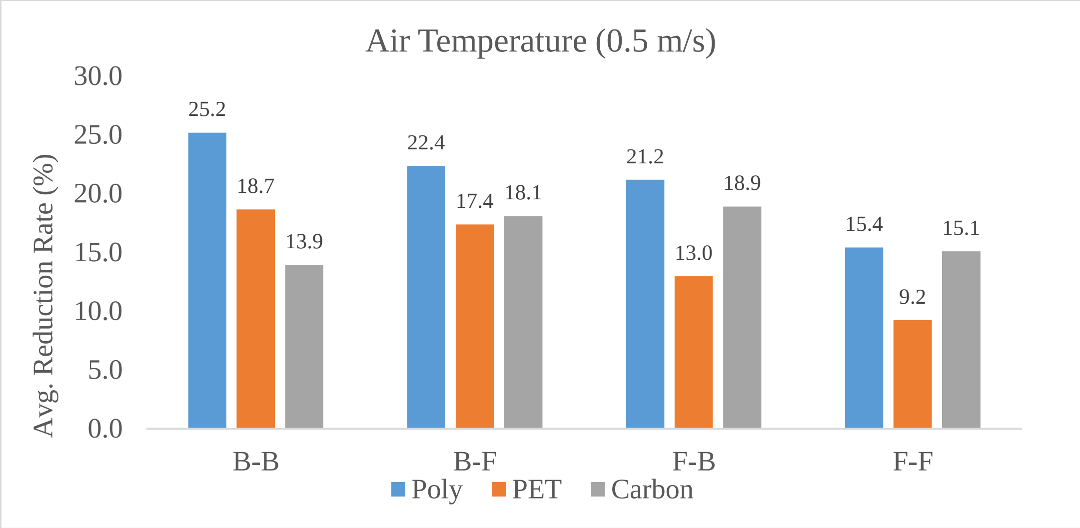
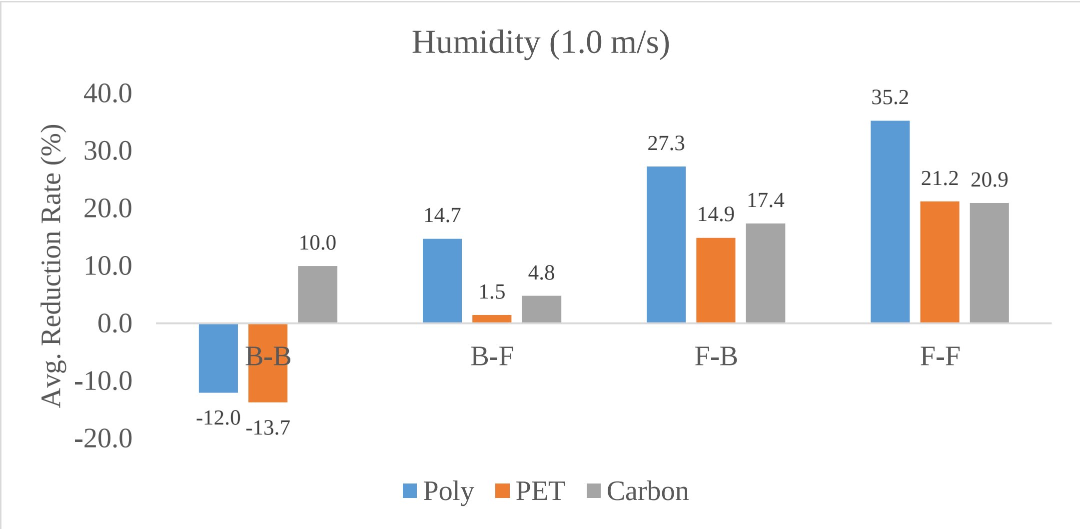


Figure 4.11: Air temperature results for different ventilation protocols and filter media.



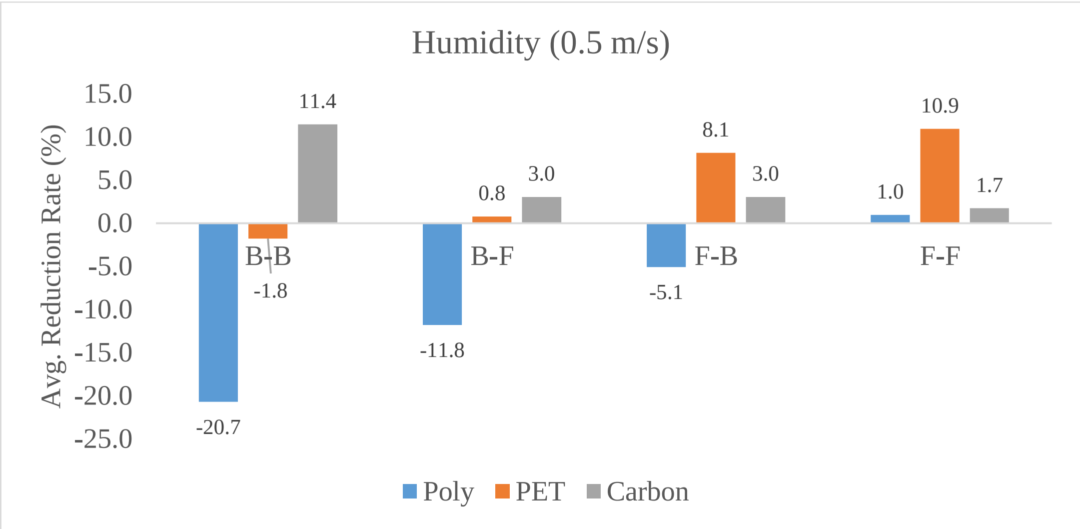


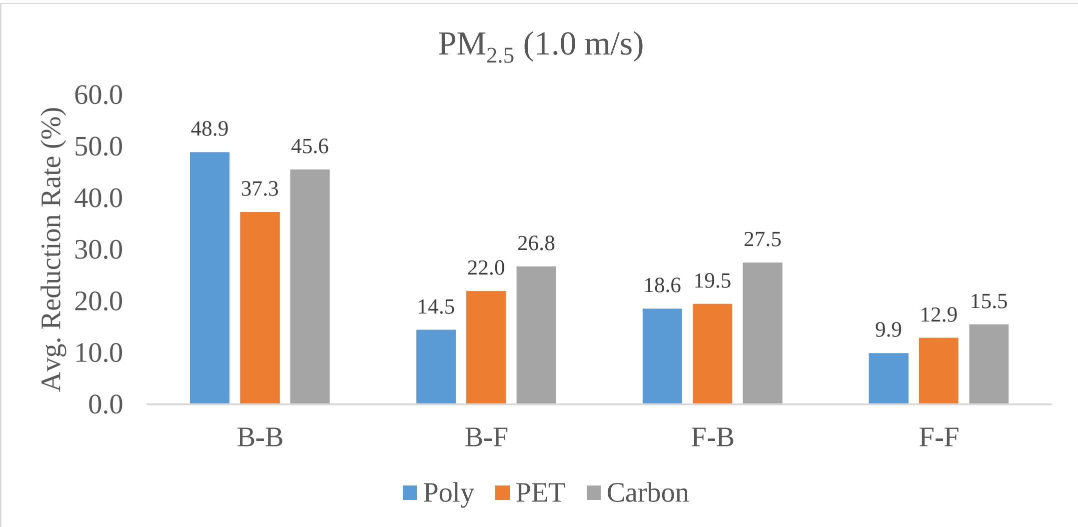
Figure 4.12: Relative humidity results for different ventilation protocols and filter media.

4.3.2 Air Quality

Particulate Matter ($PM_{2.5}$ and PM_{10})

The graphs in Figure 4.13 show the $PM_{2.5}$ results for different ventilation protocols and filter media. The patterns are decreasing from B-B to F-F for all three different media. B-B protocol reduced up to 56% of $PM_{2.5}$ due to the slow air movement that makes particles deposited well in the filter membrane. B-F protocol achieved the second-best performance, followed by the F-B and F-F protocols as the most unsuccessful options with a reduction rate below 25% (Figure 4.13). Another common feature of the results was, when the airspeed was set lower, the deposition of $PM_{2.5}$ particles in the filter membrane became higher. These results suggested that filtering the $PM_{2.5}$ could be achieved better with lower airspeed.

Similar to the $PM_{2.5}$ results, the highest reduction rate for PM_{10} (up to 56%), was achieved by the fully passive protocol (B-B) followed by the hybrid protocols (B-F and F-B) (51%) and the least was fully active protocol (F-F) (Figure 4.14). Lower airspeed of 0.5 m/s achieved better results for filtering particles than a higher airspeed of 1.0 m/s.



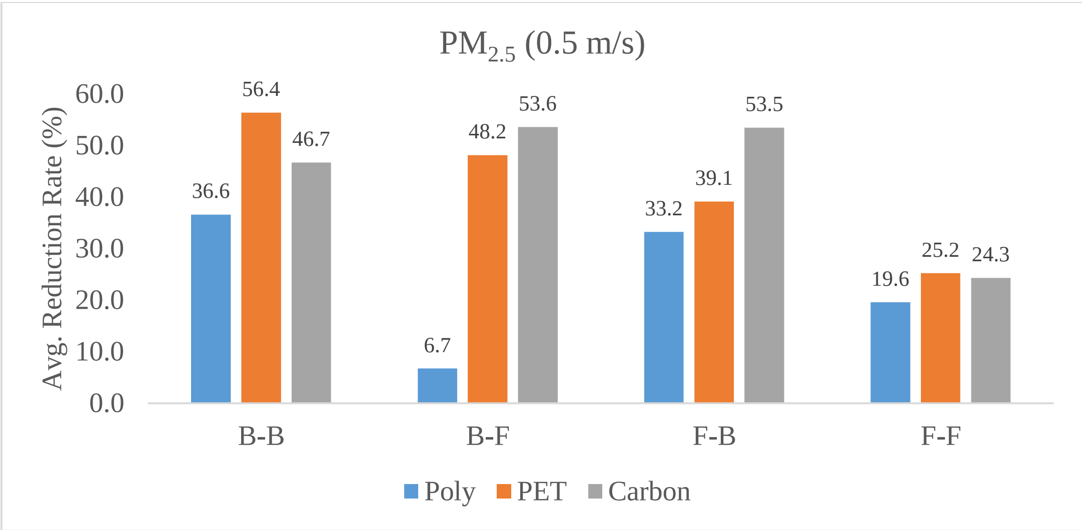


Figure 4.13: $PM_{2.5}$ results for different ventilation protocols and filter media.

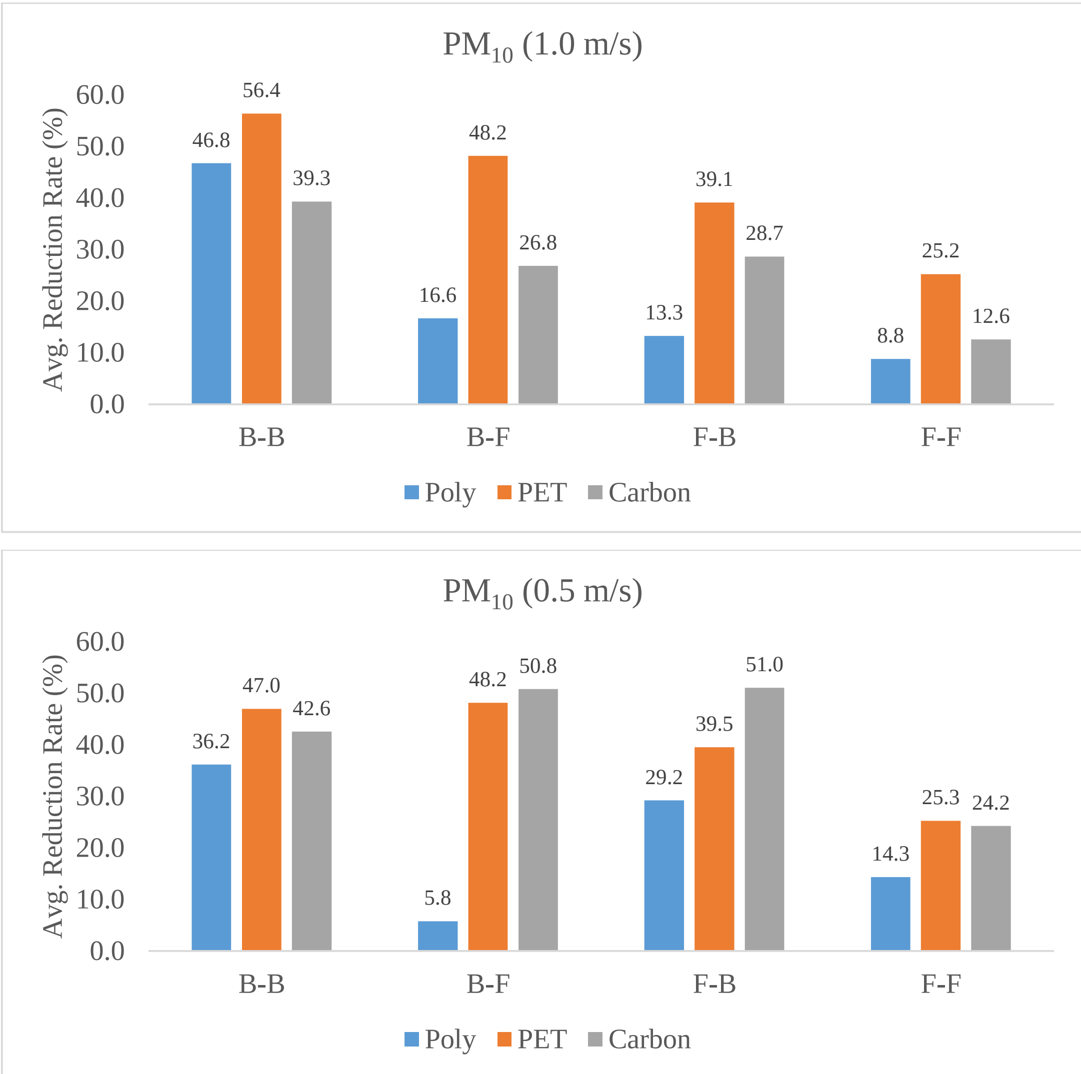


Figure 4.14: PM_{10} results for different ventilation protocols and filter media.

4.3.3 Discussion

The analysis of the results is based on the reduction rate that each of the configurations can achieve. The higher reduction rate provides the better indoor comfort and air quality. These reduction percentages should achieve several required conditions which are: air temperature of below 29.0°C, the relative humidity of below 65.0% RH (ASHRAE, 2013), $PM_{2.5}$ of below 25.0 µg/m^3 and PM_{10} of below 50.0 µg/m^3 (WHO & UNAIDS, 2006). Both particulate matter limits are for a 24-hour limit.

Among the three filtering media, the combination of carbon-PET-polyester with a depth of 50 mm achieved the best performance, especially in reducing humidity and $PM_{2.5}$. The reduction rates for humidity and $PM_{2.5}$ were up to 9% and 37% respectively (Figure 4.15). The main parameter of this achievement was the depth of the filter: a thicker filter could produce better results. However, in terms of airspeed, a thicker filter may reduce the air movement and this factor should be taken into consideration when designing an energy-efficient ventilation system. In achieving indoor comfort for the occupants with low energy usage, the right and adequate air movement are required (Bhatia, 2012a). In this test, the air movement for B-F, F-B and F-F protocols were consistently supplied and controlled using an exhaust fan. However, according to ASHRAE 55 and CIBSE Guide A, the minimum requirement of air movement is between 0.15 m/s to 0.5 m/s, which is less than the airspeeds used in this test (0.5 m/s and 1.0m/s).

As mentioned in Section 4.4.1, the ventilation protocol of fully passive (B-B) achieved a great reduction of air temperature for all the selected parameters. However, this technique depends on the wind buoyancy pressure. In an urban area context like Kuala Lumpur, wind movement is limited and unreliable (Mohd Sahabuddin & Gonzalez-Longo, 2018), therefore, this protocol may not be suitable. Although B-F and F-B protocols achieved almost similar results in terms of filtering particles (Figure 4.16) when considering air temperature reduction, B-F protocol performed better than F-B whereas F-B protocol produced a better reduction for humidity. These two protocols are considered the best options and should be explored in greater detail in the future. However, in indoor spaces, there are many other activities that contribute to indoor discomfort and poor air quality such as cooking, washing, body heat and respiration (Lenchek et al., 1987). Thus, B-F protocol is a better option due to its active mechanism that controls these factors in indoor spaces. A detailed study on reducing humidity should be carried out to make B-F protocol a more suitable option.

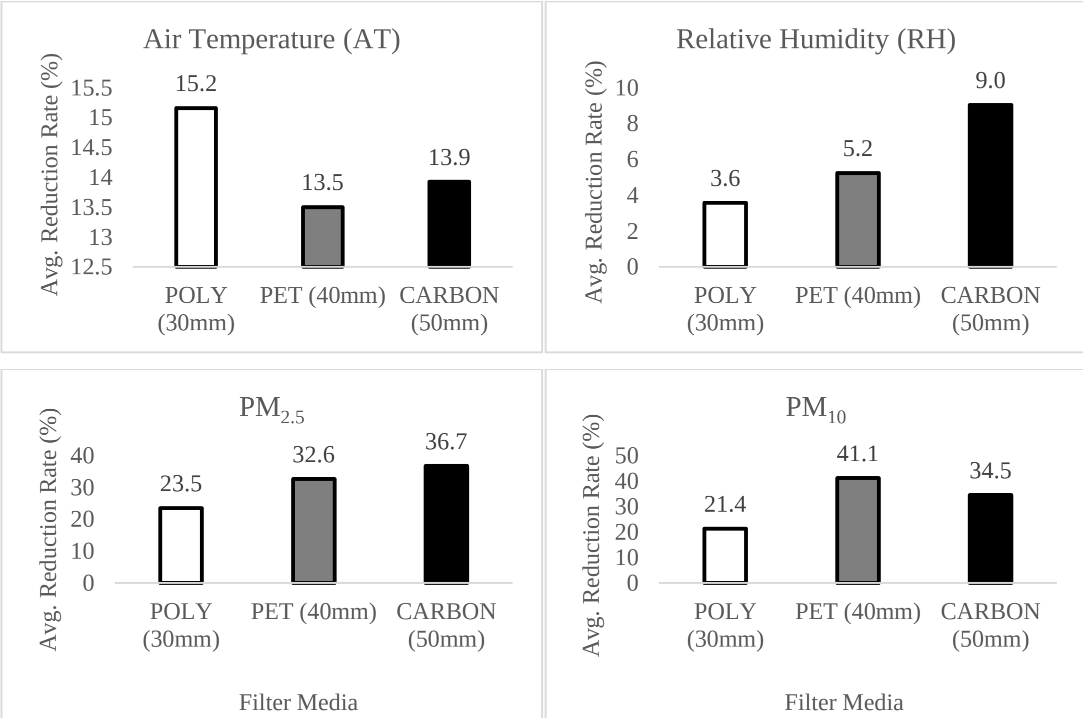


Figure 4.15: Filter media results for indoor comfort

Contrary with B-F, the F-B protocol which is typically used in 'cleanrooms', uses the driving forces that are mainly from the momentum of supply air – unidirectional ventilation (Awbi, 2002; ISO, 2015; Starke, 2012). As a result, F-B protocol achieved better reduction rate for humidity and particles and in general, this protocol recorded better results than B-F protocol (Figure 4.16). However, the other factors that contribute to indoor discomfort and poor air quality should also be taken into account: without a fan that discharges the air from inside, the contaminated indoor air would not be efficiently exhausted from the room. Thus, this F-B protocol should also be tested in greater detail in future. The F-F protocol may produce a very significant airflow from outside to the inside of the model, but the excessive airflow could easily drag particles pass through the filter membrane and this was consistent in this test with only circa 18% reduction rate (Figure 4.16). Only humidity results have achieved significant average reduction rate (15.2%) in this protocol due to the fact that, when the air continues to flow, the filter membrane effectively creates its own vapour barrier (Halliday, 1997).

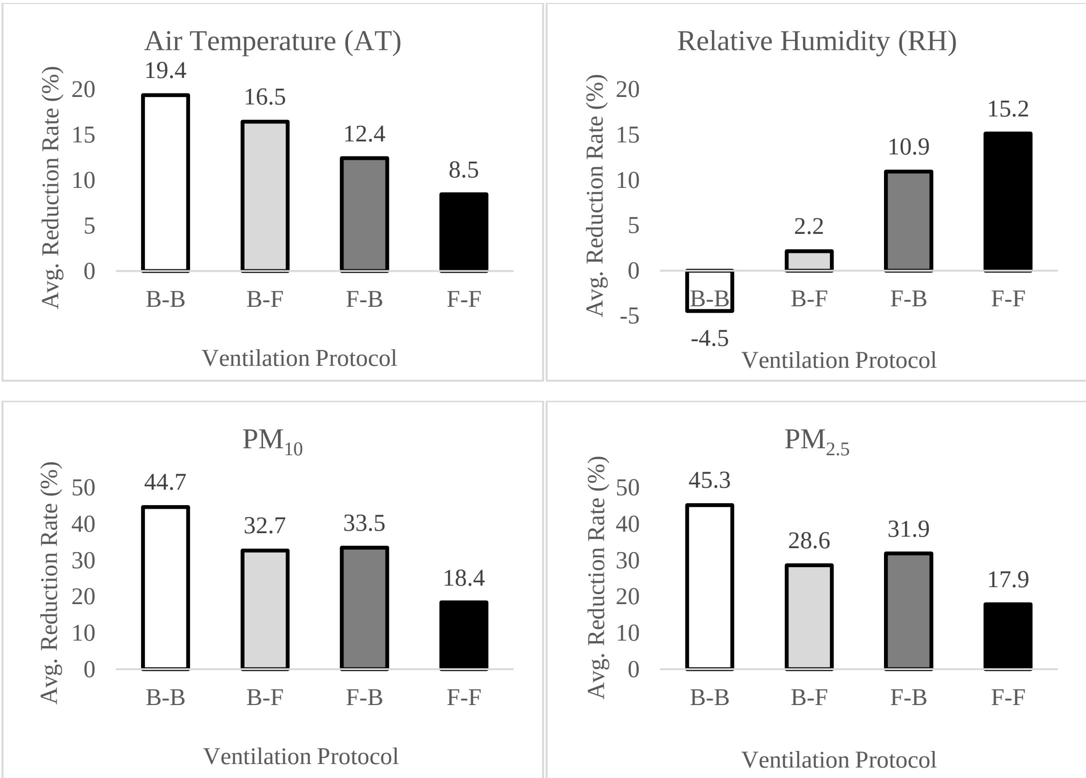
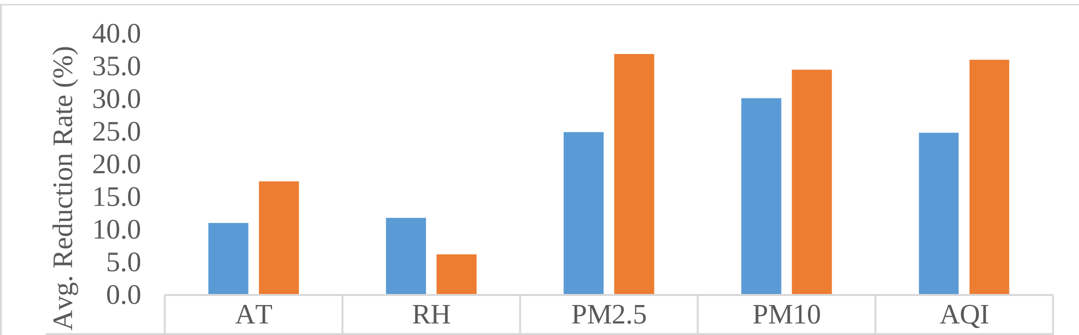


Figure 4.16: Ventilation protocol results

Figure 4.17 shows the performance of the airspeed for all parameters. Except for humidity, all of the parameters achieved better results when low airspeed was applied in this test (Figure 4.17), concluding that the lower the airspeed, the better the results would be. However, in a habitable space, as previously stated, it is important to achieve the minimum requirements of airflow for indoor comfort and of airspeed according to ASHRAE 55 and CIBSE (0.15 to 0.5 m/s). This value is still lower than the test speeds, thus, the performance of these parameters could be further improved.



	AT	RH	PM2.5	PM10	AQI
1.0 m/s	11.0	11.8	24.9	30.1	24.8
0.5 m/s	17.4	6.2	36.9	34.5	36.0

Figure 4.17: Airspeed performance on indoor comfort parameters

Table 4.5 shows the conversion results converted from the ventilation protocol's rates. Out of four protocols, only B-F and F-B protocols achieved the best results and comply with three parameters – air temperature, humidity and PM_{10}. The B-B protocol complied two parameters – air temperature and PM_{10}; while F-F protocol complied with air temperature and relative humidity only. Even though the F-B protocol achieved three requirement parameters, the B-F protocol, however, recorded better air temperature and PM_{10} reduction rates. It could be deduced that both B-F and F-B protocols showed great potential to be improved and finally met all the conditions required. In terms of particles reduction results, three protocols (except F-F protocol) achieved good reduction rate (PM_{10} below the required condition). However, for $PM_{2.5}$, none of the protocols achieved a sufficient reduction rate to lower the actual average of the substance to the required condition. Thus, another test using different materials and thickness should be conducted.

Table 4.7: Results using B-B, B-F, F-B and F-F reduction percentage rates

Config.	Parameters	Metric Scale	FW2/IES Average	Rate (%)	Results	Complied
B-B	Air Temperature	ºC	29.1	19.4	23.5	√
	Relative Humidity	%RH	66.4	-4.5	69.4	-
	$PM_{2.5}$	µg/m³	44.2	45.3	24.2	-
	PM_{10}	µg/m³	53.5	44.7	29.6	√
B-F	Air Temperature	ºC	29.1	16.5	24.3	√
	Relative Humidity	%RH	66.4	2.2	65.0	√
	$PM_{2.5}$	µg/m³	44.2	28.6	31.6	-
	PM_{10}	µg/m³	53.5	32.7	36.0	√
F-B	Air Temperature	ºC	29.1	12.4	25.5	√
	Relative Humidity	%RH	66.4	10.9	59.2	√
	$PM_{2.5}$	µg/m³	44.2	31.9	30.1	-
	PM_{10}	µg/m³	53.5	33.5	35.6	√
F-F	Air Temperature	ºC	29.1	8.5	26.6	√
	Relative Humidity	%RH	66.4	15.2	56.3	√
	$PM_{2.5}$	µg/m³	44.2	17.9	36.3	-
	PM_{10}	µg/m³	53.5	18.4	43.7	-

Note: B-B = Fully Passive, B-F = Hybrid Negative, F-B = Hybrid Positive, F-F = Fully Active

Figure 4.18 shows the tabulation results of all ventilation protocols on a psychrometric chart. The green zone was labelled as comfort zone as set by ASHRAE 55 and CIBSE Guide A. The B-F, F-B and F-F protocols were tabulated inside the comfort zone. Even though the F-F protocol was tabulated in the comfort zone, its filtering performance did not reach the required standard, whereas the B-F and F-B protocols were located at the upper limit of the zone. Based on the findings, it was deduced that another test was necessary to validate and further improve the reduction results.

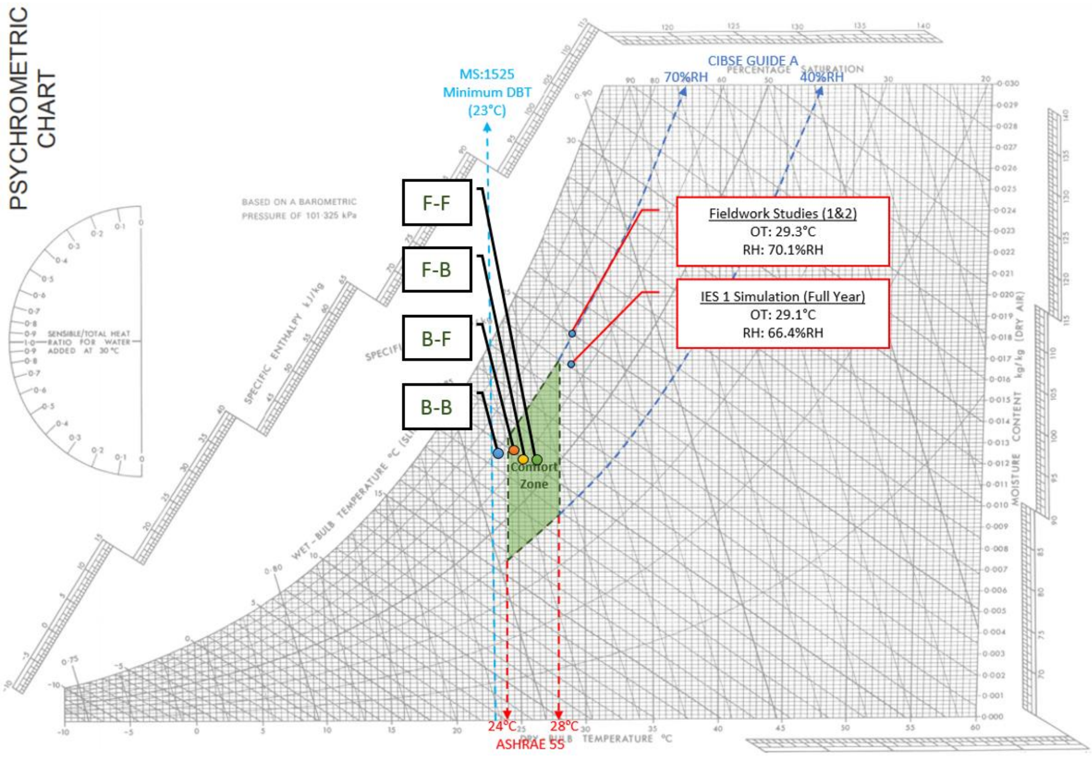


Figure 4.18: Tabulation of B-B, B-F, F-B, F-F results on Psychrometric Chart (Appendix 1F)

4.4 Test 2: Results and Analysis

4.4.1 Thermal Comfort

<u>Air Temperature and Relative Humidity</u>

For air temperature with and without AC, the average reduction rates for all the three insulations were between 10% to 18%. The highest reduction rate was recorded by the recycled wool insulation using F-B protocol with 17.7% and the lowest was 10.5% recorded by the recycled plastic, also using the same protocol (Figure 4.19).

Figure 4.20 shows the relative humidity results using the same insulation materials. The average reduction rates were between 7% to 20%. Among the highest reduction rates recorded were 19.1% and 18.8% by recycled plastic and recycled wool respectively. Both were using F-B protocol. Recycled glass recorded the lowest result of 7.2% using B-F protocol.

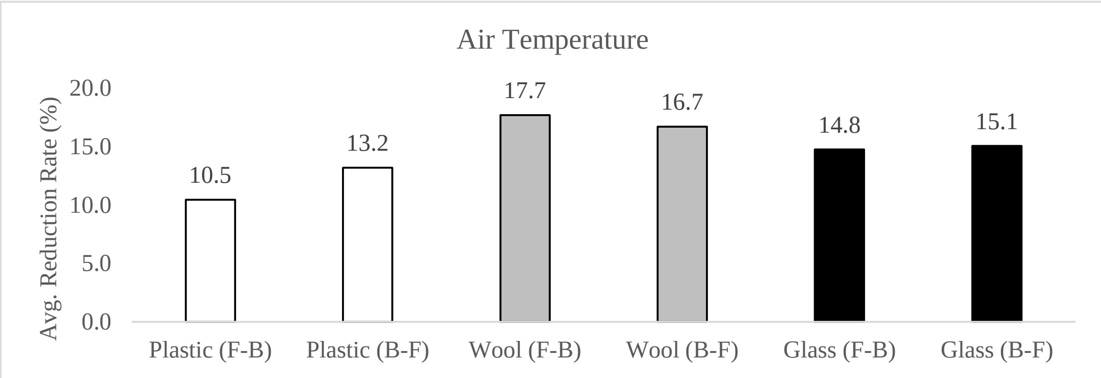


Figure 4.19: Air temperature results using three different insulation types

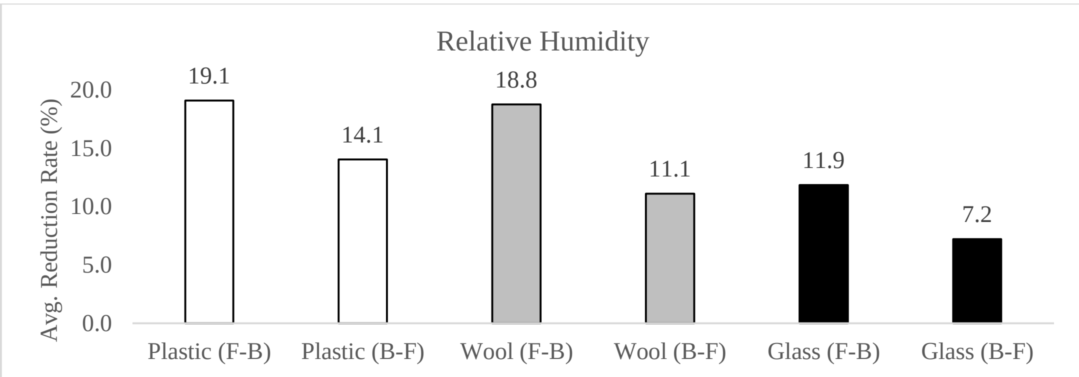


Figure 4.20: Relative humidity results using three different insulation types

4.4.2 Air Quality

Particulate Matter ($PM_{2.5}$ and PM_{10})

The average reduction rate for $PM_{2.5}$ was between 64% to 92% where recycled glass using F-B protocol recorded the highest rate of 91.2%. The same material also recorded the second highest reduction rate of 77.1% using B-F protocol (Figure 4.21). For PM_{10}, the highest reduction rate was recorded by the recycled glass using F-B protocol. The rate was 90.1% followed by the same material using B-F protocol which was 77.0% (Figure 4.22).

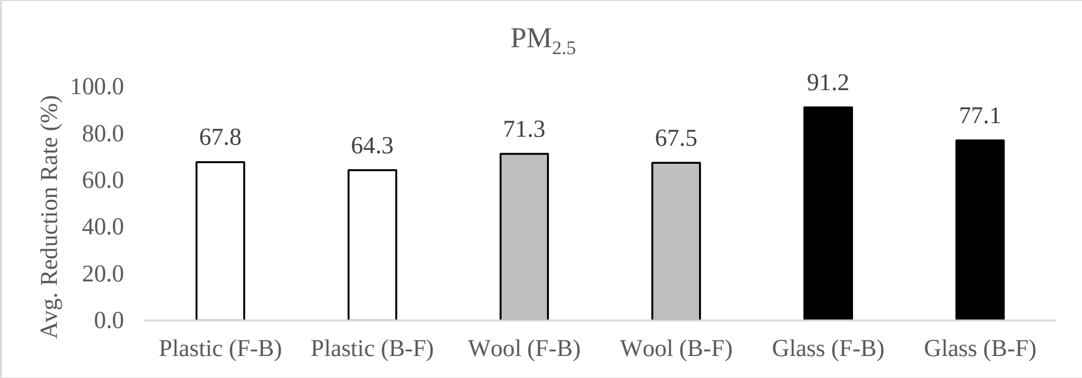


Figure 4.21: $PM_{2.5}$ results using three different insulation types

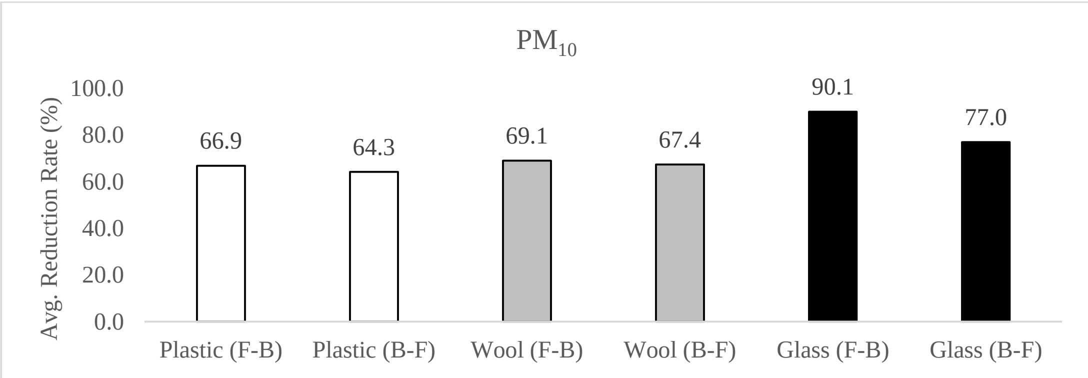


Figure 4.22: PM_{10} results using three different insulation types

4.4.3 Discussion

The recycled plastic insulation produced encouraging reduction rates for all the parameters except humidity. The reduction rates were increased when AC cartridge was introduced. It can be seen that the F-B protocol achieved higher reduction rates compared to B-F protocol. The highest particle reduction rates were obtained by the F-B protocol with 81.4% ($PM_{2.5}$) and 79.3% (PM_{10}), whereas the B-F protocol only achieved 54.1% for $PM_{2.5}$ and 54.4% for PM_{10} (Figure 4.23).

Similar to the recycled plastic results, the F-B protocol consistently recorded higher reduction rates for filtering airborne particles compared to the B-F protocol. The highest rates recorded were 80.1% for $PM_{2.5}$ and 78.4% for PM_{10} (Figure 4.24). Both values were achieved when using AC cartridge. Other remarkable results that this material produced were the reduction rates for air temperature and relative humidity, especially when applying the F-B protocol with AC cartridge. The reduction rates achieved were 23.1% for air temperature and 24.2% for relative humidity.

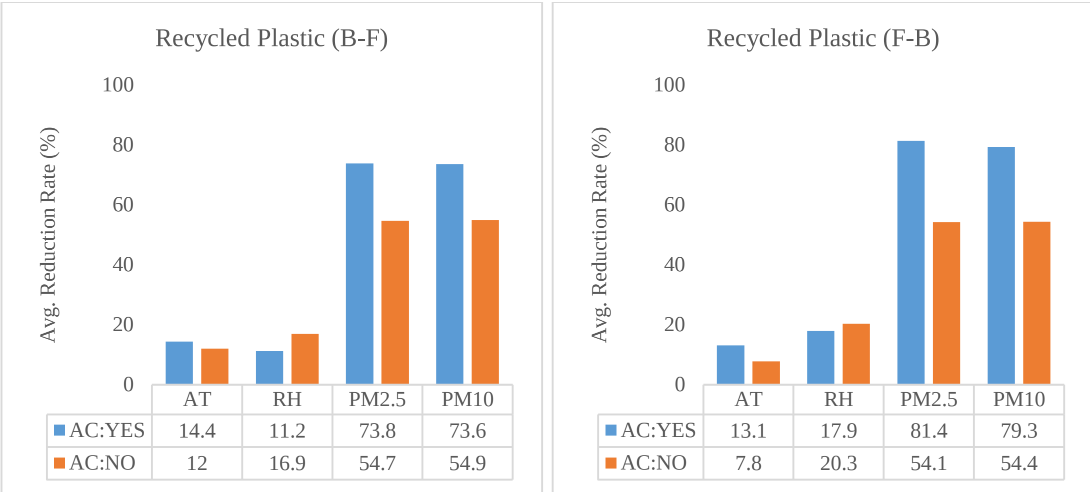


Figure 4.23: Recycled plastic performance with and without the AC cartridge.

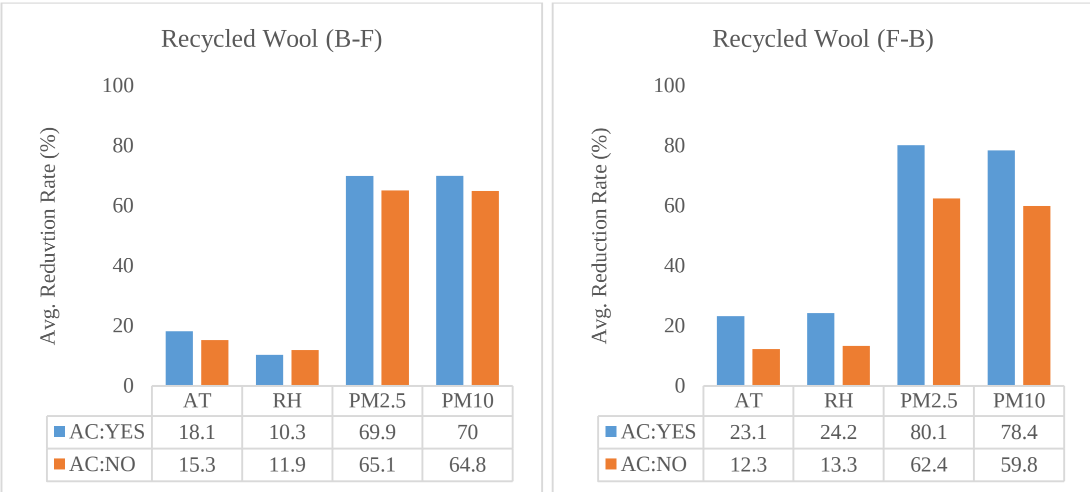


Figure 4.24: Recycled wool performance with and without the AC cartridge.

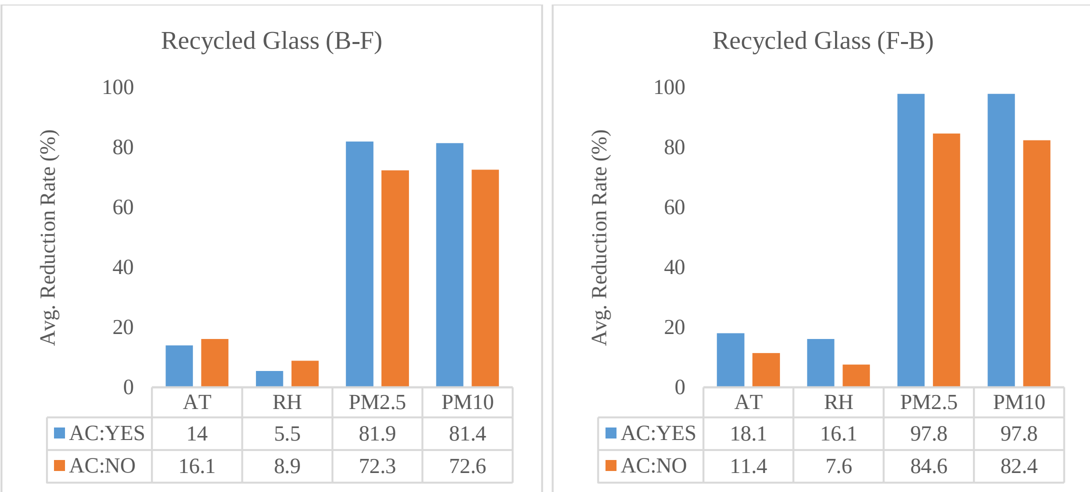
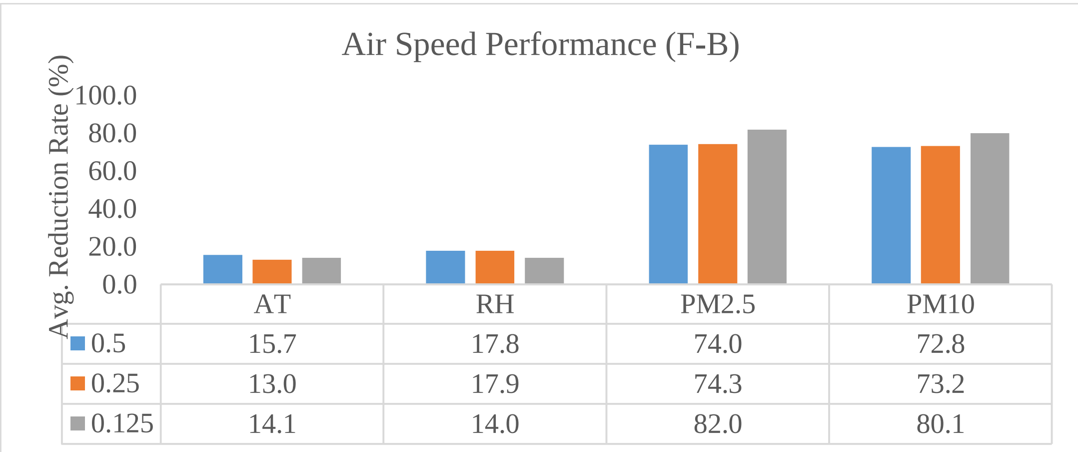


Figure 4.25: Recycled glass performance with and without AC cartridge

The recycled glass material recorded the highest reduction rates for $PM_{2.5}$ and PM_{10} among the other materials. The material, which when using AC, reduced 97.8% of both $PM_{2.5}$ and PM_{10} particles. While without AC, the rates recorded slightly lower of 84.6% ($PM_{2.5}$) and 82.4% (PM_{10}) (Figure 4.25). For B-F protocol, the reduction rates achieved were approximately 10% to 20% lower than the F-B protocol rates. In this test, in terms of filtering particles, the recycled glass material achieved the best performance.

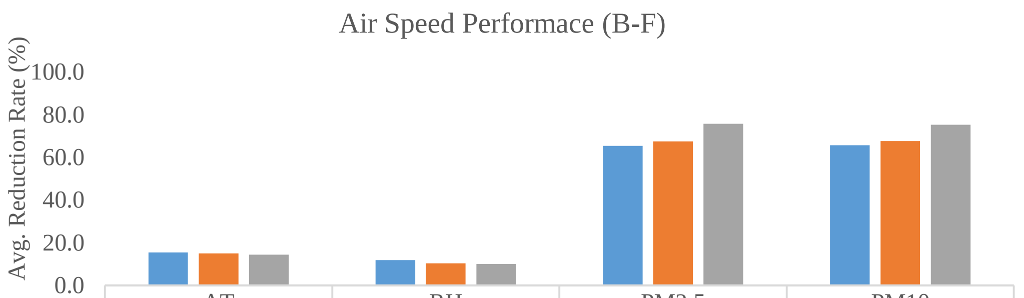
Figure 4.26 shows the different airspeed performance results for the F-B system regardless of insulation materials, with or without AC cartridge. For air temperature and relative humidity, the results were in a balance order from 0.5 m/s to 0.125 m/s. It means that there was no significant reduction in air temperature and humidity when the airspeed was getting slower. However, for $PM_{2.5}$ and PM_{10}, the results were different when the airspeed decreases. The gap between 0.5 m/s and 0.125 m/s was within 8% difference for both $PM_{2.5}$ and PM_{10}.

Figure 4.27 shows the results for B-F protocol where the air temperature and humidity rates were slightly decreasing while the $PM_{2.5}$ and PM_{10} rates were moderately increasing, showing the same patterns as the F-B protocol. For the airspeeds results, the air temperature and humidity differences were approximately 1°C and 2% RH respectively. Meanwhile, for the $PM_{2.5}$, the difference was 10.4% and PM_{10}, 9.7%. These results were averagely calculated regardless of the insulation materials and with or without activated carbon filter.



	AT	RH	PM2.5	PM10
0.5	15.7	17.8	74.0	72.8
0.25	13.0	17.9	74.3	73.2
0.125	14.1	14.0	82.0	80.1

Figure 4.26: Airspeed performance for F-B protocol on indoor comfort parameters



	AT	RH	PM2.5	PM10
0.5	15.5	11.8	65.4	65.7
0.25	15.0	10.3	67.6	67.6
0.125	14.4	10.1	75.8	75.4

Figure 4.27: Airspeed performance for B-F protocol on indoor comfort parameters

From the findings above, it can be deduced that the lowest airspeed of 0.125 m/s was proven to be able to produce better reduction results (for $PM_{2.5}$ and PM_{10}) than other airspeeds because it reduces the speed of particles and makes them easier to get caught in the filter membrane. Table 4.8 shows the conversion results for all the four parameters using the reduction rates of the 0.125 m/s results. Both protocols, F-B and B-F using recycled insulation materials, with or without AC can fully comply with the indoor comfort requirements explained in Chapter 2.

This study found that the recycled glass material produced the best reduction rates for filtering the airborne particles as well as reducing heat and humidity. As listed in Table 4.8, the best conversion results were achieved by using recycled glass with F-B protocol. The F-B (II) conversion results were considered the best result achieved in this test with all values within the lower threshold of the required limits.

Figure 4.28 shows the tabulation of the results using 0.125 m/s and recycled glass reduction rates. Both results using 0.125 m/s reduction rates were located in the comfort zone suggested by ASHRAE 55 and CIBSE Guide A. Meanwhile, the results using recycled glass reduction rates were located between the comfort zone and the minimum air temperature as suggested by the Malaysian Standard 1525. When compared to the fieldwork studies and IES baseline simulation results, these conversion results were significantly improved, both in comfort and health aspects. Given the above findings, this Test 2 validated that DHAPC system had achieved its optimum performance when hybrid ventilation of B-F and F-B protocols, recycled glass membrane and 0.125 m/s of airspeed were applied in its system. Applying these criteria had fulfilled the indoor comfort requirements set in this research.

Table 4.8: Conversion results using the averages of 0.125 m/s reduction rates

Conf.	Parameters	Metric Scale	IES/FW2 Average	Reduction Rate (%) 0.125 m/s	Conversion Results	Compliance
B-F (I)	Air Temperature	°C	29.1	14.4	24.9	√
	Relative Humidity	%RH	66.4	10.1	59.7	√
	$PM_{2.5}$	$\mu g/m^3$	44.2	75.8	10.7	√
	PM_{10}	$\mu g/m^3$	53.5	75.4	13.2	√
F-B (I)	Air Temperature	°C	29.1	14.1	25.0	√
	Relative Humidity	%RH	66.4	14.0	57.1	√
	$PM_{2.5}$	$\mu g/m^3$	44.2	82.0	7.9	√
	PM_{10}	$\mu g/m^3$	53.5	80.1	10.6	√

Table 4.9: Conversion results using recycled glass (with AC) reduction rates

Conf.	Parameters	Metric Scale	IES1/FW 2 Average	Reduction Rate (%) Recycled Glass	Conversion Results	Compliance
B-F (II)	Air Temperature	°C	29.1	16.1	24.4	√
	Relative Humidity	%RH	66.4	8.9	60.5	√
	$PM_{2.5}$	$\mu g/m^3$	44.2	81.9	8.0	√
	PM_{10}	$\mu g/m^3$	53.5	81.4	9.9	√
F-B (II)	Air Temperature	°C	29.1	18.1	23.8	√
	Relative Humidity	%RH	66.4	16.1	55.7	√
	$PM_{2.5}$	$\mu g/m^3$	44.2	97.8	1.0	√
	PM_{10}	$\mu g/m^3$	53.5	97.8	1.2	√

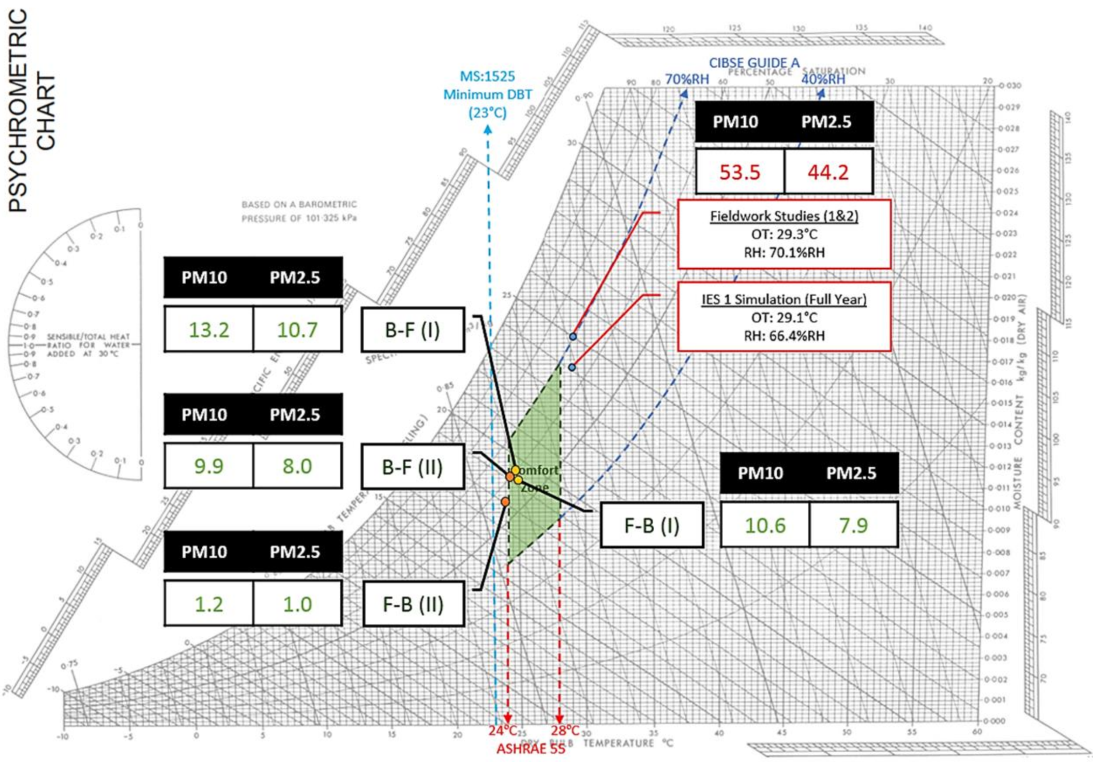


Figure 4.28: Tabulation of B-F and F-B results using 0.125 m/s and recycled glass with AC on a psychrometric chart (Appendix 1G).

4.5 Test 3: Results and Analysis

4.5.1 Air Quality

<u>Toxic Gases and Particulate Matter</u>

Figure 4.29 shows the average reduction rates for the tests that used AC (cartridge or loose-fill) and without AC. These rates represent both F-B and B-F average reduction rates. For CO without any AC applications, the average reduction rate was 50%. However, when AC cartridge and AC loose-fill were introduced, the rates were improved by 50% and 15.4% respectively. Similarly, for benzene, the baseline reduction rate without AC applications was 59.8% and it was improved to 93.9% and 86.8% when AC cartridge and AC loose-fill were applied, at approximately 30% improvement. Much lower rates were achieved for SO_2 which the baseline was 38.9% and slight improvements of 20% to 25% when AC applications were used.

For the particulate matter of PM_1, $PM_{2.5}$ and PM_{10}, the baseline rates were circa 50%. Meanwhile, when using AC cartridge, the improvements of 65% to 70% were achieved and with AC loose-fill, they improved up to 88%. It can be deduced that the AC cartridge gave better results for filtering gases and AC loose-fill was better in filtering the particulate matter. The filtration improvements when using AC for filtering gases (CO, Benzene and SO_2) were between 20% to 45% and for particles (PM_1, $PM_{2.5}$ and PM_{10}), between 10% to 35%.

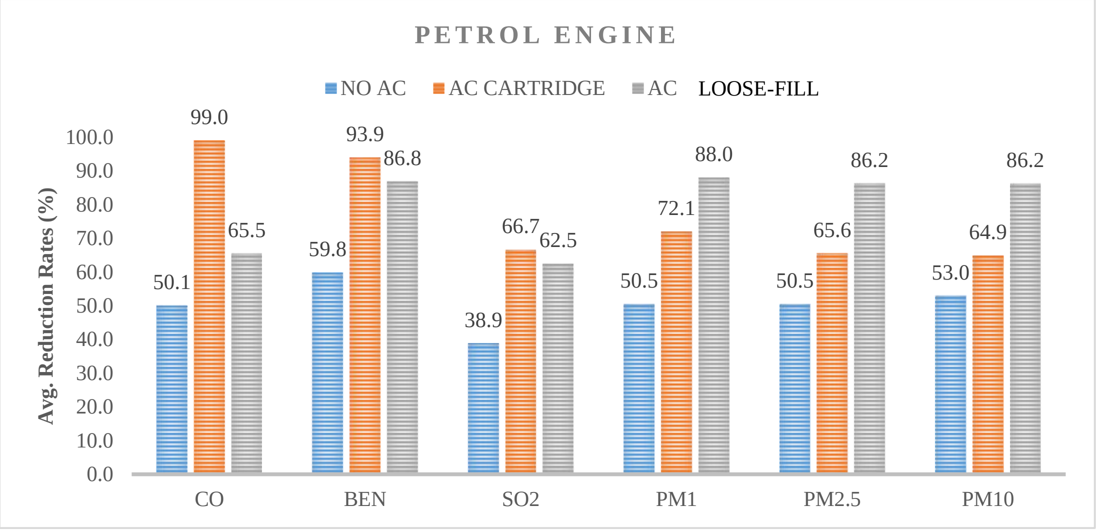


Figure 4.29: Average reduction rates for the tests using AC (cartridge or loose-fill) and without AC

The average reduction rates for CO when using AC cartridge was between 94% to 99%, however, when using AC loose-fill, the reduction rates recorded were lower, in between 42% to 73% (Figure 4.30). These rates were for both petrol and diesel engines. It shows that AC cartridge performed better in filtering CO compared to the AC loose-fill, at approximately 40% difference. This was due to the compact arrangement of AC in the cartridge that restricted the amount of CO gas from entering the DHAPC compartment.

For ventilation protocol results, B-F protocol showed better performance than F-B protocol in filtering CO in this test. In the case of the petrol engine, the reduction rates for B-F and F-B protocols using AC cartridge were similar which were up to 99%. However, when using AC loose-fill, the reduction rate for B-F protocol recorded was higher by 14.2% than the F-B protocol. For the diesel engine, the reduction rates of B-F protocol were also higher than the F-B protocol in both AC cartridge and AC loose-fill. The rates were 97% and 58.7% against 94% and 42.1% respectively. As it can be seen from Figure 4.30, CO in petrol and diesel engines can be filtered efficiently using DHAPC system, especially when using AC cartridge.

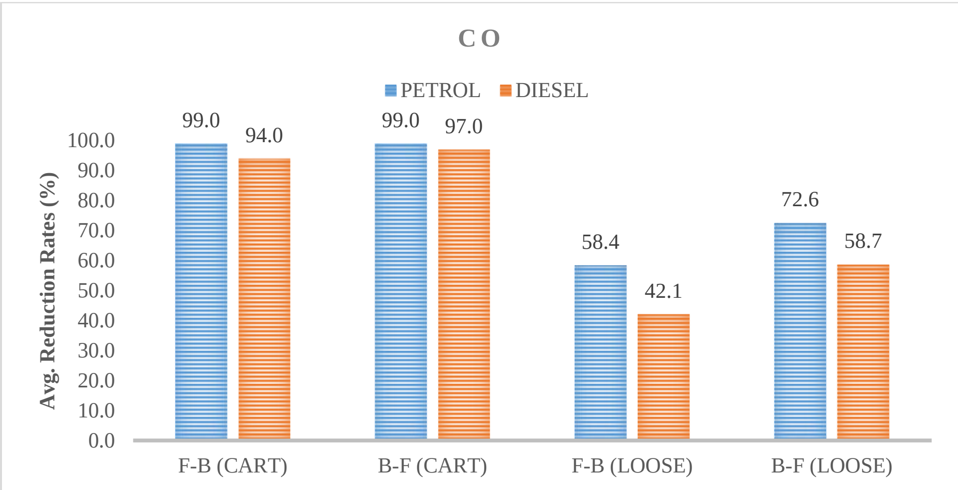


Figure 4.30: The average reduction rates for CO from petrol and diesel engines

For benzene, DHAPC system could filter the gas circa 90%. This included the reduction rates from petrol and diesel engines ranging from 80% to 95% and 93% to 99% respectively (Figure 4.31). The combination of AC applications, recycled glass filter, B-F and F-B protocols and the airspeed of 0.125 m/s could significantly filter benzene from entering the indoor space compartment with high reduction rates, especially benzene from the diesel engine. It can be seen that B-F protocol had a slight advantage in filtering the gas than F-B protocol.

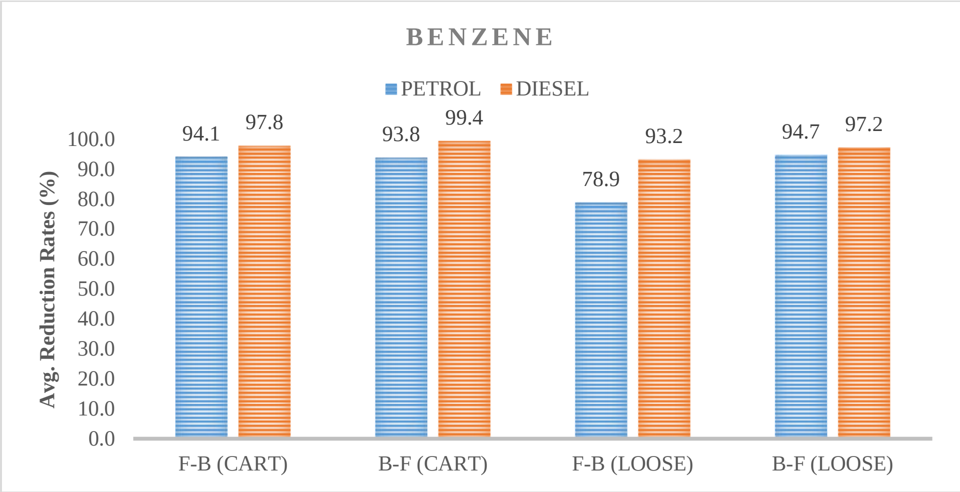


Figure 4.31: The average reduction rates for benzene from petrol and diesel engines

For SO_2, the reduction rates recorded were between 57.1% to 66.7% (for both petrol and diesel engines and either using AC cartridge or AC loose-fill). Figure 4.32 shows the average reduction rates for benzene from petrol and diesel engines where it could be seen that SO_2 from petrol engine could be reduced higher (approximately 5.5%) than SO_2 from diesel engine by using DHAPC system. The B-F protocol produced slightly a better performance than the F-B protocol. In the same way, the AC loose-fill also produced more reduction of the gas than AC cartridge. In general, AC cartridge had a slight advantage in reducing SO_2 from petrol and diesel engines.

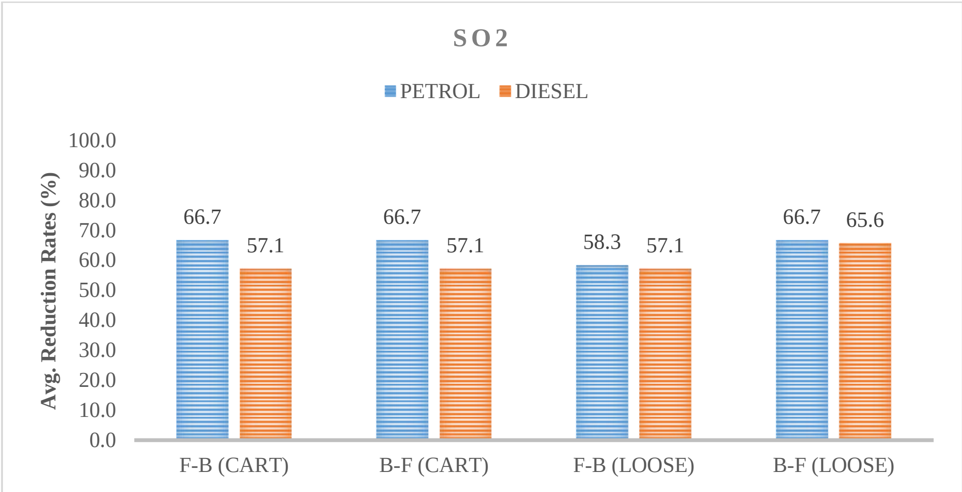


Figure 4.32: The average reduction rates for SO_2 from petrol and diesel engines

For PM_1, DHAPC system using F-B ventilation protocol filtered the airborne particles up to 95% and when using B-F ventilation protocol, a reduction of 81% was achieved. Figure 4.33 shows the average reduction rates for PM_1 from petrol and diesel engines where more particles from the petrol engine could be filtered than particles from a diesel engine. Moreover, AC loose-fill produced better results than AC cartridge. In all types of test configurations, AC loose-fill recorded higher reduction rates.

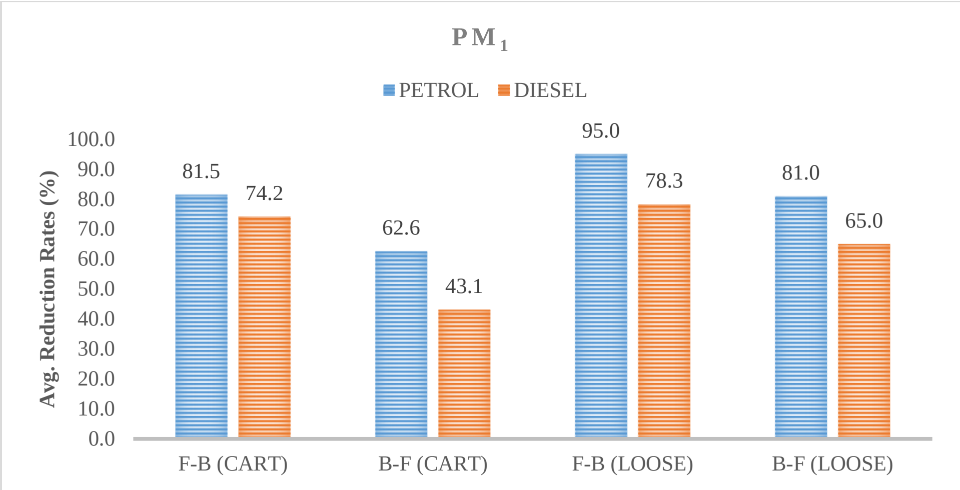


Figure 4.33: The average reduction rates for PM_1 from petrol and diesel engines

Likewise, PM_1 and $PM_{2.5}$ results (Figure 4.34) show better performance of reduction rates from F-B protocol than B-F protocol. For AC cartridge approach, F-B protocol recorded higher reduction rates (66.3% to 72.2%) than B-F protocol (33.3% to 58.9%). In the same way, for AC loose-fill approach, the F-B protocol recorded higher reduction rates (83.3% to 93.9%) than B-F protocol (40.5% to 78.6%). These results suggested that AC loose-fill was more efficient than AC cartridge in terms of filtering the particulate matter ($PM_{2.5}$).

For PM_{10}, the reduction rates for F-B protocol were consistently higher than B-F protocol regardless of the AC applications used. However, better performance was achieved by the AC loose-fill application (up to 94.4%) than AC cartridge (up to 74.6%) (Figure 4.35). This pattern was observed similar and consistent with PM_1 and $PM_{2.5}$ results. These results strongly suggested that the AC loose-fill application could efficiently filter particulate matter better than AC cartridge application.

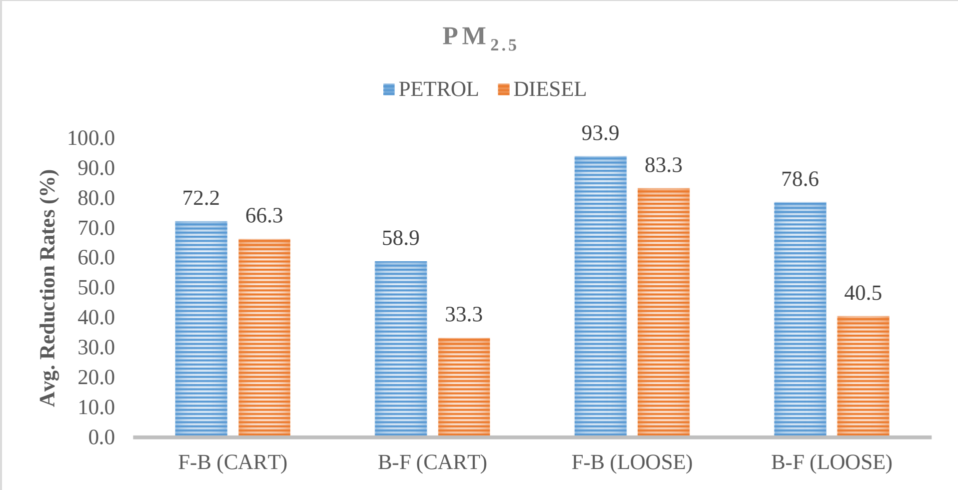


Figure 4.34: The average reduction rates for $PM_{2.5}$ from petrol and diesel engines

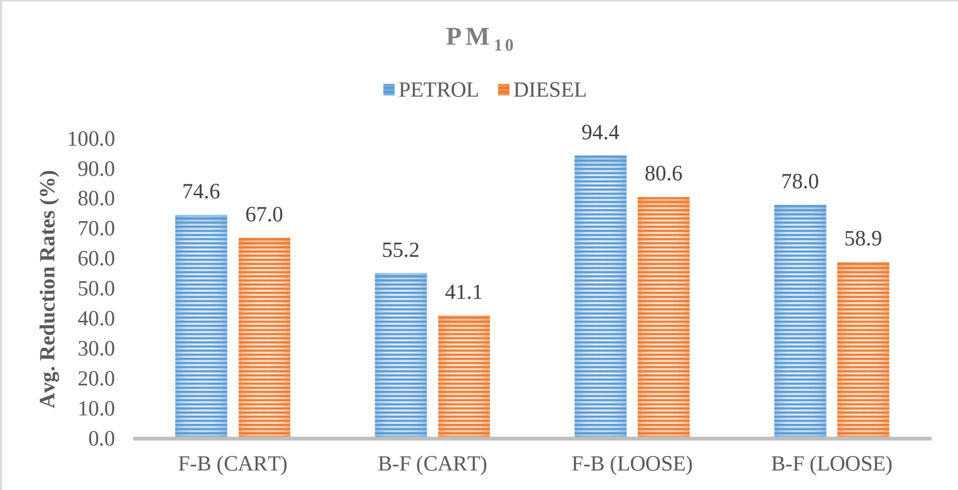


Figure 4.35: The average reduction rates for PM_{10} from petrol and diesel engines

4.5.2 Discussion

The comparison of reduction rates for substances from petrol and diesel engines using AC cartridge and AC loose-fill applications is shown in Figure 4.36. For AC cartridge, the results show that the gases such as CO, benzene and SO_2 could be efficiently reduced (up to 90%) compared to using AC loose-fill (up to 70%). Conversely, this technique could reduce more particulate matter (up to 88%) than AC cartridge (up to 66%). The cartridge that had a compact amount of AC granules, would have better 'adsorption' of gases compared to AC loose-fill which had more gaps. Meanwhile, the AC loose-fill on the DHAPC membrane would have better 'adsorption' of particulate matter due to more contact surfaces. All of the reduction rates shown are the averaged results using F-B and B-F protocols.

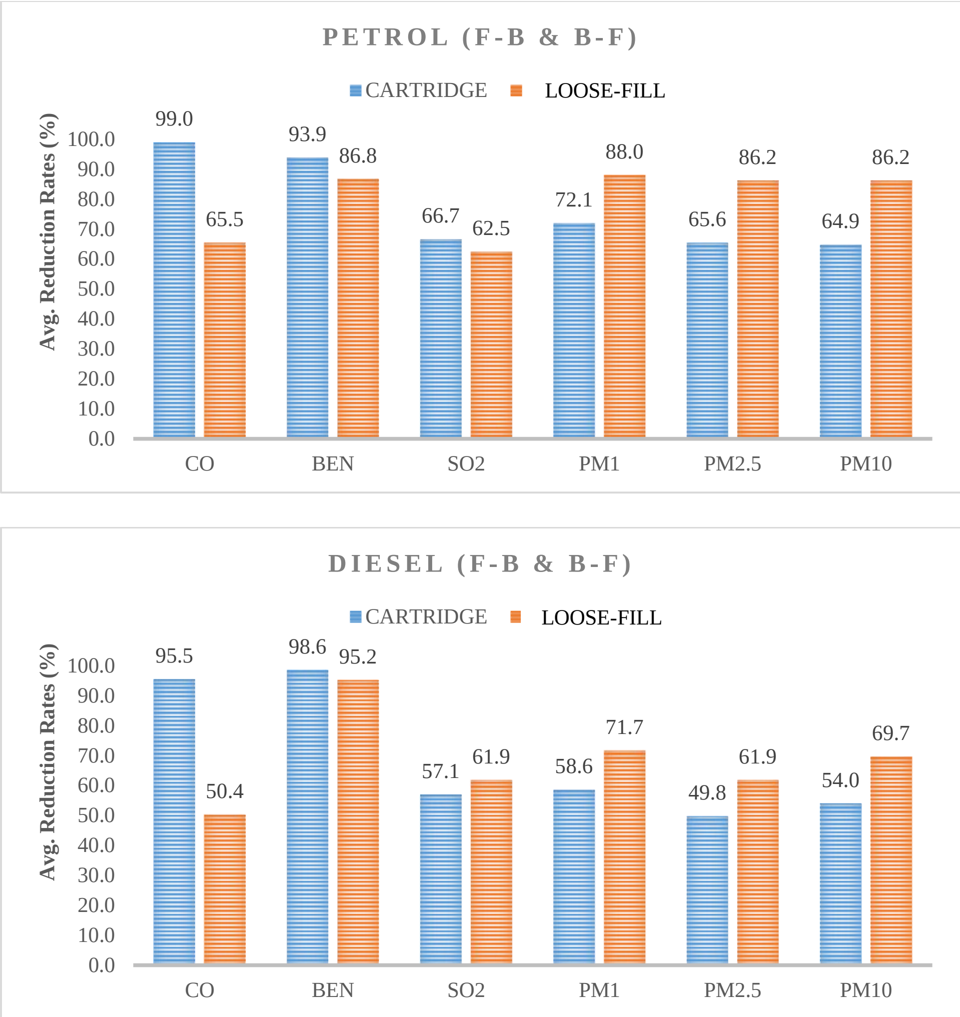


Figure 4.36: The comparison of average reduction rates for substances from petrol and diesel engines using AC cartridge and AC loose-fill applications

The reduction rates using F-B and B-F ventilation protocols on reducing gases from petrol engine show that the baseline readings for the protocol were ranged from 40% to 55% and particles, from 60% to 65% (Figure 4.37). While for B-F, the reduction rates for gases were between 40% to 60% and for particles was approximately 40%. The results suggested that F-B protocol has the advantage of reducing particles and vice versa for B-F protocol. For petrol and diesel engines, the same patterns occurred where the F-B results showed a better reduction on particles and B-F results on gases. Generally, B-F protocol produced low reduction rates compared to F-B protocol. This suggests that hybrid-negative protocol (B-F) which introduces suction pressure could drag more gases and particles than the positive-hybrid protocol (F-B) that applied repulsion pressure.

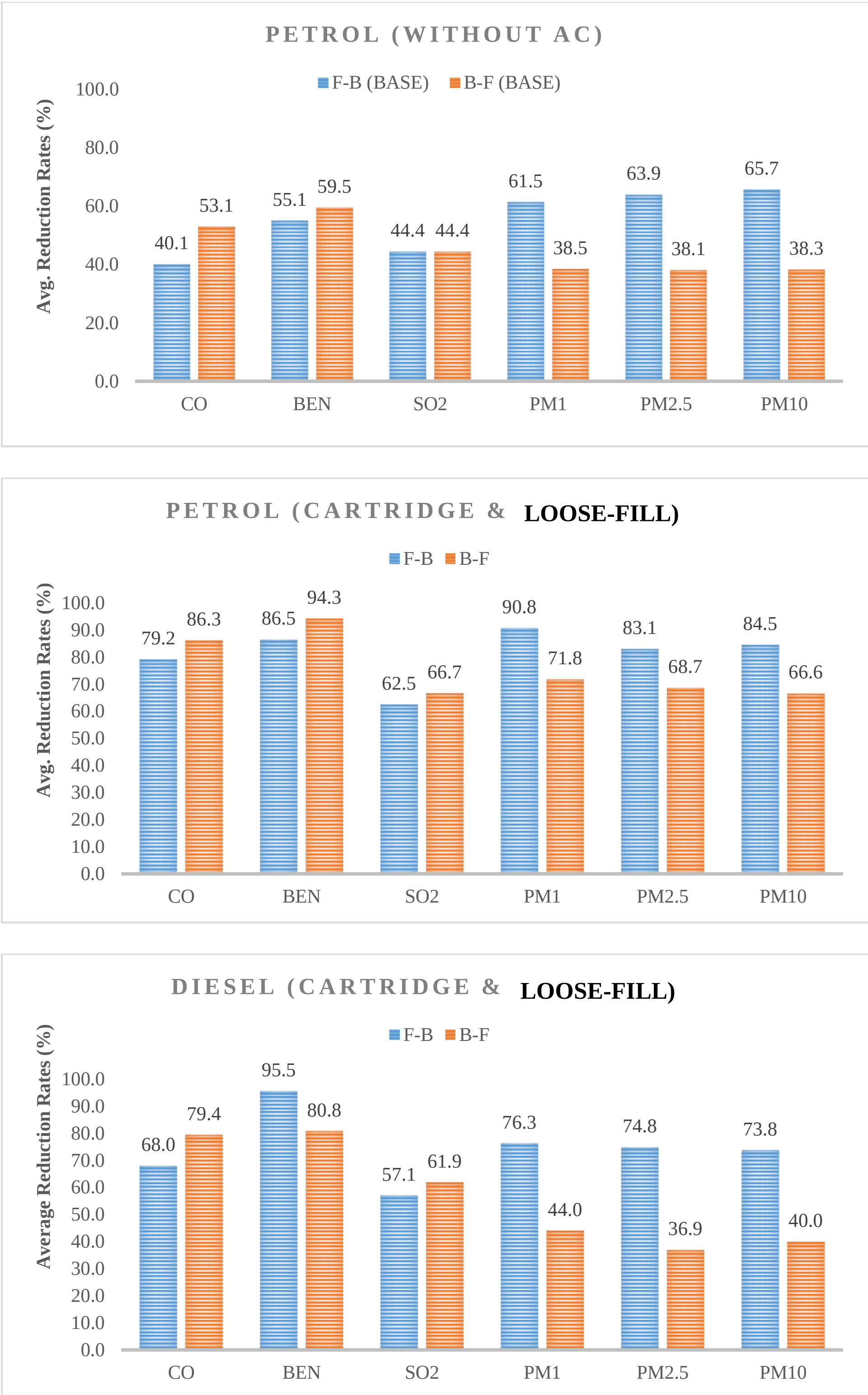


Figure 4.37: The comparison of average reduction rates for substances from petrol engine using F-B and B-F ventilation protocols

The average rates for petrol and diesel engines using AC filtering applications and hybrid ventilation protocols could be divided into two categories – gases and particles (Figure 4.38). For substances from the petrol engine, DHAPC could reduce 65% to 95% of gases and 75% to 80% of particles from entering the indoor compartment of the test model. On the other hand, for waste substances from a diesel engine, DHAPC could filter 60% to 90% of gases and 55% to 65% of particles. Each of the reduction rates in this test was recorded at three minutes starting from the first instrument that produced an alarm.

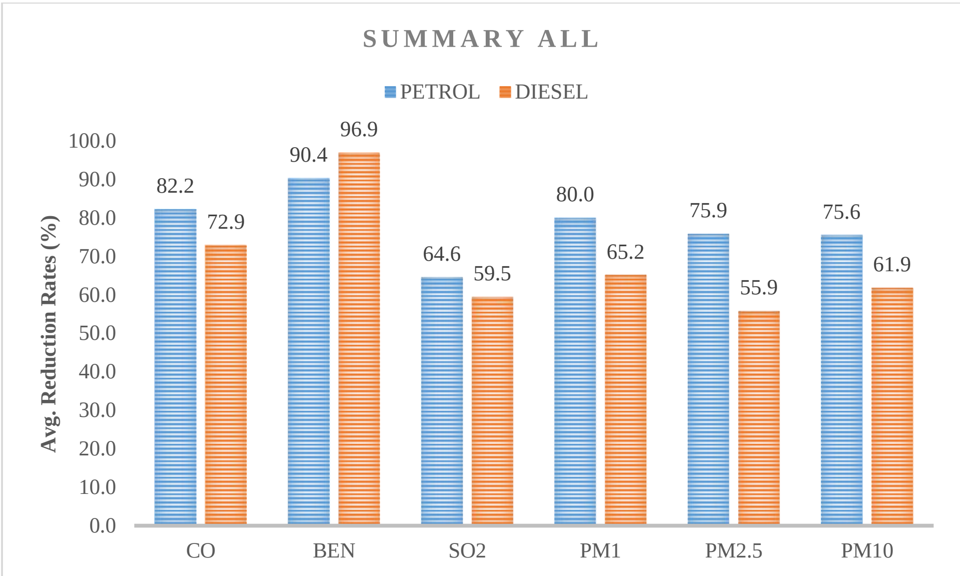
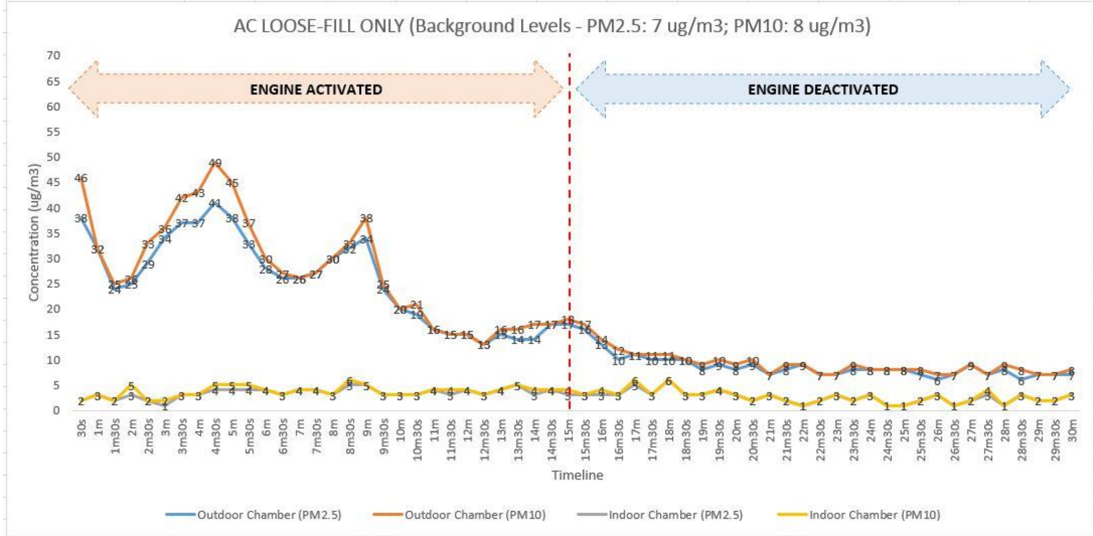


Figure 4.38: Summary of all average rates results

The logged values and concentration patterns of particulate matter in the tests are shown in Figure 4.39. In 15 minutes, the petrol engine produced a maximum level of 59 µg/m^3 for PM_{10} and 49 µg/m^3 for $PM_{2.5}$. The ambient background levels were 8 µg/m^3 for PM_{10} and 7 µg/m^3 for $PM_{2.5}$. After 15 minutes of concentrations, both particle sizes stabilised at circa 3 µg/m^3. The DHAPC and activated carbon (loose-fill), reduced particulates by circa 83%. The larger exposed contact area of the AC loose-fill may account for the improvement. An additional reduction of 6% was produced when the AC loose-fill and cartridge were combined in tandem (Figure 4.39). This phenomenon suggested that DHAPC could successfully filter the airborne particles not only from organic smoke (i.e. joss sticks) but also particles from petrol and diesel engines. However, in terms of filtering gases, the DHAPC performance appeared to be more sensitive to airflow rates.



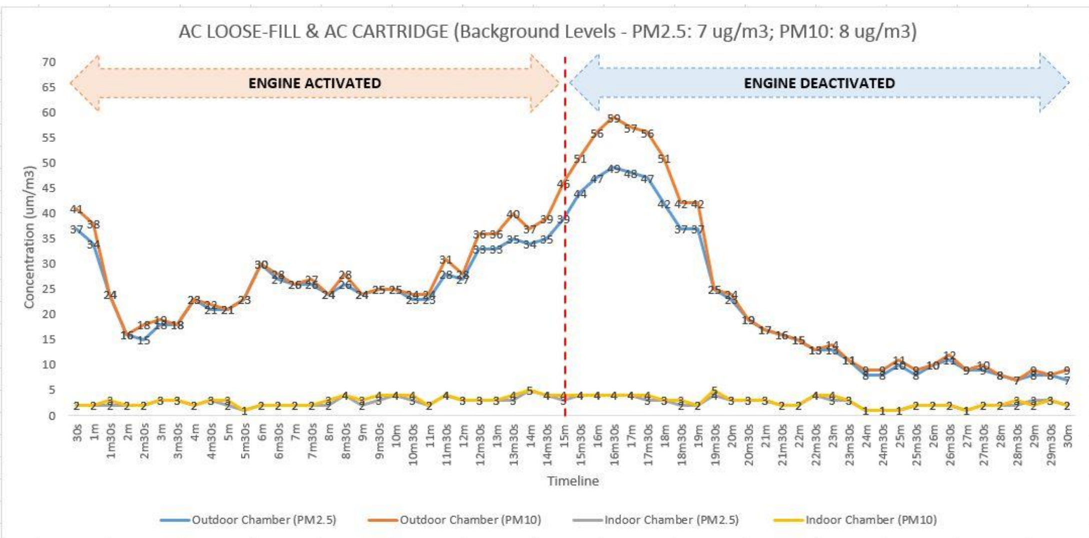


Figure 4.39: Logged values and concentration patterns of PM in the tests (Appendices 1H-1 and 1H-2)

Based on the above findings, it also proposed that the hybrid-negative protocol (B-F) produced lower reduction rates than the hybrid-positive protocol (F-B). This was due to the greater force of suction than repulsion even though similar air velocity was introduced in both techniques. This scenario suggested that pollutants in the hybrid-positive protocol have a weaker force to penetrate the DHAPC membrane but when the hybrid-negative protocol was applied, more amount of pollutants were dragged together with the air to penetrate the membrane.

As mentioned before, AC had the advantage properties at trapping gases and VOCs using a process known as 'adsorption' – pollutants stick to the outside of the AC molecules (Figure 4.40). An article mentioned that AC could not remove fine particles like mould, dust and pollen from the air (Myers, 2018). This argument was consistent with the test results where the reduction rates for particles were generally lower than the reduction rates for gases. The only setback of using AC for adsorbing gases was when the gaseous pollutants filled up the adsorption sites, the filter then, could no longer trap the pollutants (Myers, 2018). In this case, AC loose-fill application which had large contact areas than in a cartridge form seemed to be a better solution.

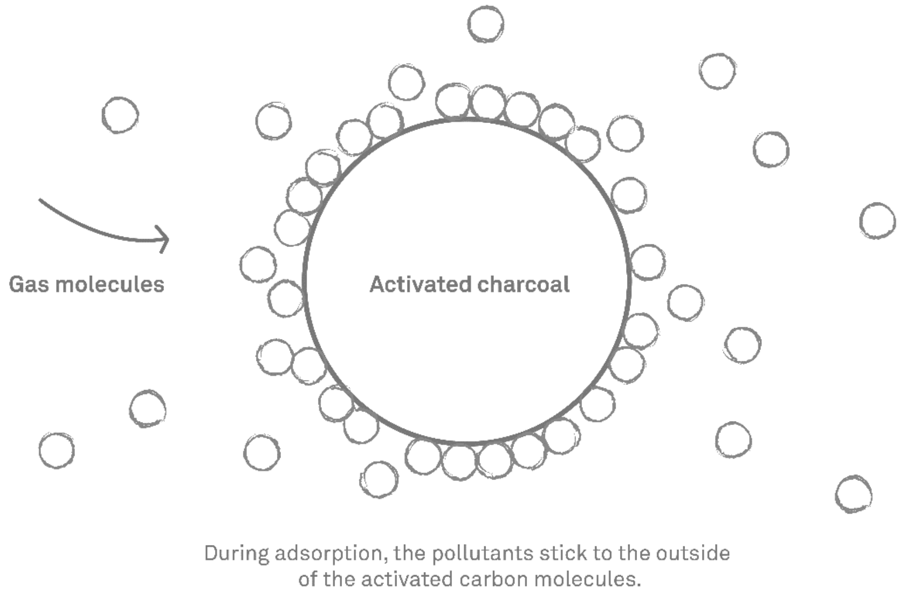


Figure 4.40: Airborne gaseous chemicals or VOCs stick the surface of carbon air filters until the filter surface is fully saturated. Image from Myers (2018)

4.6 Key Findings from the Physical Model Tests

In Test 1, among the three filtering media, the combination of 'Carbon-Charcoal-PET-Polyester' with the thickest depth of 50 mm achieved the best performance especially in reducing humidity and $PM_{2.5}$. Three out of four parameters (except for humidity) achieved better results when low airspeed was applied in the test, concluding that lower airspeed would give better results. This test also found that the fully-passive protocol (B-B) can provide more reductions in all parameters except humidity. However, this system depended on the wind buoyancy pressure where in an urban area like Kuala Lumpur, the wind movement is limited and unreliable, therefore, this protocol might not be suitable. Meanwhile, the fully-mechanical protocol (F-F) might have produced a very significant airflow from outside to the inside of the model but the excessive airflow reduced the particles in the indoor environment.

Hence, this test suggested that the ventilation protocol of the hybrid-positive protocol (F-B) is the best option for reducing polluted air and indoor discomfort in an urban area like Kuala Lumpur. The F-B protocol recorded significant reduction rates for air temperature, humidity and PM_{10}. In general, this protocol achieved better results than other protocols. However, the other factors that contribute to indoor discomfort and poor air quality should also be taken into consideration and this contaminated air should be discharged efficiently from the inside. On that reason, hybrid-negative protocol (B-F) also becomes an appropriate option.

This test also suggested that the lower the airspeed, the better the reduction rate would be. However, in a habitable space, it is important to achieve the minimum airflow requirement for indoor comfort and the minimum requirement of airspeed, which according to ASHRAE 55 and CIBSE Guide A should be between 0.15 m/s to 0.5 m/s. Meanwhile, for the ventilation air requirement (cfm), for a three-bedroom housing unit with 46.5 to 92.9 m^2, a minimum 30 l/s of airflow is required (ASHRAE, 2016b).

Test 2 verified that the ventilation protocols of B-F and the F-B could be considered as the right options to reduce the indoor discomfort and indoor air pollution in urban areas. Both systems, in this test, could successfully achieve thermal and air quality requirement set by the international and local established standards, and with the assistance from an adequate airspeed and activated carbon cartridge, the reduction rates could be significantly improved. Through this test, the activated carbon cartridge could add up another 10% to 30% improvement of airborne particle reduction.

The lower airspeed, 0.125 m/s particularly, had not only achieved and fulfilled the air movement requirement but also could constantly provide excellent indoor comfort and air quality for the occupants. Recycled glass material as dynamic insulation membrane had also produced remarkable results in reducing airborne particles as well as heat and humidity. This test concluded that recycled materials are very suitable to become the air filter materials, and taking into account of current waste dumps all around the world, this initiative could generate another useful purpose for waste dumps as air filter product.

By considering the current design of high-rise social housing in tropical countries that emphasises on natural ventilation method, this test found that the integrated strategy of DHAPC system using recycled glass material with hybrid ventilation and airspeed of 0.125 m/s could be one of the best problem solving of high air temperature, high humidity, high air pollution and low air movement in tropical urban areas. Hence, in Test 3, this system was studied in detail with other contaminants (particles and gases) from diesel and petrol engines.

Given the above findings, in providing air filtration that included all sources of pollution, Test 3 that evaluated the performance of DHAPC in filtering substances from petrol and diesel engines was conducted. Several substances from the engines such as carbon monoxide (CO), benzene, sulphur dioxide (SO_2), PM_1, $PM_{2.5}$ and PM_{10} were selected and tested. This test also sought for improvement on the performance of AC in filtering the substances using two different applications – AC in a cartridge and AC loose-fill. Among the key findings that could be deduced from Test 3 are explained below:

a. The application of AC cartridge in DHAPC system could produce better reduction rates on gases than particles. This scenario happened due to the compact amount of AC that could adsorb more gases from both petrol and diesel engines (Figure 4.41).

b. However, the AC loose-fill approach could efficiently reduce particles than gases. It suggested that more particles were ‘adsorbed’ on the AC molecules and also ‘absorbed’ in the DHAPC insulation membrane (Figure 4.41).

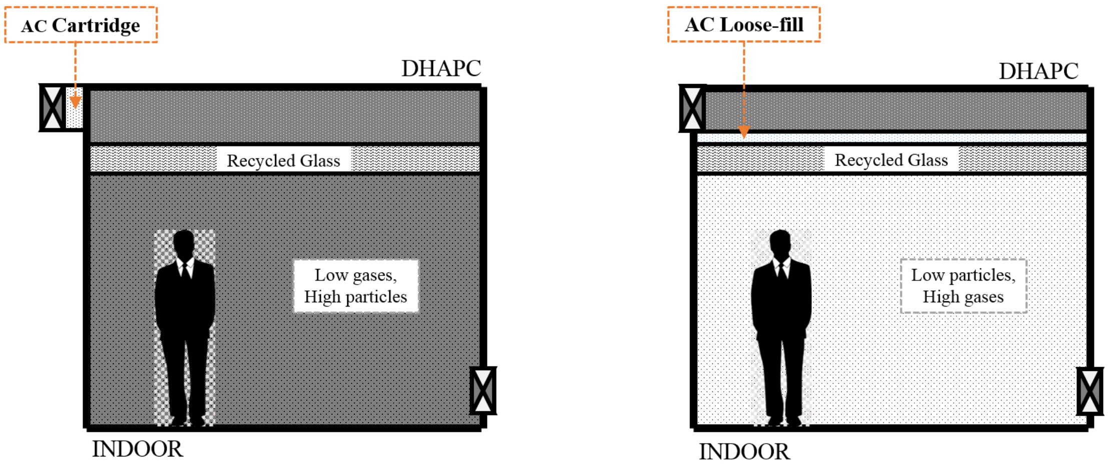


Figure 4.41: AC Cartridge vs AC Loose-fill

c. Ventilation protocols gave different effects in reducing air pollution from petrol and diesel engines. The F-B protocol, for instance, significantly produced higher reduction rates on particles. This was due to the repulsion force that made more ‘larger’ airborne particles trapped inside the membrane (Figure 4.42).

d. While the B-F protocol that was dominantly powered by suction pressure had dragged and released more particles from the insulation membrane, but not gases. It seems that more adsorption process occurred when B-F protocol was in use (Figure 4.42).

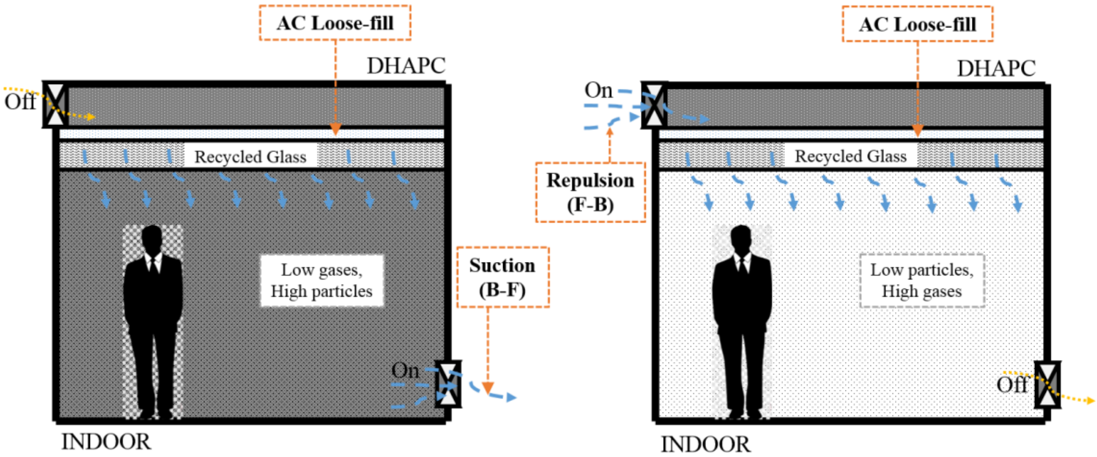


Figure 4.42: Suction (B-F) vs Repulsion (F-B)

e. According to this test, filtering gases from petrol and diesel engines using DHAPC and AC applications met a new barrier. After a certain period, the amount of gases in the indoor space of the test model gradually increased. A mechanism that could suck and channel out the gases (in the DHAPC compartment) before it permeates the indoor space should be studied in the future (Figure 4.43).

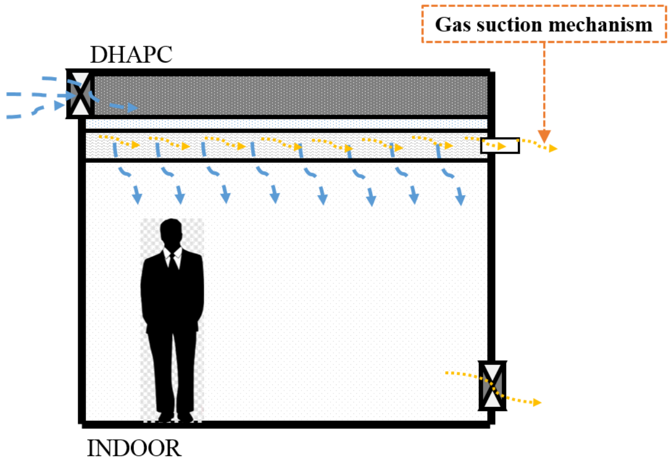


Figure 4.43: A proposed technique to the new barrier

It could be concluded that DHAPC system with AC applications (AC cartridge or AC loose-fill) and hybrid ventilation protocols (F-B and B-F) have a great potential to be developed in full scale as a solution for filtering heat, moisture and air pollution as well as providing constant and adequate airflow. These techniques now will require to be replicated at 1:1 scale. However, the initial data suggested that they could make a major contribution to improving thermal comfort and indoor air quality with a much-reduced carbon penalty.

As mentioned in Chapter 2, one of the limitations in this research was the environmental conditions of the location used in the tests. The ambient air temperature and humidity conditions whether indoor (Test 1 and Test 2) or outdoor (Test 3) were in a temperate country. Even though the tests were conducted in summer, the effects of lower temperature and humidity should be expected. As achieved in Tests 1 and 2, the reduction rates for temperature and humidity were slightly low. An energy-efficient strategy for air cooling system was paired with DHAPC system to improve the thermal comfort condition achieved in the tests. Therefore, in the next chapter, two computer simulations were conducted using the actual climatic contexts of Kuala Lumpur.

5 CHAPTER 5: Dynamic Hybrid Chilled Beam Ceiling (DHCBC)

5.1 Chilled Beam Systems: Precedents

In Chapter 4, the physical experiments (test 1, 2 and 3) demonstrated that the airborne particles of PM_1, $PM_{2.5}$ and PM_{10} could be reduced to circa 90% by using DHAPC system. These reduction rates were achieved with hybrid ventilation and activated carbon filter. This system had not only reduced the particles from organic smoke but also the toxic gases from petrol and diesel engines. However, the reduction rates for air temperature and humidity were insignificant and it is believed that it was because of the local environmental conditions where these tests were conducted. The results could be more significant if the more realistic Kuala Lumpur's air temperature and humidity conditions were applied.

The physical modelling results have demonstrated that by applying the 'Dynamic Hybrid Air Permeable Ceiling' (DHAPC) in the ceiling compartment could reduce the high ambient air temperature and filter the excessive humidity and particles in the air. Therefore, a detailed study has been conducted to investigate on how to further reduce the temperature and relative humidity of indoor air supply. A low-energy air cooling strategy such as chilled beam system has been carried out. This system has been integrated as a supporting system to the main system (DHAPC).

Since its creation in the last two decades, chilled beam systems have been in application mostly in Europe and North America (Azad et al., 2018). It has two basic types in use – passive and active (Roth, Dieckmann, Zogg, & Brodrick, 2007; Rumsey & Weale, 2007). Usually, a passive chilled beam consists of a small coil in a box that recesses in the ceiling or hangs from the ceiling (Roth et al., 2007). These boxes are used for cooling which depend on natural convection. Chilled water flows through the coil and the air around the coil is cooled and fills the room's space (Figure 5.1) (Rumsey & Weale, 2007). Similarly to the passive chilled beams, active chilled beams which also known as induction diffusers (Roth et al., 2007), consist of coils in boxes and mounted in the ceiling compartment. However, this technique uses ventilation air that is introduced into the diffuser box using fans (Rumsey & Weale, 2007). The use of fans to induce the airflow gives active chilled beams much higher cooling capacities than passive chilled beams (Rumsey & Weale, 2007).

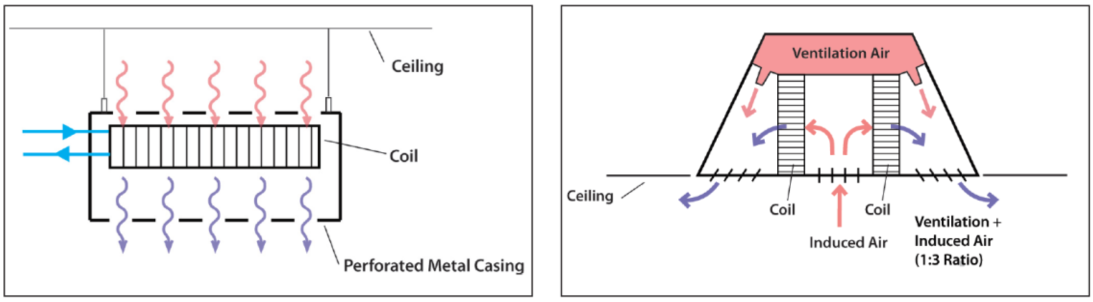


Figure 5.1: Passive chilled beam (left) and active chilled beam (right)(Rumsey & Weale, 2007)

The selection of this system to be integrated with DHAPC system is based on three factors – 1) smaller space requirements, 2) thermal comfort and air quality performance, and 3) energy savings potential. As mentioned earlier, the ceiling area is chosen due to the availability of ample unused surface in most naturally ventilated buildings in Malaysia which could be fully used for placing ventilation devices. Large surface areas contribute to better air distribution and reduce clog problems of filter membranes. Furthermore, DHAPC system has been designed to be allocated in limited ceiling areas (maximum of 600 mm depth) and chilled beams which do not require high-volume ductworks. It can fit in tighter spaces as well, making it adaptable into multiple floors buildings (Rumsey & Weale, 2007). Compared to conventional all-air systems, chilled beam systems (also known as water-air systems) can be fitted into a space as small as 150 mm to 460 mm (Rumsey & Weale, 2007). This becomes one of the crucial criteria for its selection.

Second, a few studies have found that the active chilled beam can perform better compared to the conventional air-conditioning system such as fan coil unit (Azad et al., 2018; Cehlin et al., 2019). A study in a tropical climate contexts was done to evaluate the thermal comfort criteria using active chilled beam and it was found that only 12% of the data points were tabulated outside the psychrometric chart's comfort zone (Azad et al., 2018). Meanwhile, about 53% of data points were found outside the comfort zone when applying conventional air-conditioning system. For air quality, a study has found that air quality and thermal condition are sensitive to the airflow and the temperature pattern created by the active chilled beam (Cehlin et al., 2019). The direction of the supply air from ceiling to floor and the bounce flow from floor to ceiling has established a large air circulation in a space (Cehlin et al., 2019).

Third, chilled beam systems could save energy by three ways – 1) by using sensible cooling directly to spaces can greatly reduce the ventilation fan energy consumed to deliver cooling, 2) by combining the chilled beam and the dedicated outdoor air systems (DOAS) can meet ASHRAE Standard 62 ventilation requirements with less ventilation airflow, 3) chilled beams use higher chilled water temperatures than conventional air-conditioning systems (approximately 10°C lower), a chiller dedicated for chilled beam cooling has a lower temperature lift and operates at a 15% to 20% higher efficiency than for a conventional system, and 4) the higher chilled water system temperatures together with active chilled beams can retain large quantities of room air which greatly reduces the need for energy-consuming reheat of the cooled air (Roth et al., 2007). On the other hand, by lowering supply airflow volumes will efficiently reduce the energy to cooling the outdoor air (Roth et al., 2007). The chilled beam systems, in a few studies, can achieve savings of up to 20% to 30% compared to the conventional air-conditioning systems (Azad et al., 2018; Roth et al., 2007).

However, by using a conventional chilled beam system (Figure 5.2), the air distribution in the room is influenced by the supply and induced airflows which create mixing ventilation (Nielsen et al., 2018). This pattern of airflow has given a limited capacity for the system to distribute air evenly throughout the space (Cehlin et al., 2019; Roth et al., 2007). Thus, in this research, chilled beam system has been integrated into DHAPC system to provide extra thermal comfort capacities. The system has been re-designed and suited to the main system – DHAPC system. Thus, two IES simulations have been conducted to test the new strategy of chilled beam system called ‘Dynamic Hybrid Chilled Beam Ceiling’ (DHCBC). These simulations were aimed to reduce the actual average operative temperature to be below 28°C as suggested by ASHRAE 55 and at the same time maintaining the relative humidity levels between 40% to 70% RH as set by CIBSE Guide A. Both requirements need to be achieved while taking into consideration the system’s total energy consumption.

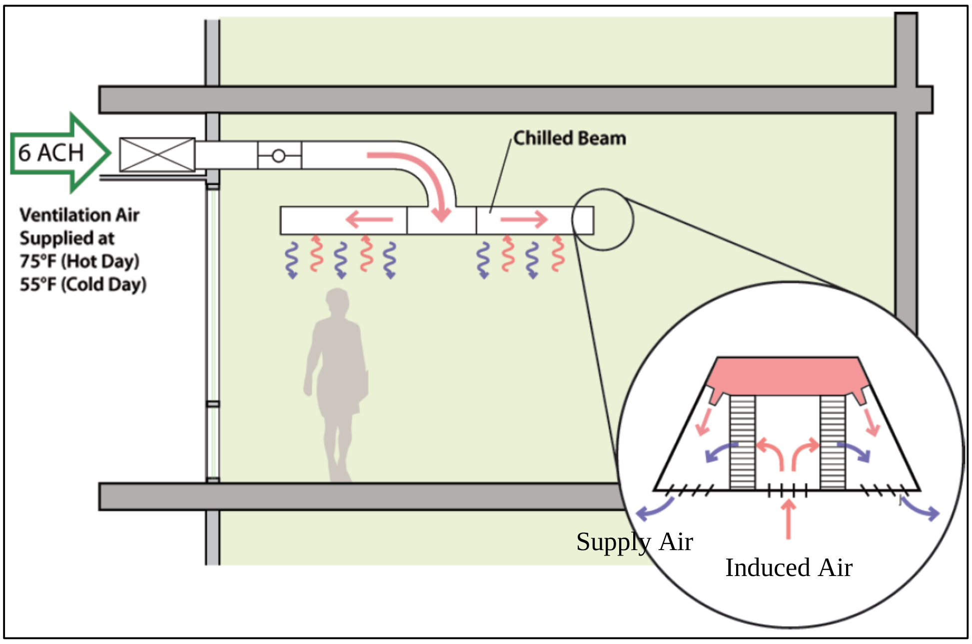


Figure 5.2: Schematic design of a conventional active chilled beam system (Rumsey & Weale, 2007)

The DHCBC has different approaches than the conventional chilled beam systems in several ways. CHCBC consist of coils and aluminium plates in boxes and mounted in the ceiling compartment. Chilled water of 15°C from the main chilled water tank is supplied into the coils. It first enters the secondary chilled water tank dedicated to each housing unit to regulate the water flow speed. Supply fans located on the building façade introduce direct ventilation air (Figure 5.3). When the outdoor air (temperature range between 29°C to 35°C) passes through the coils and plates, convection and radiation effects reduce the air temperature. When the air temperature reduced below dew point temperature (23°C), moisture turns into fluid. This effect reduces humidity in the air. The warm return water enters the hot water tank and heat exchanger stores the heat for hot water supply. Finally, the neutral water is pumped up to the main supply water tank. This water tank supplies the water to the cooling tower to produce chilled water for the next cycle (Figure 5.3).

The main different approach in DHCBC is the air distribution technique. The conventional chilled beam systems through diffusers, introduce the supply and induced airflows which create mixing ventilation and reduce the air distribution coverage (Cehlin et al., 2019) (Figure 5.2). However, in this new system, DHCBC reduces the outside air temperature and humidity only. The air is retained in the DHAPC compartment for a while before the positive pressure from the supply fans together with negative suction pressure from the exhaust fans push and drag the air passes through the DHAPC membrane. This technique supplies cool and clean air through the entire ceiling surface. Furthermore, the DHCBC system uses directional airflow technique where supply air flows downward from the ceiling and exits through the exhaust fan located at the floor level (Figure 5.3). This ventilation technique as typically applied in cleanrooms eliminates induced airflow, creating a better supply air distribution and air quality throughout the space (Bhatia, 2012a).

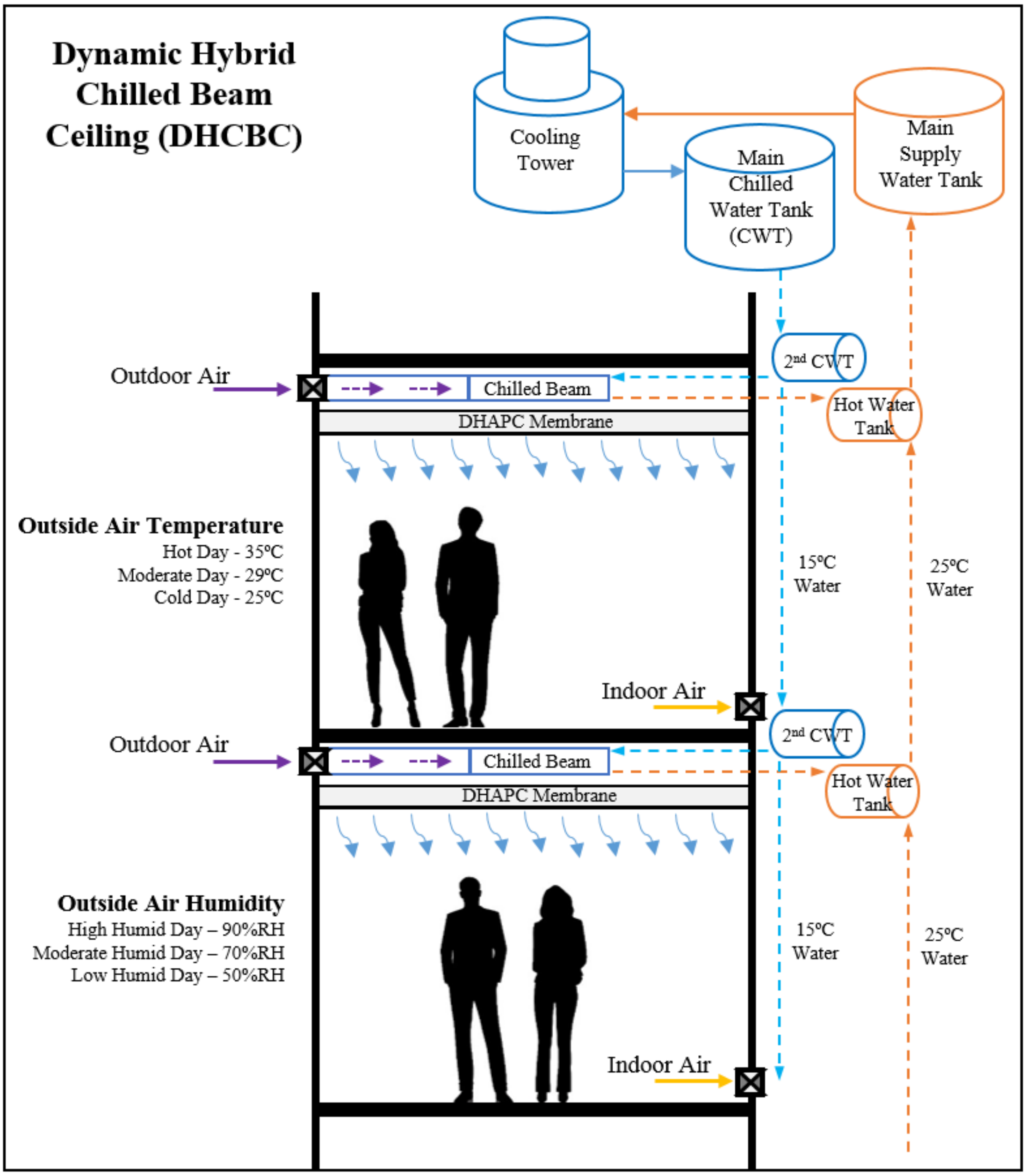


Figure 5.3: Schematic design of Dynamic Hybrid Chilled Beam Ceiling (DHCBC)

5.1.1 The DHCBC System

This system works by supplying the outside air using supply fan into the DHAPC compartment. In this compartment, the coil pipes and aluminium plates are located to reduce the air temperature and humidity of the incoming air intake. As suggested by ASHRAE 55 and CIBSE Guide A, the range for air temperature is in between 24°C and 28°C, thus, the supply air temperature that enters the indoor space should be lower than 28°C. In this case, the mean temperature for the range is 26°C and these simulations set a lower value of 25°C to be the targeted temperature value. Therefore, flowing the chilled water of 15°C inside the coil pipes is required to reduce the temperature of air intake which typically as high as 35°C (Figure 5.4).

This chilled water is supplied from the main chilled water tank located at the rooftop level. There is a temporary chilled water tank for every housing unit to regulate the water flow to the desired pressure before the water enters the coils. Due to the local environment (hot and humid), the warm outside air will enter and flow around the coil pipes and plates. The dew point temperature in Kuala Lumpur is below 23°C (MS1525, 2014) and with 15°C of chilled water, condensation will occur where dripping of condensate water will happen. This condensate water will be collected by the aluminium trays provided underneath the coils and plates. It then will be channelled to the condensate water tank located in the nearest bathrooms. These tanks will be the main water supply for the flushing system. However, in a situation of short condensate water supply, normal water supply will be used as a second option (Figure 5.4).

The chilled water will flow through the coil pipes and absorb the heat through convective and radiative heat transfer. Using aluminium plates, the heat absorption will be more efficient because the plates have a large area of contact. Eventually, the warm and humid air will be cooled down and dried up before entering the indoor spaces. The warm return water will enter the hot water storage tanks and the heat will be absorbed by the heat exchanger and stored for daily hot water supply. Each of the housing units will be allocated a hot water tank that is linked to the hot water pump and regulator inside the bathrooms. Then, the neutral return water will be pumped up to the main water tank at the rooftop level. The water will be chilled, and the next cycle will start again. This air cooling cycle using chilled water is recommended only during the hot times of the day, which is from 9 am to 9 pm daily.

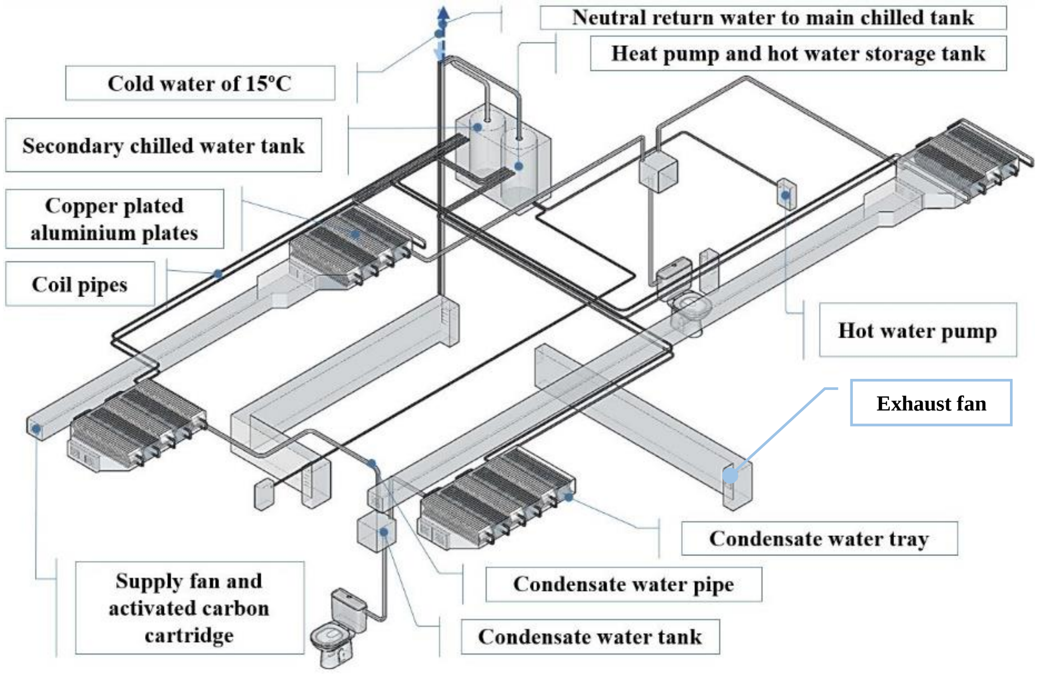


Figure 5.4: Full diagram of DHCBC system

5.2 Computer Simulation Models

This methodology of research consists of two computational modelling exercises – simulation 1 tests the system in small scale (two bedrooms only) without active light-well and simulation 2 for testing the system for the whole housing unit with an active light-well. Figure 5.4 shows the actual simulation model used in simulation 1. Twelve rooms were defined, located at level 1, level 10 and level 20. Four rooms were selected for each floor level where two of them were facing the south and the other two were facing the north. The location of the housing units and the sample rooms were consistent with the actual samples used in the PPR second generation block in Kuala Lumpur (as explained in Chapter 3).

Table 5.1 shows the 12 simulation names derived from three criteria – height level, façade facing direction and type of bedroom. These names were assigned to the simulation model as shown in Figure 5.14. Two variables were applied in this model calculations which were the cooling design supply air temperatures and cooling design airflow rates. The selected cooling design supply air temperatures were 25°C and 20°C, while the cooling design airflow rates were 30 l/s and 60 l/s. According to the ASHRAE 62.2, 30 l/s (60 cfm) of airflow rate is required for a housing unit that has three bedrooms with an area between 46.5 to 92.9 m^2 (ASHRAE, 2016).

Table 5.1: Configuration of sample names in simulation 1 model

No.	Level	Simulation Names	Type of Room	Facing Direction
1	1	L1S_P1	Bedroom 1	South
2	1	L1S_P2	Bedroom 3	South
3	1	L1N_P1	Bedroom 1	North
4	1	L1N_P2	Bedroom 3	North
5	10	L10S_P1	Bedroom 1	South
6	10	L10S_P2	Bedroom 3	South
7	10	L10N_P1	Bedroom 1	North
8	10	L10N_P2	Bedroom 3	North
9	20	L20S_P1	Bedroom 1	South
10	20	L20S_P2	Bedroom 3	South
11	20	L20N_P1	Bedroom 1	North
12	20	L20N_P2	Bedroom 3	North

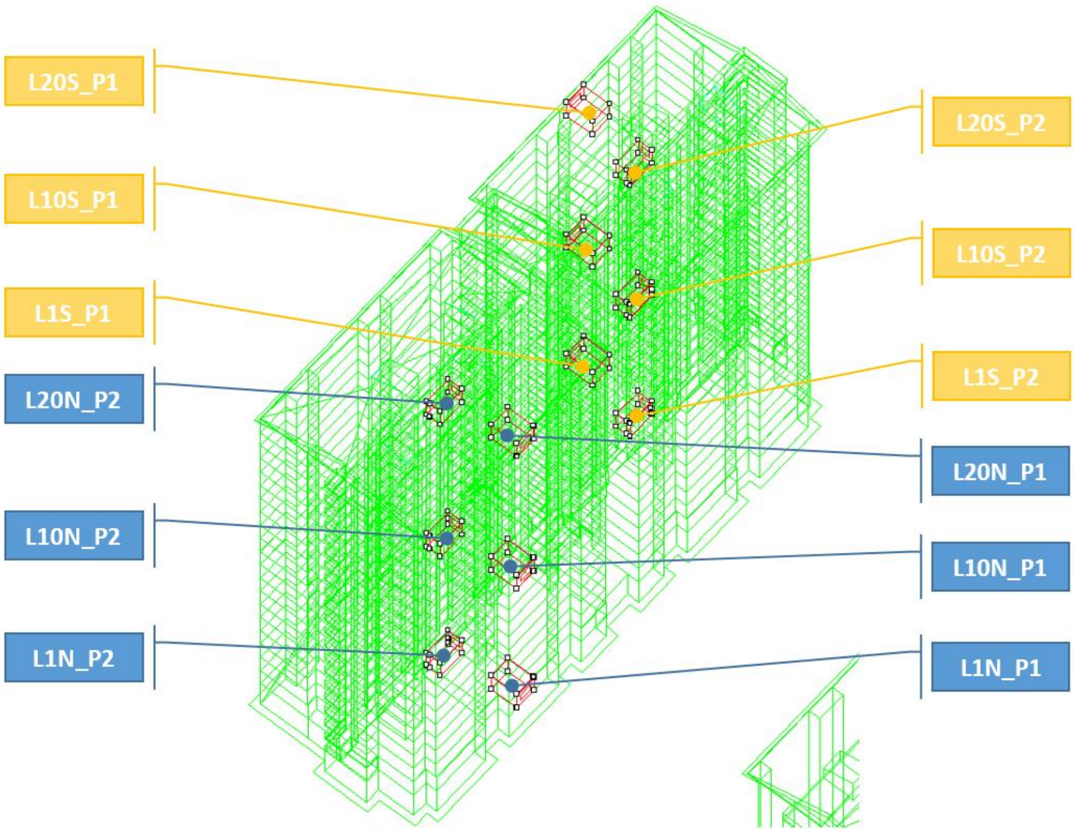


Figure 5.5: The actual simulation 1 model in IES

In the simulation 2 exercise, the more accurate actual housing scale has been simulated. Three housing unit samples were defined, located at level 1, level 10 and level 20. In each unit, four rooms were selected – master bedroom (MB), bedroom 2 (BR2), bedroom 3 (BR3) and living room-dining area (LR-DN). One light-well that directly connected to the BR2 and BR3 would also be simulated. A light-well was selected and equipped with an exhaust fan at the top. In this simulation, this light-well would be called active light-well (ALW). In total, there were twelve habitable rooms and one unoccupied area being simulated in this simulation 2 exercise (Figure 5.5).

Table 5.2 lists the 13 simulation names that were assigned to the simulation 2 model as shown in Figure 5.6. The living room-dining area was the largest space in the housing unit which has 81.35 m^3. Bedroom 1, bedroom 2 and bedroom 3 have smaller areas of 40.19 m^3, 33.18 m^3 and 27.09 m^3 respectively. In general, each housing units will have a total volume of 181.81 m^3 and 57.72 m^2 (621.3 ft^2) for the total floor area. Light-well, the only unoccupied area that connects all the housing units, has a volume of 1,214 m^3. Two variables applied in this simulation model's calculations were the cooling design supply air temperatures and cooling design airflow rates. The cooling design supply air temperatures (25°C and 20°C) and the cooling design airflow rates (30 l/s and 60 l/s) selected were the same as used in simulation 1 exercise.

Table 5.2: Sample's Name, Floor Area and Volume

No.	Level	Simulation Names	Type of Room	Volume (m^3)
1	1	MB-1	Bedroom 1	40.19
2	1	BR2-1	Bedroom 2	33.18
3	1	BR3-1	Bedroom 3	27.09
4	1	LR-DN-1	Living Room	81.35
5	10	MB-10	Bedroom 1	40.19
6	10	BR2-10	Bedroom 2	33.18
7	10	BR3-10	Bedroom 3	27.09
8	10	LR-DN-10	Living Room	81.35
9	20	MB-20	Bedroom 1	40.19
10	20	BR2-20	Bedroom 2	33.18
11	20	BR3-20	Bedroom 3	27.09
12	20	LR-DN-20	Living Room	81.35
13	All	ALW	Light-Well	1,214.00

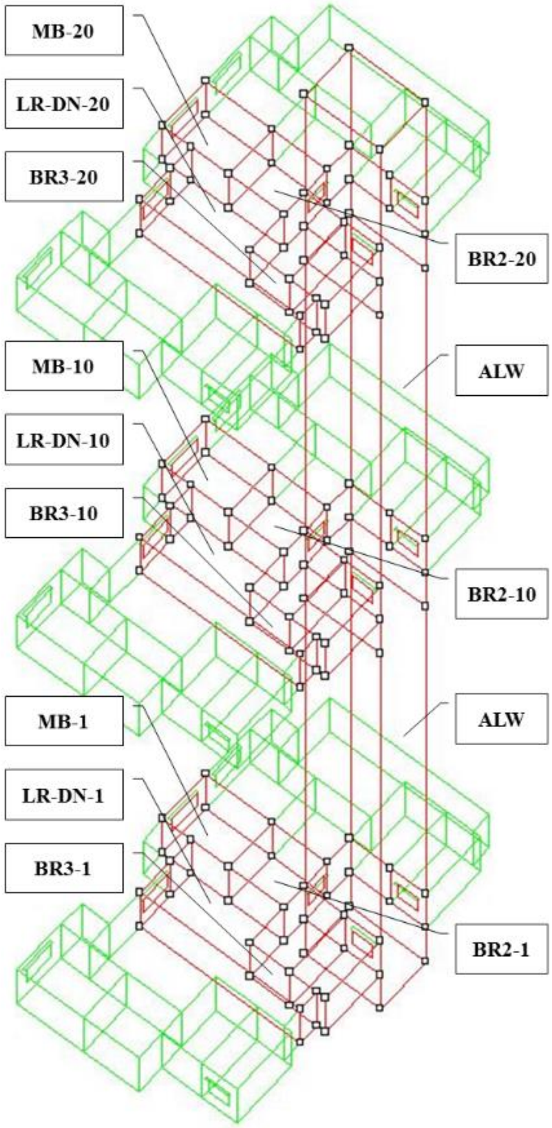


Figure 5.6: The actual simulation 2 model in IES

5.3 Validation of the Simulations

5.3.1 Methodology

The interrogation of the simulation exercises was addressed in three stages. Using an actual case study, a baseline thermal performance was simulated (simulation 1) followed by an actual thermal performance of the system (simulation 2). It then, followed with a validation of the integration of the final systems (DHAPC and DHCBC). The initial task was to generate a baseline analysis for the thermal performance of a typical high-rise social housing in Kuala Lumpur using DHCBC system. The second stage involved developing a more accurate system in the case study that could handle such high ambient temperatures and humidity with low energy consumption. The task involved designing a cooling system that can integrate into DHAPC system to reduce the air temperature and humidity of the supply air ventilation. The design of this system required a series of methodologies including fieldwork studies and physical model experiments. This DHCBC system became the subject of simulation modelling using computational software. The third task was then to assess the results and validate the thermal efficiency and energy consumption of the measures compared to the baseline case (Figure 5.7).

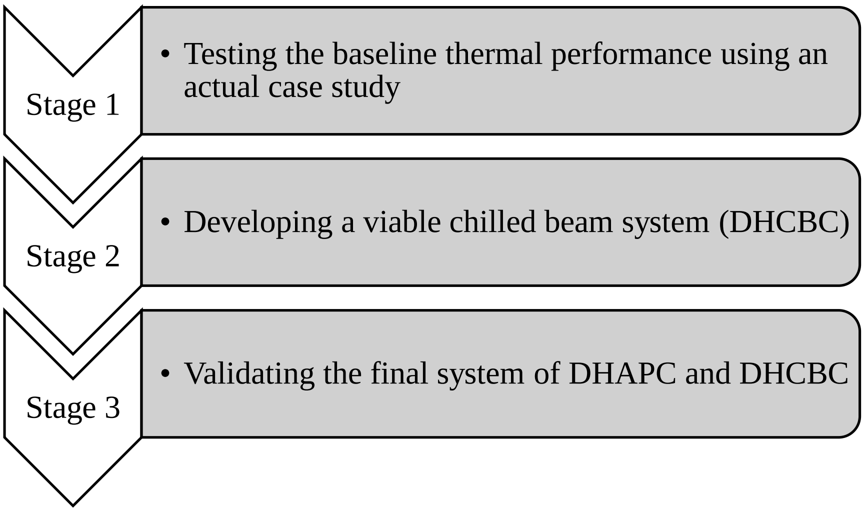


Figure 5.7: Method for assessing the computer simulation models

5.3.2 Software

The ‘Integrated Environmental Solutions’ (IES) is chosen because of its high reputation and reliability as one of the most commonly used simulation software by many researchers (Marko Jarić et al., 2013). The software is suitable for simulating naturally ventilated buildings through its ‘Macroflo’ (Crawley et al., 2008) and ‘ApacheHVAC’ for the detailing of the building systems, allowing their optimisation taking into account the criteria such as comfort and energy (Sousa, 2012). Apart from its economic aspect, this software costs the least times for simulating and calculating the environmental conditions of a 3D model (Li, 2015). In this research, a 20-storey PPR second generation building was modelled using this software.

5.3.3 Simulation Settings

The settings for simulation 1 applied a basic DHCBC system started with an inlet (green arrow) followed with a supply fan that connects to an air filter [2]. This air filter represents the DHAPC system, but its total pressure dropped only as this software was unable to simulate the air quality within its parameters. A cooling coil box was placed after the air filter box, both components were located in the DHAPC compartment in the ceiling area. The zone (indoor space) has an exhaust fan at its bottom level for system outlet (red arrow) (Figure 5.8). Using the similar set-up like simulation 1 (Figure 5.8), simulation 2 was designed with the active light-well (ALW) in tandem as shown in Figure 5.9.

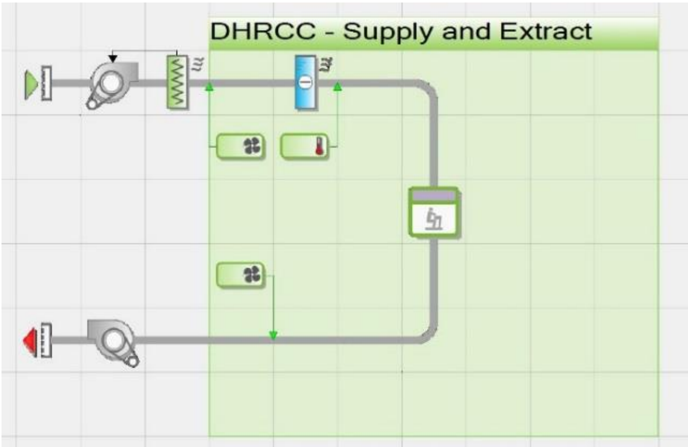


Figure 5.8: The schematic design of DHCBC for simulation 1

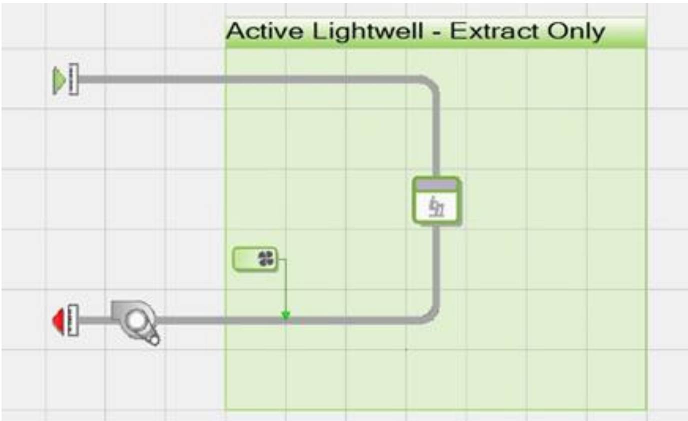


Figure 5.9: The schematic design of additional ALW component for simulation 2

The supply fan was the first component in these simulations. This fan has a maximum power of 0.100 kW and maximum design flow rate of 180 l/s. This fan capacity is equivalent to six numbers of 100 mm diameter axial exhaust fans. The 100 mm diameter axial fan is typically used for the bathroom in a housing unit and can exhaust or supply the air up to 100 m^3/h. According to the ASHRAE 62.2, 30 l/s (60 cfm) of airflow rate is suggested for a housing unit that has three bedrooms and an area of between 501 to 1000 ft^2. For these simulations, the airflow rates used were 30 l/s and 60 l/s (Table 5.3). An additional 60 l /s of airflow rate in this simulation was due to the high-pressure drop that the filter membrane in the DHAPC system created. The second component in these simulations was the air filter. It represents the DHAPC filter membrane. As explained in Chapter 4, the best insulation material that efficiently filtered $PM_{2.5}$ and PM_{10} was the recycled glass insulation. The material depth during the test was 100 mm with 100 Pa of total pressure drop. Therefore, in these simulations, the same total pressure drop has been applied.

The third component was the cooling coils that work with a chilled water loop system. The chilled water loop power capacity is 23.89 kW with 0.86 l/s of water flow rate inside the coils. The temperature for the chilled water supply in this system was 15°C. Using a water pump, the chilled water was supplied in the cooling coils and distributed throughout the housing units. The pump power was 69.74 w/(l/s). This cooling coils used two different cooling dry-bulb temperatures – 25°C and 20°C (Table 5.3). The selection of these temperature values was to represent the values before and after the dew point temperature (23°C) set by the Malaysian Standard (MS1525, 2014). These three components – supply fan, air filter and cooling coils, were placed in the ceiling compartment as a part of DHAPC system and assigned as chilled beam ceiling in the computer simulation models. Four configurations were used in these simulations (Table 5.3) with two aims: 1) to achieve more than 70% of the total hours in a year that falls in between 24°C to 28°C for operative temperature and 40% - 70% RH for relative humidity, and 2) to achieve the mean operative temperature below 28°C and the mean relative humidity below 70%.

Table 5.3: The configurations used in simulation 1 and 2

Configuration	Supply Air Temperature	Supply Airflow Rate
1	25°C	30 l/s
2	25°C	60 l/s
3	20°C	30 l/s
4	20°C	60 l/s

The last component in these simulations was the exhaust fan. The total fan power for this fan was 0.033 kW with a maximum 60 l/s of airflow rate. The fan’s maximum airflow rate was set to be not less than 30 l/s during the test to create the hybrid-positive pressure effect (B-F) as suggested in the physical model tests. In simulation 2, an additional space component was integrated with the DHCBC system - an active light-well (ALW). The total fan power for this ALW was 0.840 kW with a maximum 337.33 l/s of airflow rate.

For this simulation, the DHCBC system was active only from 10 am to 10 pm. By referring to the IES baseline simulation, the period was chosen because from 10 am, the air temperature increases until its peak at 5 to 6 pm and decreases after that until 10 pm. Only during this period, the cooling coil system was in use. However, the supply and exhaust fans were left active to supply clean air using DHAPC system.

In addition, this system did not require any heating equipment because in this type of climate, heating demand is very low which usually is for showers only. It could be supplied through the heat collected and stored by this DHCBC system. The zone's humidity was set at the minimum value of 40% RH. For the zone's ventilation and exhaust, the ASHRAE 62.1 has set that the people outdoor air rate is 2.5 l/s/person and thus, the ventilation requirement for two people in a 26 m^3 room is 10 l/s. However, the smallest exhaust fan available in the market could supply 27.78 l/s of flow rate, thus, these simulations used a constant 30 l/s in its calculation.

5.4 Simulation 1: Results and Analysis

5.4.1 Thermal Comfort

Operative Temperature (OT)

Table 5.4 lists the OT results for the configuration that used the 25°C of supply air temperature and 30 l/s of airflow rate. The minimum temperature range was between 24.42°C to 24.78°C whereas the mean OT range was from 27.63°C to 28.25°C. These mean the temperatures are slightly above the ASHRAE recommended operative temperature of 28°C. In total hours in a year, 53.1% were within the indoor comfort temperatures of 24°C to 28°C while the rest exceeded 28°C (Table 5.4). For the 25°C and 60 l/s configuration, the minimum temperatures were recorded between 24.10°C to 24.50°C and the mean temperatures were ranged from 27.00°C to 27.75°C. For the percentage hours range, approximately 71.4% hours in a year were within the comfort temperature range while the rest recorded above 28°C (Table 5.5).

Table 5.4: OT percentage hours range for 25°C and 30 l/s configuration

	OT % hours in range	OT % hours in range	OT % hours in range
Location	**<= 24.00**	**>24.00 to <=28.00**	**> 28.00**
L1S_P2	0	61.9	38.1
L1N_P2	0	61.9	38.1
L1S_P1	0	42.8	57.2
L1N_P1	0	48.3	51.7
L10N_P1	0	47.3	52.7
L10S_P2	0	60.4	39.6
L10S_P1	0	42.8	57.2
L10N_P2	0	61.8	38.2
L20N_P1	0	45	55
L20S_P2	0	58.8	41.2
L20N_P2	0	61.8	38.2
L20S_P1	0	44.8	55.2
Total hours (%)	**0**	**53.1**	**46.9**

Table 5.5: OT percentage hours range for 25°C and 60 l/s configuration

	OT % hours in range	OT % hours in range	OT % hours in range
Location	**<= 24.00**	**>24.00 to <=28.00**	**> 28.00**
L1S_P2	0	83.3	16.7
L1N_P2	0	83.4	16.6
L1S_P1	0	57.4	42.6
L1N_P1	0	63.8	36.2
L10N_P1	0	62.7	37.3
L10S_P2	0	82.2	17.8
L10S_P1	0	57.5	42.5
L10N_P2	0	83.3	16.7
L20N_P1	0	59.9	40.1
L20S_P2	0	80.9	19.1
L20N_P2	0	83.2	16.8
L20S_P1	0	59.6	40.4
Total hours (%)	**0**	**71.4**	**28.6**

For the 20°C and 30 l/s configuration, the minimum temperatures were recorded between 23.33°C to 23.76°C and the mean temperatures were in the range of 26.14°C to 26.81°C. For the percentage hours range, 89.8% hours in a year were recorded within the comfort temperatures (Table 5.6). For the 20°C and 60 l/s configuration, the minimum temperatures were between 22.54°C to 23.12°C and the mean temperatures were ranged from 24.85°C to 25.81°C. For the percentage hours range, 85.7% hours in a year were within the comfort temperatures range (Table 5.7).

Table 5.6: OT percentage hours range for 20°C and 30 l/s configuration

Location	OT % hours in range <= 24.00	OT % hours in range >24.00 to <=28.00	OT % hours in range > 28.00
L1S_P2	1	94.2	4.8
L1N_P2	1	94.3	4.7
L1S_P1	0.1	83.7	16.2
L1N_P1	0.2	87.8	12.1
L10N_P1	0.1	86.9	13
L10S_P2	0.8	94	5.3
L10S_P1	0.1	83.7	16.2
L10N_P2	1	94.3	4.7
L20N_P1	0.1	85.4	14.5
L20S_P2	0.7	93.5	5.8
L20N_P2	1	94.2	4.8
L20S_P1	0.1	85.5	14.4
Total hours (%)	**0.5**	**89.8**	**9.7**

Table 5.7: OT percentage hours range for 20°C and 60 l/s configuration

Location	OT % hours in range <= 24.00	OT % hours in range >24.00 to <=28.00	OT % hours in range > 28.00
L1S_P2	22.4	76.4	1.2
L1N_P2	22.6	76.2	1.2
L1S_P1	3	94.8	2.3
L1N_P1	4.4	93.7	1.9
L10N_P1	4.2	93.8	2
L10S_P2	20.7	78.1	1.2
L10S_P1	3	94.8	2.3
L10N_P2	22.5	76.3	1.2
L20N_P1	3.6	94.2	2.2
L20S_P2	20.1	78.7	1.2
L20N_P2	22.5	76.4	1.2
L20S_P1	3.6	94.4	2
Total hours (%)	**12.7**	**85.7**	**1.6**

Figure 5.10 shows the comparison of the average OT results achieved in simulation 1 with the IES baseline simulation result. The IES baseline simulation found that the average OT for a year in Kuala Lumpur was 29.1°C. This value exceeded 1.1°C above the ASHRAE 55 recommended value. By referring to the IES

simulation 1 results, the DHCBC system could reduce the OT temperatures below the ASHRAE 55 limit. All of the samples achieved the range of OT in between 25.30°C to 27.91°C. The best average OT was produced by the configuration of 20°C and 60 l/s, while the worst was 25°C and 30 l/s. As stated in the Malaysian Standard 1525, the recommended design dry-bulb temperature range is 24°C to 26°C and the minimum is 23°C (MS1525, 2014). Therefore, the configurations that achieved the average OT temperatures within or near the range could potentially be used in the final system. Figure 5.11 shows the average percentages of total hours between 24°C to 28°C. The highest percentage was achieved by the configuration of 20°C and 30l/s with 89.8%.

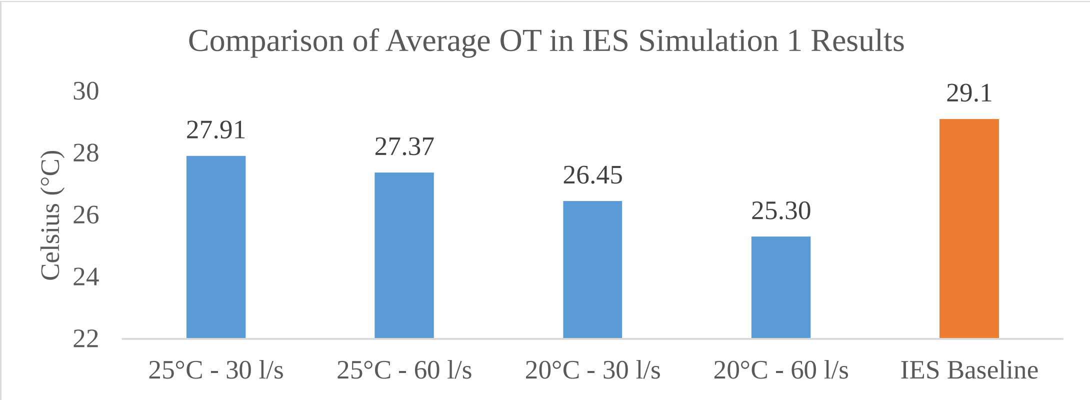


Figure 5.10: Comparison of average OT's results and IES simulation 1 result

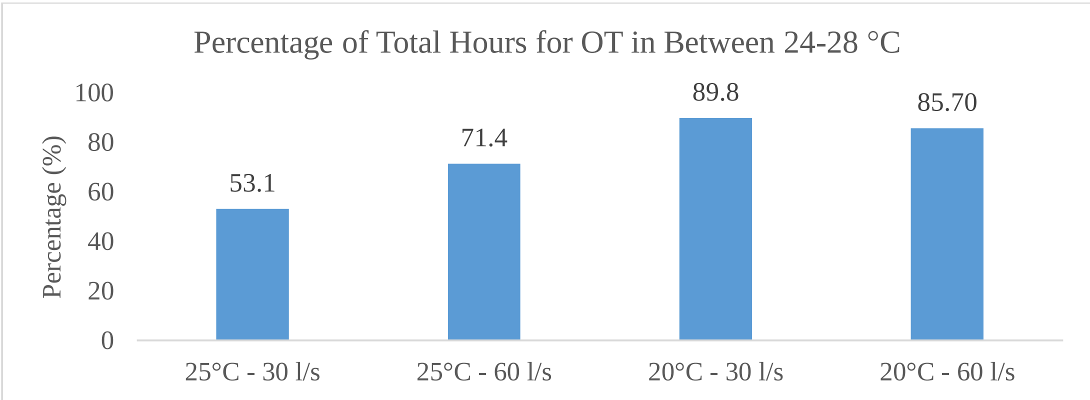


Figure 5.11: Percentage of total hours for OT in between 24-28^{o}C

Relative Humidity (RH)

Table 5.8 lists the RH results for the configuration using 25°C of supply air temperature and 30 l/s of airflow rate. The minimum RH was recorded between 45.23% to 46.76% RH and the mean temperatures were in the range of 79.28% to 81.42% RH. For the percentage hours range, only 4.5% hours in a year were within the comfort RH range of 40% to 70% RH and the rest were well above 70% RH

(Table 5.8). For the 25°C and 60 l/s configuration. The minimum RH was between 46.22% to 48.31% RH and the mean temperatures were ranged between 80.97% to 83.68% RH. For the percentage hours range, only 2.3% hours in a year were simulated within the comfort RH range of 40% to 70% RH and the rest exceeded 70% RH (Table 5.9).

Table 5.8: RH's percentage hours range for 25 °C – 30 l/s configuration

	RH % hours in range	**RH % hours in range**	**RH % hours in range**
Location	**<= 40.00**	**>40.00 to <=70.00**	**> 70.00**
L1S_P2	0	3.1	96.8
L1N_P2	0	3.1	96.9
L1S_P1	0	6.5	93.5
L1N_P1	0	4.9	95
L10N_P1	0	5.2	94.7
L10S_P2	0	3.2	96.8
L10S_P1	0	6.5	93.5
L10N_P2	0	3.1	96.9
L20N_P1	0	5.8	94.2
L20S_P2	0	3.4	96.6
L20N_P2	0	3.1	96.8
L20S_P1	0	6.1	93.9
Total hours (%)	**0**	**4.5**	**95.5**

Table 5.9: RH's percentage hours range for 25 °C – 60 l/s configuration

	RH % hours in range	**RH % hours in range**	**RH % hours in range**
Location	**<= 40.00**	**>40.00 to <=70.00**	**> 70.00**
L1S_P2	0	1.4	98.6
L1N_P2	0	1.4	98.6
L1S_P1	0	3.7	96.3
L1N_P1	0	2.6	97.4
L10N_P1	0	2.8	97.2
L10S_P2	0	1.4	98.6
L10S_P1	0	3.7	96.3
L10N_P2	0	1.4	98.6
L20N_P1	0	3	96.9
L20S_P2	0	1.5	98.5
L20N_P2	0	1.4	98.6
L20S_P1	0	3.3	96.6
Total hours (%)	**0**	**2.3**	**97.7**

For the 20°C and 30 l/s configuration, the mean temperatures were in the range of 82.72% to 85.23% RH and only 5.9% hours in a year were located in the comfort RH range (40% to 70% RH) while the rest exceeded 70% RH (Table 5.10). For the 20°C and 60 l/s configuration, the mean temperatures were ranged of 85.79% to 88.47% RH and for the percentage hours range, only 1.0% hours in a year were within the comfort RH range and the rest were well above 70% RH (Table 5.11).

Table 5.10: RH's percentage hours range for 20 °C –30 l/s configuration

	RH % hours in range	**RH % hours in range**	**RH % hours in range**
Location	**<= 40.00**	**>40.00 to <=70.00**	**> 70.00**
L1S_P2	0	4.3	95.7
L1N_P2	0	4.3	95.7
L1S_P1	0	8.3	91.7
L1N_P1	0	6.4	93.6
L10N_P1	0	6.8	93.2
L10S_P2	0	4.4	95.6
L10S_P1	0	8.3	91.7
L10N_P2	0	4.3	95.7
L20N_P1	0	7.4	92.6
L20S_P2	0	4.6	95.4
L20N_P2	0	4.3	95.7
L20S_P1	0	7.7	92.3
Total hours (%)	**0**	**5.9**	**94.1**

Table 5.11: RH's percentage hours range for 20 °C – 60 l/s configuration

	RH % hours in range	**RH % hours in range**	**RH % hours in range**
Location	**<= 40.00**	**>40.00 to <=70.00**	**> 70.00**
L1S_P2	0	0.3	99.7
L1N_P2	0	0.3	99.7
L1S_P1	0	1.9	98.1
L1N_P1	0	1.3	98.7
L10N_P1	0	1.4	98.6
L10S_P2	0	0.4	99.6
L10S_P1	0	1.9	98.1
L10N_P2	0	0.3	99.7
L20N_P1	0	1.6	98.4
L20S_P2	0	0.4	99.6
L20N_P2	0	0.3	99.7
L20S_P1	0	1.7	98.3
Total hours (%)	**0**	**1**	**99**

Figure 5.12 shows the comparison of the average RH results achieved in simulation 1 with the IES baseline simulation result. As explained in Chapter 3, the IES simulation baseline has found that the average RH in a year in Kuala Lumpur was 66.43% RH. According to the IES simulation 1 results, the lowest average RH recorded was for the configuration that used 25°C and 30 l/s with 80.48% RH. It could be deduced that all configurations recorded high average RH results above 70% RH. It means that DHCBC system which was simulated without ALW was unable to reduce humidity in indoor spaces below the recommended limit set by CIBSE Guide A.

Referring to Figure 5.13, no configurations could produce an average RH between 40% to 70% RH more than 70% of total hours in a year. This might due to the inefficient of airflow rate using an exhaust fan that could channel out the moisture from indoor spaces using passive light-well. It is worthwhile to simulate another computer simulation model on a more realistic scale (full housing unit) by combining an active light-well strategy to improve the RH results.

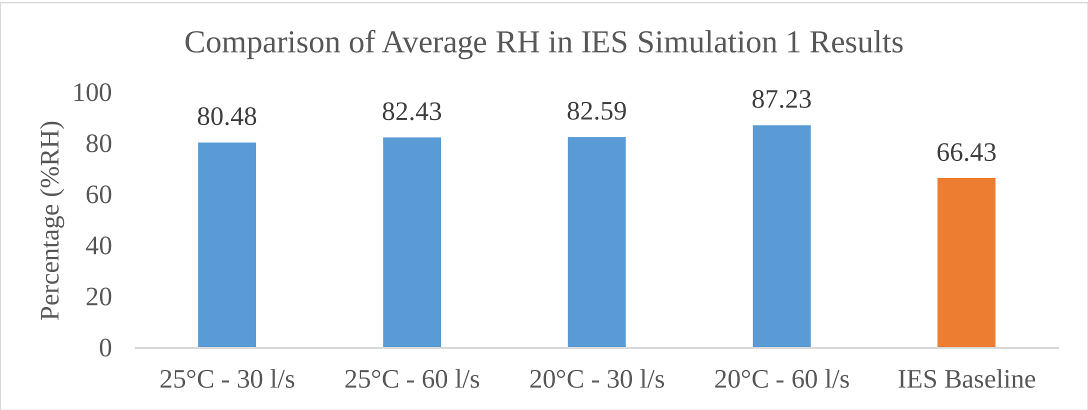


Figure 5.12: Comparison of average RH results and IES 1 result

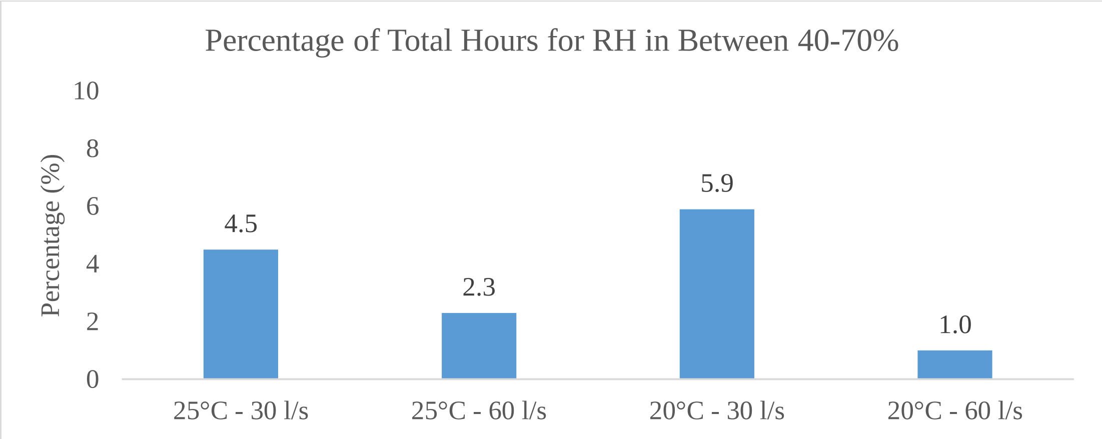


Figure 5.13: Percentage of total hours for RH in between 40-70%RH

5.4.2 Discussion

Table 5.12 lists the total system energy (TE) results for every configuration. The configuration that used the least energy consumption was 25°C and 30 l/s with 0.786 kW and the highest was the 20°C and 60 l/s with 2.309 kW. These results were expected because of the high energy demand to cool the chilled water to 20°C compared to 25°C and energy consumption for turning the fan to 60 l/s than 30 l/s.

Table 5.12: Total system energy results

Configuration	**Type**	**Min.**	**Max.**	**Mean**
20°C and 60 l/s	Power (kW)	0.196	5.395	2.309
20°C and 30 l/s	Power (kW)	0.196	3.386	1.470
25°C and 60 l/s	Power (kW)	0.200	3.911	1.102
25°C and 30 l/s	Power (kW)	0.196	2.648	0.786

Table 5.13 summarises all the results of average OT, RH and TE in achieved IES simulation 1. According to the ASHRAE 55 and CIBSE Guide A, the recommended indoor design conditions for OT and RH are 24°C to 28°C and 40% to 70% RH respectively. This research has set that over 70% of the total hours in a year, both for OT and RH, shall be within the recommended range. As a result, for the OT, all configurations recorded OT values below the maximum limit of 28°C and three configurations achieved 70% or more of total hours within the recommended OT range (Table 5.13). For RH, no configurations have achieved an average RH below 70% and the percentage of total hours between 40% to 70% RH were more than 70%. Meanwhile, for TE, three configurations achieved the average energy consumption of below 2.0 kW (Table 5.13).

Table 5.13: Summary of OT, RH and TE results in IES simulation 1

Parameters	Unit	25°C & 30 l/s	25°C & 60 l/s	20°C & 30 l/s	20°C & 60 l/s
OT	ºC	27.91	27.37	26.45	25.30
>24-28 ºC<	%	53.1	71.4	89.8	85.7
RH	%RH	80.48	82.43	82.59	87.23
>40-70%RH<	%	4.5	2.3	5.9	1.0
TE	kW	0.786	1.102	1.470	2.309

Based on the findings, simulation 1 recommends that DHCBC system with 20°C and 30 l/s has a great potential for improving thermal comfort. However, this simulation only measured two rooms with the passive light well approach. Thus, another simulation exercise is demanded to validate the results using a more accurate computer model of the actual PPR second generation housing unit by combining an active light-well component.

5.5 Simulation 2: Results and Analysis

5.5.1 Thermal Comfort

Operative Temperature (OT)

For 25°C and 30 l/s configuration, the mean OT was ranged from 28.45°C to 29.36°C. These average mean temperatures were approximately 0.8°C above the recommended OT range's upper value (28°C). For total hours in a year, only 26.3% were within the indoor comfort temperatures while the rest surpassed 28°C (Table 5.14). For the configuration of 25°C and 60 l/s, the mean OT range was from 27.63°C to 28.63°C. The average mean temperature was 0.06°C above the ASHRAE 55 recommended OT limit. For total hours in a year, 51.8% were within the indoor comfort temperatures while the rest were above 28°C (Table 5.15).

Table 5.14: OT percentage hours range for 25°C and 30 l/s configuration

	OT % hours in range	**OT % hours in range**	**OT % hours in range**
Location	**<= 24.00**	**>24.00 to <=28.00**	**> 28.00**
ALW	0	34.8	65.2
MB-1	0	20.8	79.2
LR-DN-20	0	15.6	84.4
BR2-20	0	26.6	73.4
BR3-1	0	38.6	61.4
BR2-1	0	27.5	72.5
LR-DN-1	0	16	84
LR-DN-10	0	16.1	83.9
MB-10	0	20.9	79.1
BR2-10	0	27.6	72.4
BR3-10	0	38.6	61.4
MB-20	0	20.3	79.7
BR3-20	0	38.2	61.8
Total hours (%)	**0**	**26.3**	**73.7**

Table 5.15: OT percentage hours range for 25°C and 60 l/s configuration

	OT % hours in range	**OT % hours in range**	**OT % hours in range**
Location	**<= 24.00**	**>24.00 to <=28.00**	**> 28.00**
ALW	0	35.3	64.7
MB-1	0	47.6	52.4
LR-DN-20	0	33.9	66.1
BR2-20	0	66.9	33.1
BR3-1	0	63.4	36.6
BR2-1	0	68.1	31.9
LR-DN-1	0	34.8	65.2
LR-DN-10	0	34.8	65.2
MB-10	0	47.7	52.3
BR2-10	0	68.2	31.8
BR3-10	0	63.4	36.6
MB-20	0	46.7	53.3
BR3-20	0	62.9	37.1
Total hours (%)	**0**	**51.8**	**48.2**

For the configuration of 20°C and 30 l/s, the mean OT was ranged from 26.85°C to 28.31°C. The average mean temperature was 0.49°C below the ASHRAE recommended operative temperature of 28°C. Among all hours in a year, 67.3% were within the indoor comfort temperatures of 24°C to 28°C while the rest were above 28°C (Table 5.16). For the 20°C and 30 l/s configuration, the mean OT was from 25.11°C to 26.96°C. The average mean temperature was also 0.49°C below the ASHRAE recommended limit. In a year, 87.8% were within the indoor comfort temperature range while 9.9% were above 28°C (Table 5.17).

The IES baseline simulation has suggested that the average OT for a year in Kuala Lumpur was 29.1°C. This value was 1.1°C above the ASHRAE recommended value. By referring to the IES simulation 1 and 2 results, the DHCBC system could reduce the OT values below the ASHRAE 55 limit of 28°C.

In IES 2 simulation, two out of four configurations recorded were below the limit of 28°C (Figure 5.14). Therefore, these configurations that achieved the average OT temperature within or near the limit had the potential to be used in the final system. Figure 5.15 shows the average percentages of total hours between 24°C to 28°C. The highest percentage result was achieved by the configuration that used 20°C and 60 l/s at 87.8% followed by 20°C and 30 l/s at 67.3%.

Table 5.16: OT percentage hours range for 20°C and 30 l/s configuration

Location	OT % hours in range <= 24.00	OT % hours in range >24.00 to <=28.00	OT % hours in range > 28.00
ALW	0	35.7	64.3
MB-1	0	64.4	35.6
LR-DN-20	0	44.1	55.9
BR2-20	0	89.6	10.4
BR3-1	0	80.7	19.3
BR2-1	0	90.4	9.6
LR-DN-1	0	45.4	54.6
LR-DN-10	0	45.5	54.5
MB-10	0	64.6	35.4
BR2-10	0	90.5	9.5
BR3-10	0	80.7	19.3
MB-20	0	63.2	36.8
BR3-20	0	80.3	19.7
Total hours (%)	**0**	**67.3**	**32.7**

Table 5.17: OT percentage hours range for 20°C and 60 l/s configuration

Location	OT % hours in range <= 24.00	OT % hours in range >24.00 to <=28.00	OT % hours in range > 28.00
ALW	0	36.5	63.5
MB-1	1	98	1
LR-DN-20	0	78.8	21.2
BR2-20	3.1	96.9	0
BR3-1	5.5	94.3	0.3
BR2-1	3.3	96.7	0
LR-DN-1	0	79.7	20.3
LR-DN-10	0	79.8	20.2
MB-10	1	98	1
BR2-10	3.3	96.7	0
BR3-10	5.5	94.3	0.3
MB-20	1	97.9	1.1
BR3-20	5.3	94.4	0.3
Total hours (%)	**2.2**	**87.8**	**9.9**

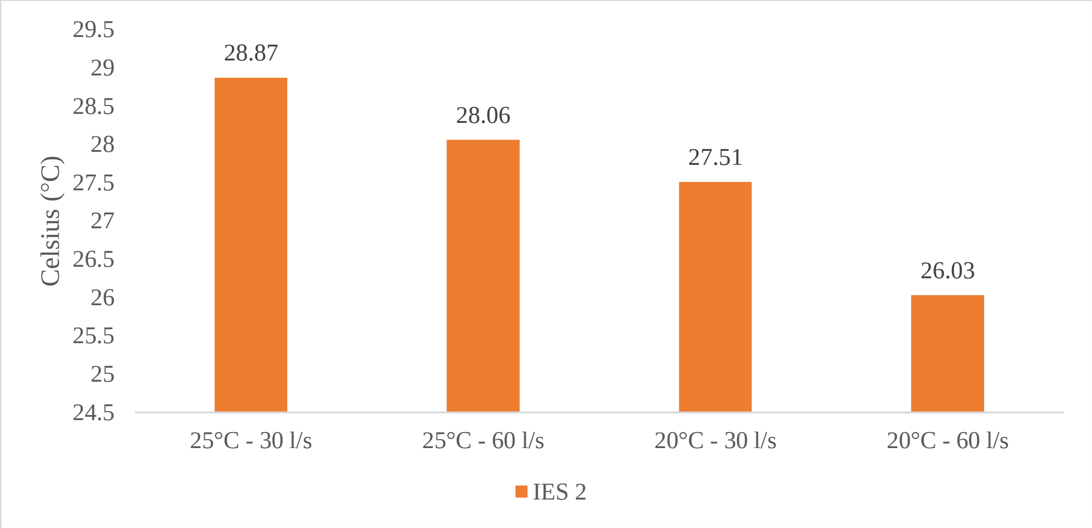


Figure 5.14: Average OT results in IES 2 simulation

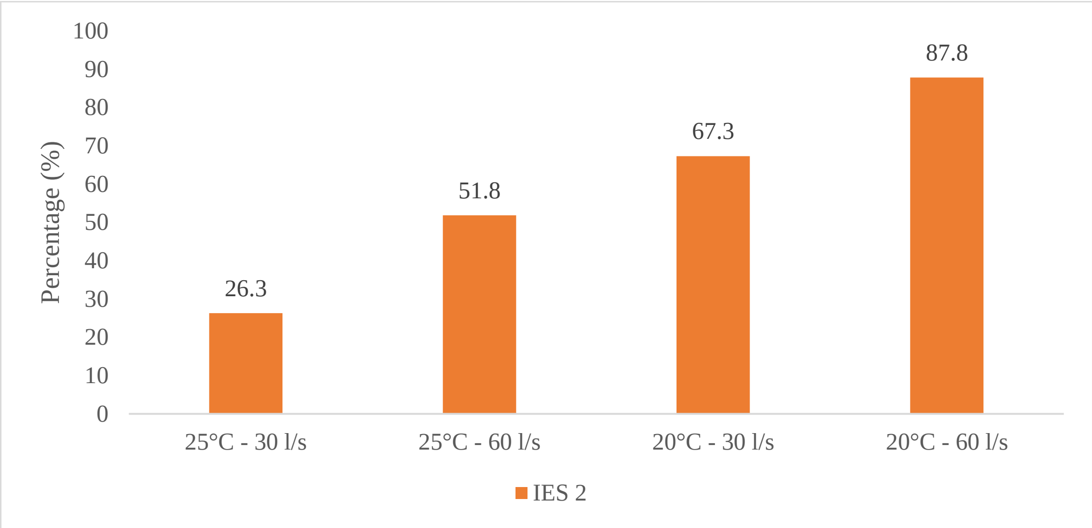


Figure 5.15: Percentages of total hours for OT in between 24-28^{o}C

Relative Humidity (RH)

Table 5.18 lists the RH results for 25°C and 30 l/s configuration. The minimum RH was ranged between 42.91% to 45.92% RH and the mean temperatures were in the range of 74.09% to 76.52% RH. For the percentage hours range, only 16.8% hours in a year were within the comfort RH range of 40% to 70% RH and the rest were above 70% RH (Table 5.18). For 25°C and 60 l/s configuration, the minimum RH range was between 44.47% to 48.48% RH and the mean temperatures were in the range of 76.12% to 80% RH. For the percentage hours range, only 8% hours in a year were within the comfort RH range and the rest were above 70% RH (Table 5.19).

Table 5.18: RH's percentage hours range for 25°C and 30 l/s configuration

	RH % hours in range	RH % hours in range	RH % hours in range
Location	**<= 40.00**	**>40.00 to <=70.00**	**> 70.00**
ALW	0.1	29.7	70.2
MB-1	0	21.3	78.6
LR-DN-20	0	22.7	77.2
BR2-20	0	9	91
BR3-1	0	10.5	89.5
BR2-1	0	8.7	91.3
LR-DN-1	0	21.6	78.3
LR-DN-10	0	21.5	78.4
MB-10	0	21.2	78.7
BR2-10	0	8.7	91.3
BR3-10	0	10.5	89.5
MB-20	0	22	77.9
BR3-20	0	10.7	89.3
Total hours (%)	**0**	**16.8**	**83.2**

Table 5.19: RH's percentage hours range for 25°C and 60 l/s configuration

	RH % hours in range	RH % hours in range	RH % hours in range
Location	**<= 40.00**	**>40.00 to <=70.00**	**> 70.00**
ALW	0.1	29.2	70.7
MB-1	0	7.2	92.8
LR-DN-20	0	12.7	87.3
BR2-20	0	2.4	97.6
BR3-1	0	3.1	96.9
BR2-1	0	2.3	97.7
LR-DN-1	0	12.2	87.8
LR-DN-10	0	12.2	87.8
MB-10	0	7.1	92.9
BR2-10	0	2.3	97.7
BR3-10	0	3.1	96.9
MB-20	0	7.5	92.5
BR3-20	0	3.2	96.8
Total hours (%)	**0**	**8**	**91.9**

Table 5.20 lists the RH results for 20°C and 30 l/s configuration. The minimum RH range was between 47.13% to 51.27% RH and the mean temperatures were ranged at 66.11% to 69.49% RH. For the percentage hours range, 61.7% hours in a year were within the comfort RH range and the rest were above 70% RH. For 20°C and 60 l/s

configuration, the minimum RH range was between 52.72% to 57.08% RH and the mean temperatures were in the range of 69.52% to 76.41%RH. For the percentage hours range, only 21.2% hours in a year were within the comfort RH range and the rest were well above 70% RH (Table 5.21).

Table 5.20: RH's percentage hours range for 20°C and 30 l/s configuration

	RH % hours in range	RH % hours in range	RH % hours in range
Location	**<= 40.00**	**>40.00 to <=70.00**	**> 70.00**
ALW	0.1	28.8	71.1
MB-1	0	69.6	30.4
LR-DN-20	0	77	23
BR2-20	0	55.8	44.2
BR3-1	0	56.2	43.8
BR2-1	0	54.5	45.5
LR-DN-1	0	76.6	23.4
LR-DN-10	0	76.6	23.4
MB-10	0	69.5	30.5
BR2-10	0	54.4	45.6
BR3-10	0	56.1	43.9
MB-20	0	70	30
BR3-20	0	56.7	43.3
Total hours (%)	**0**	**61.7**	**38.3**

Table 5.21: RH's percentage hours range for 20°C and 60 l/s configuration

	RH % hours in range	RH % hours in range	RH % hours in range
Location	**<= 40.00**	**>40.00 to <=70.00**	**> 70.00**
ALW	0.1	28	72
MB-1	0	21.6	78.4
LR-DN-20	0	52.2	47.8
BR2-20	0	1.1	98.9
BR3-1	0	8.3	91.7
BR2-1	0	0.9	99.1
LR-DN-1	0	50.9	49.1
LR-DN-10	0	50.8	49.2
MB-10	0	21.4	78.6
BR2-10	0	0.9	99.1
BR3-10	0	8.3	91.7
MB-20	0	22.7	77.3
BR3-20	0	8.6	91.4
Total hours (%)	**0**	**21.2**	**78.8**

Figure 5.16 shows the comparison of the average RH results in IES 2 simulation. The IES baseline simulation proposed that the average RH in a year in Kuala Lumpur to be 66.43% RH. According to the IES simulation 2 results, the lowest average RH recorded by the 20°C and 30l/s configuration and the other configurations recorded the average RH results above 70% RH. Thus, the application of 20°C of supply air temperature with 30 l/s of airflow was validated and could achieve the required RH of below 70%. Referring to the same results, the configuration that used 20°C and 30 l/s was the most convincing configuration that can achieve 61.7% of total hours between 40% and 70% RH (Figure 5.17). This is due to the configuration that controls the indoor spaces in good moisture content compared to the other configurations. The 20°C of supply air temperature was cool enough to change moisture into liquid and 30 l/s of airflow rate was sufficient to make the humidity condensate.

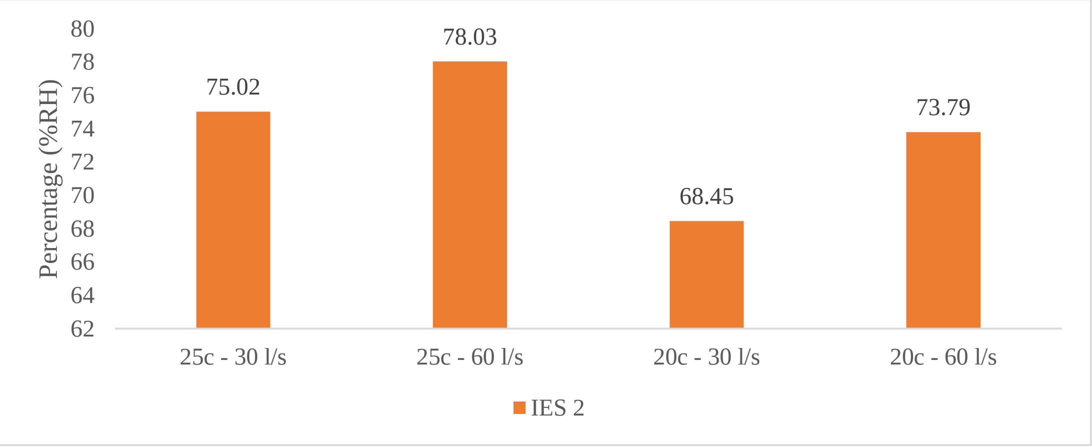


Figure 5.16: Average RH results in IES 2 simulation

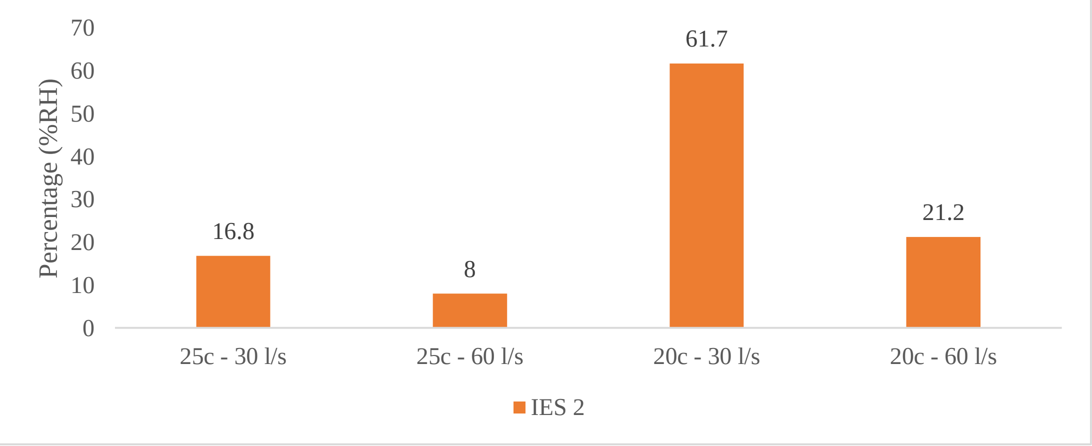


Figure 5.17: Percentage of total hours for RH in between 40-70%RH

5.5.2 Discussion

Table 5.22 lists the mean OT and percentages of total hours within 24°C to 28°C range for ALW. Despite different configurations being applied in simulation 2, the mean OT values for ALW were consistent within the range of 28.74°C to 28.83°C. For the percentage hours range, ALW recorded consistent results between 34 % to 37% hours in the range 24°C to 28°C. Table 5.23 lists the mean RH readings and percentages of total hours within 40% to 70% RH range for ALW. Similar like OT, the mean RH for ALW was also consistent within the range of 73.85°C to 74.26°C and between 28% to 30% hours in range of 40% to 70% RH.

It could be deduced that a constant airflow within the ALW compound has successfully maintained the OT and RH levels. The average levels of mean OT and RH (28.8°C and 74% RH) slightly surpassed the upper limits of ASHRAE 55 limits. However, this condition was acceptable as this was an uninhabited space. As mentioned in Chapter 3, the actual passive light-well has reduced the thermal conditions in the rooms adjacent to it, thus, transforming this space to be an active element that could create a steady-state condition within acceptable boundaries.

Table 5.22: Mean OT and percentages of total hours within 24-28°C for ALW

Configurations	Mean OT (°C)	% Hours in Range 24-28°C
25°C and 30 l/s	28.83	34.8
25°C and 60 l/s	28.81	35.3
20°C and 30 l/s	28.79	35.7
20°C and 60 l/s	28.75	36.5

Table 5.23: Mean RH and percentages of total hours within 40-70%RH for ALW

Configurations	Mean %RH	% Hours in Range 40-70%RH
25°C and 30 l/s	73.85	29.7
25°C and 60 l/s	73.95	29.2
20°C and 30 l/s	74.02	28.8
20°C and 60 l/s	74.19	28.0

Table 5.24 lists the total system energy (TE) results for every configuration. Similar to the simulation 1 results, the configuration that used the least energy consumption was 25°C and 30 l/s and the highest was 20°C and 60 l/s configuration.

These results were expected because of the high energy demand to cool the chilled water to 20°C compared to 25°C and the energy consumption for turning the fan to 60 l/s rather than 30 l/s. However, there were three configurations that achieved total system energy consumption below 2.0 kW; 25°C and 30 l/s (0.995 kW), 25°C and 60 l/s (1.396 kW), and 20°C and 30 l/s (1.861 kW).

Table 5.24: Total system energy results

Configuration	Type	Mean
20°C and 60l/s	Power (kW)	2.924
20°C and 30l/s	Power (kW)	1.861
25°C and 60l/s	Power (kW)	1.396
25°C and 30l/s	Power (kW)	0.995

Based on the OT and RH results in this simulation 2, the best configuration determined in this simulation was 20°C and 30 l/s. Having three housing samples in this simulation 2 model located at level 1, 10 and 20, the total system energy for each housing unit (when using DHCBC system with 20°C and 30 l/s configuration) was 1.861 kW (Figure 5.18). This means that in a year, every house that uses DHCBC system will consume approximately 679.27 kWh/year for cooling purposes. According to a study done in Malaysia, the annual energy consumption for cooling (air-conditioning and ceiling fans) in a housing unit accounted for 29% (1,973.6 kWh/year) of the total annual energy demand (6,805.6 kWh/year) (Kubota, Jeong, Toe, & Ossen, 2011). Similarly, the DHCBC system also provides cooling through the chilled beam system and fans but in a more economical way. It can be deduced that, by using this system, the energy demand for cooling purposes could be reduced up to 66%.

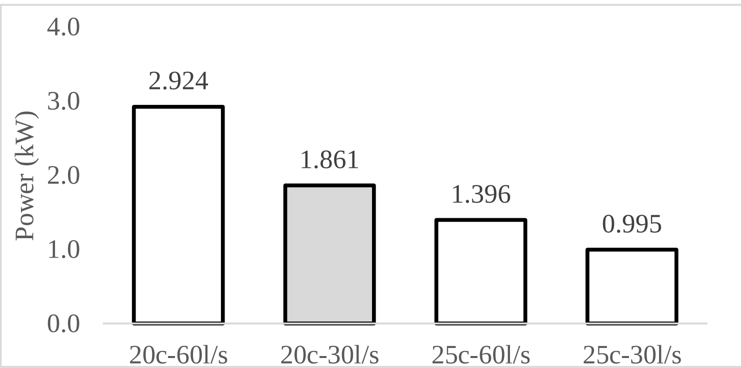


Figure 5.18: Total system energy for the tested combinations

It should be borne in mind that the energy savings results obtained in these simulations were simply estimated by calculating the electricity consumption of a chilled water loop system combined with supply and extract fans employed in a number of rooms in a housing unit. A very detailed electricity usage analysis and potential savings would represent a significant task, given the very large number of variables involved, and was considered to be beyond the scope of this study.

Table 5.25 lists the summary of the average OT, RH and TE results in IES simulation 2. According to ASHRAE 55 and CIBSE Guide A, the recommended indoor design conditions for operative temperature and relative humidity are 24°C to 28°C and 40% to 70% RH respectively. Based on the ranges, the only configuration that complies with both conditions was 20°C and 30 l/s. These results were consistent with the simulation 1 results and validated the configuration which was to be used in the final system.

Table 5.25: Summary of Average OT, RH and TE results in IES 2 simulation

Parameters	**25°C & 30 l/s**	**25°C & 60 l/s**	**20°C & 30 l/s**	**20°C & 60 l/s**
OT (°C)	28.87	28.06	27.51	26.03
24-28 °C	26.3	51.8	67.3	87.8
RH (%RH)	75.02	78.03	68.45	73.79
40-70%RH	16.8	8	61.7	21.2
TE (kW)	0.995	1.396	1.861	2.924

Table 5.26 shows the conversion results of OT and RH by using DHCBC results and DHAPC reduction rates. Using the DHCBC system as achieved by 20°C and 30 l/s configuration in IES simulation 2, the average OT and RH were 27.5°C and 68.5% RH respectively. The DHAPC reduction rates for OT and RH using hybrid-positive (F-B) protocol are 14.1% and 14.0%. Thus, when the DHAPC rates and DHCBC results were combined, the final average for OT was 23.6°C and RH was 58.9% RH. Meanwhile, if the 20°C and 30 l/s configuration results were converted using hybrid-negative (B-F) ventilation protocol, the final average for OT was 23.5°C and RH was 61.6% RH. When both systems were being integrated, both ventilation protocols complied with the recommended limits.

Table 5.26: Conversion Results Using DHAPC Reduction Rate

Config.	Parameters	DHCBC Average (IES2)	DHAPC Rate (%)	Results	Complied
F-B	Operative Temperature	27.5 °C	14.1	23.6°C	√
	Relative Humidity	68.5%RH	14.0	58.9%RH	√
B-F	Operative Temperature	27.5 °C	14.4	23.5°C	√
	Relative Humidity	68.5%RH	10.1	61.6%RH	√

The psychrometric chart (Figure 5.19) shows the indoor comfort zone (green area) for Kuala Lumpur which was set according to ASHRAE 55 and CIBSE Guide A. The actual indoor thermal conditions for a year in Kuala Lumpur, based on IES baseline simulation were 29.1°C for operative temperature and 66.4% RH for relative humidity. The two final averages of 20°C and 30 l/s configuration using B-F and F-B ventilation protocols were tabulated on the chart (Figure 5.19). It shows that the average results in terms of OT were located outside the comfort zone and close to the dew point temperature limit. This suggested that the integrated system (DHAPC and DHCBC) achieved the lowest requirement of OT that this research could propose – circa 23°C. For relative humidity, the average results were located in the middle of the comfort zone – circa 60%RH.

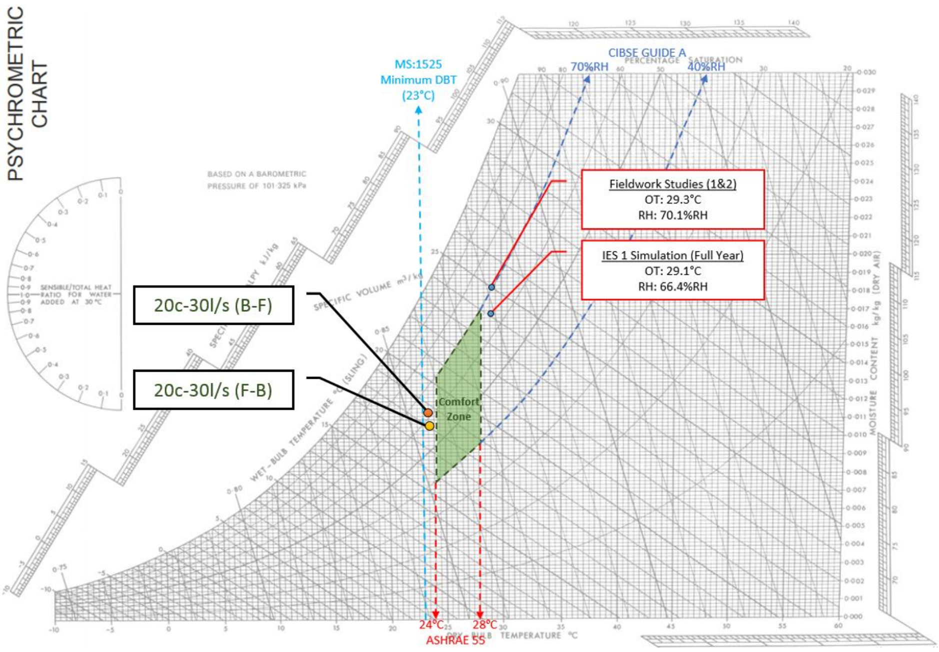


Figure 5.19: Tabulation of the final average results on the psychrometric chart

Given the above findings, using these systems, additional airflow would enter the light-wells from the housing units via exhaust fans, hence, without an active mechanism, this airflow would create a short circuit of air movement in the light-wells. It is worthwhile to suggest that high-rise residential buildings shall apply the active light-wells technique to control the excessive airflow from directly affecting the thermal comfort (temperature, humidity and airflow) and indoor air quality in the light-wells and concurrently the housing units.

5.6 Summary of All Results

As a conclusion, the combination of DHAPC and DHCBC systems could achieve the recommended indoor comfort and air quality in the housing units as suggested by the established international and local standards. These systems reduce the ambient air temperature and humidity up to 20% and 14% respectively and also efficiently filter the particulate matters and toxic gases circa 90% from the incoming outdoor air intake.

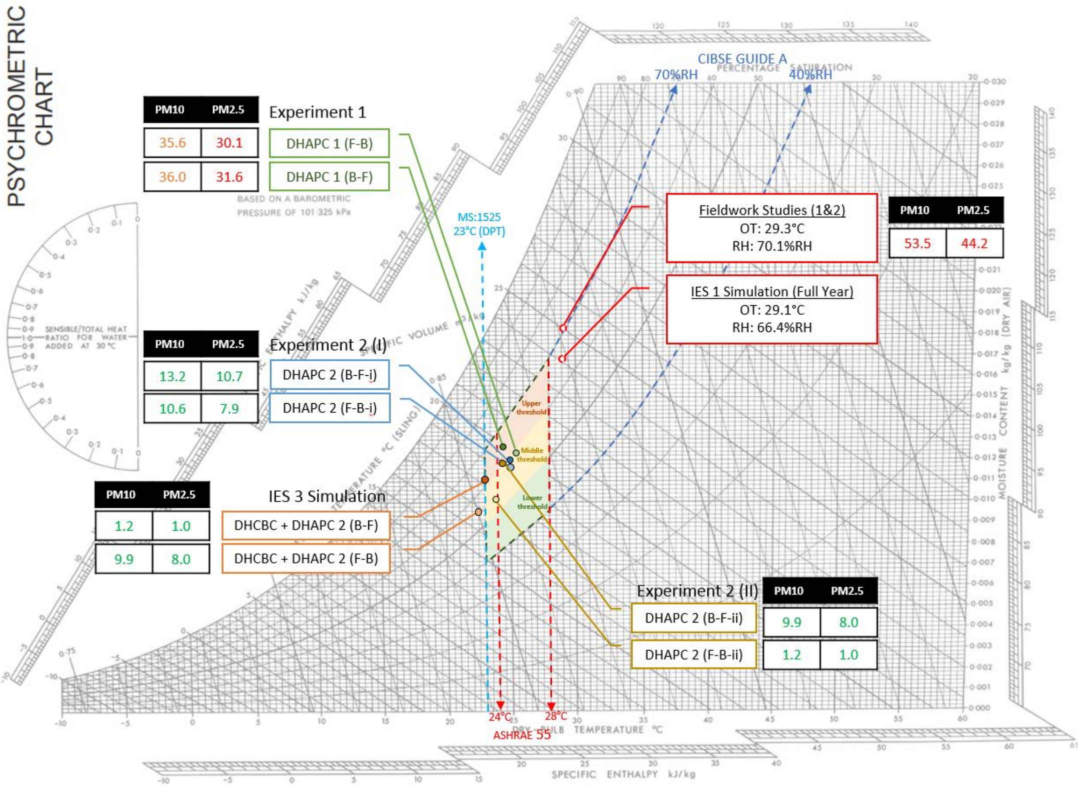


Figure 5.20: The tabulation of all results from fieldwork studies, physical tests and IES simulations on the psychrometric chart (Appendix 1J).

Figure 5.20 shows the tabulation of all results from the fieldwork studies, physical tests and IES simulations on a psychrometric chart. It shows that the average results of OT, RH, PM_{10} and $PM_{2.5}$ significantly dropped to the lower threshold of the comfort zone. In terms of thermal comfort, both systems when being combined, produced the maximum reduction rate for temperature from 29.1°C to 23.5°C and for humidity from 66.4% to 57.4%. Meanwhile, for indoor air quality, these systems reduced PM_{10} levels from 53.5 µg/m^3 to 1.2 µg/m^3 and $PM_{2.5}$ levels from 44.2 µg/m^3 to 1.0 µg/m^3. It could be concluded that the integration of these systems could provide thermal comfort and 'healthy' indoor air quality in high-rise residential buildings.

On the success of this integrated system, it could be concluded that these two systems could be well integrated which shall establish a new set of conditions for the 'Airhouse' Concept. The next chapter discusses in detail the technical aspects in implementing the 'Airhouse' Concept in the real context of high-rise social housing in Kuala Lumpur. The application of the concept in new buildings is also explained in detail.

6 CHAPTER 6: Discussion and Refining the 'Airhouse' Concept

6.1 Key Findings

This chapter discusses the physical applications of the 'Airhouse' Concept into the real context of high-rise social housing in Kuala Lumpur. The applications of the system in the existing and new buildings are explained in detail in this chapter. This chapter also concludes the impact of 'Airhouse' Concept on housing development in Malaysia for short, medium and long terms including its benefits as a fire control mechanism. It also predicts and suggests the implication of this research in the building industry in Malaysia and other tropical countries.

As explained in Chapter 5, the thermal comfort performance could be improved by integrating the DHCBC system in tandem with the main system (DHAPC). As mentioned in Chapter 4, when the DHAPC system works in isolation, it can achieve the right indoor comfort and air quality conditions as set by several established international and local standards. The system reduces the heat and moisture circa 16% while the airborne particles and toxicant gases circa 90%. Thus, activating the DHCBC system in tandem could further improve the thermal conditions (temperature and humidity) performance up to another 10% to 20%. The integration of these systems has formed a new concept called 'Airhouse'.

This research has suggested that the concept works well with the hybrid ventilation protocols – hybrid-positive and hybrid-negative. The hybrid-positive protocol has consistently produced better results than the hybrid-negative protocol, especially for air quality (particulate matter reductions – circa 15%) but for thermal comfort criteria (temperature and humidity) both protocols achieved almost similar performance. Given the above findings, the hybrid-positive protocol has a slight advantage, however, in a larger space, the hybrid-negative protocol is also needed. Especially for sucking indoor contaminants out from the internal space.

Therefore, these ventilation protocols are designed to have a certain level of controls by the end-users according to their needs. Meaning that the ventilation protocols can be activated and deactivated at any time as required by the occupants. It is suggested that every room should be equipped with a device that can monitor the actual thermal and air quality conditions. As technologies in these areas are actively developing in many countries, the availability of such reliable devices at affordable prices is considerably high.

Through this research, it can be seen that the DHAPC system could be considered as the main system in the ‘Airhouse’ Concept while the DHCBC is only a supporting system. This system can provide additional reduction rates for temperature and humidity circa 10% only. It is worth to be used during the hottest times of the day only. As a hybrid system, DHAPC requires energy only for its fans. Thus, it consumes a very minimum energy consumption but yet could provide the right indoor comfort and air quality conditions. Given the above explanation, the ‘Airhouse’ Concept has a great potential to be implemented in housing development in Malaysia, not only for high-rise but also to all types of buildings.

Fortunately, the conventional construction methods in Malaysia is already in place in adapting to this system. Even though the Uniform Building By-Law (UBBL) – Clause 44(1a) has set the minimum height of living rooms and bedrooms that should not be less than 2,500 mm (UBBL, 2013), these rooms have commonly been built with higher height – between 3,000 mm to 3,500 mm. It is for allowing the ceiling fans to be installed as they are considered as a basic requirement in buildings in Malaysia. This readily available extra space could be added and transformed with the ‘Airhouse’ Concept systems. In the short-term overview, the application of the concept in the construction industry in Malaysia is possible to be achieved in less than five years, both for existing and new buildings.

Through this research, recycled materials such as plastic, wool and glass, have achieved excellent results in filtering the airborne particulate matter. The reduction rates were circa 55%, 65% and 80% for recycled plastic, recycled wool and recycled glass respectively. The results could give positive insight on the current efforts by the Malaysian government to reuse and recycle the existing waste stock in the country. In the medium-term overview, this concept could help to significantly reduce the existing waste stock in the next five to ten years’ time.

The conventional HVAC approaches – such as air conditioning systems, can improve thermal comfort in tropical countries. However, they create high energy demand, produce high carbon emissions and require high maintenance. As tested in several methodologies in this research, the 'Airhouse' Concept has successfully addressed the thermal comfort and air quality issues with low energy consumption and low carbon emissions. This solution has high commercial values in the long-term overview. The standard can be widely implemented not only in Malaysia but also in other tropical countries.

6.2 Refining the 'Airhouse' Concept in High-Rise Social Housing Buildings

As explained in detail in chapter 2, the first 'Airhouse' Concept has been established by the author in 2012 (Mohd Sahabuddin & Gonzalez-Longo, 2015). However, the concept was set entirely in response to the natural ventilation approaches without the awareness of outdoor air quality conditions in Kuala Lumpur. Based on that reason, this research has re-visited and refined the concept with some improvements on the existing conditions and insertions of indoor air quality criteria (Table 6.1).

In general, all the new proposed criteria are set lower than the previous values. For thermal comfort conditions, the new recommendation for air temperature is set between 23°C to 24°C where the previous value was 25°C to 27°C. For humidity, a 5% improvement is suggested from maximum 60%RH to 55%RH, and for air movement, it has been reduced from 0.3 to 1.5 m/s to the minimum of 0.125 m/s. The two criteria for indoor air quality set the values for PM_{10} and $PM_{2.5}$ which should be no more than 1.2 µg/m^3 and 1.0 µg/m^3 respectively (Table 6.1).

For energy consumption and carbon emissions, the previous recommendations have set that they should be less than 5,000 kWh/year and 2,500 kgCO_2/year respectively. These values were set high and the new values have set much lower figures of less than 700 kWh/year and 200 kgCO_2/year for energy consumption and carbon emissions, respectively. The old version of the concept emphasised on natural ventilation with passive openings strategy while the new concept has introduced a hybrid ventilation approach with active light-well in tandem (Table 6.1).

Table 6.1: Comparison of the initial 'Airhouse' Concept (2012) and the new concept (2019)

	Recommendations	Initial 'Airhouse' (2012)	New 'Airhouse' (2019)
Thermal	Air Temperature	25 – 27°C	23 – 24°C
	Humidity	30 – 60%RH	< 55%RH
	Air Movement	0.30 – 1.5 m/s	> 0.125 m/s
IAQ	PM_{10} level	-	< 1.2 µg/m^3
	$PM_{2.5}$ level	-	< 1.0 µg/m^3
Additional	Energy Consumption	< 5,000 kWh/year	< 700 kWh/year
	Carbon Emissions	< 2,500 kgCO_2/year	< 200 kgCO_2/year
	Ventilation Approach	Natural	Hybrid
	Tandem Strategy	Hierarchy of Openings	Active Light-Well

The previous recommendations only emphasised in promoting air movement using passive elements such as opening ratios according to altitude, the hierarchy of opening design and effective plan layout to achieve thermal comfort (Mohd Sahabuddin & Gonzalez-Longo, 2015). On the contrary, to achieve indoor comfort conditions (thermal and health), the new recommendations emphasise the use of an integrated strategy of dynamic insulation, hybrid ventilation and radiant cooling ceiling. These improvements reflect the actual conditions of thermal and health in high-rise social housing in Kuala Lumpur.

As proven through a series of physical experiments (as explained in Chapter 4) and computational simulations (as explained in Chapter 5), it was found that DHAPC is capable to filter the heat, moisture, particulate matter and toxicant gases while DHCBC can further reduce the air temperature and humidity. As a result, the cool and clean air could be supplied into the indoor spaces with a constant and adequate air flow rate. This result will improve the indoor comfort and air quality and solve the problems of indoor discomfort and indoor air pollution. Following the successful achievement by DHAPC and DHCBC systems in a social housing prototype model, it is highly encouraged that the combination of these systems which is called the 'Airhouse' Concept should be implemented in a real housing project.

6.2.1 Application in Existing Buildings

The People's Housing Programme (PPR) across Malaysia is developed by the Ministry of Urban Wellbeing, Housing, and Local Government of Malaysia (KPKT). PPR is a part of the Malaysian Government initiatives to build one million affordable housing units across the country, and approximately more than 80,000 PPR units were built from 1998 to 2016 (MAMPU, 2016b). Based on the figure, nearly 50% of the units are located in Kuala Lumpur and all of them are in high-rise format (DBKL, 2019).

The typical construction method for the PPR second generation is concrete 'post and beam' and single-layer brick wall from ground to the top level of the block. Ceiling fans are included in the building design from the beginning, thus, a net gap of 600 mm in between concrete slab soffit and beams is available (Figure 6.1 and Figure 6.2). This space is for allowing the installation of the fans and lightings. Therefore, it also can be used for installing this new system in the building.

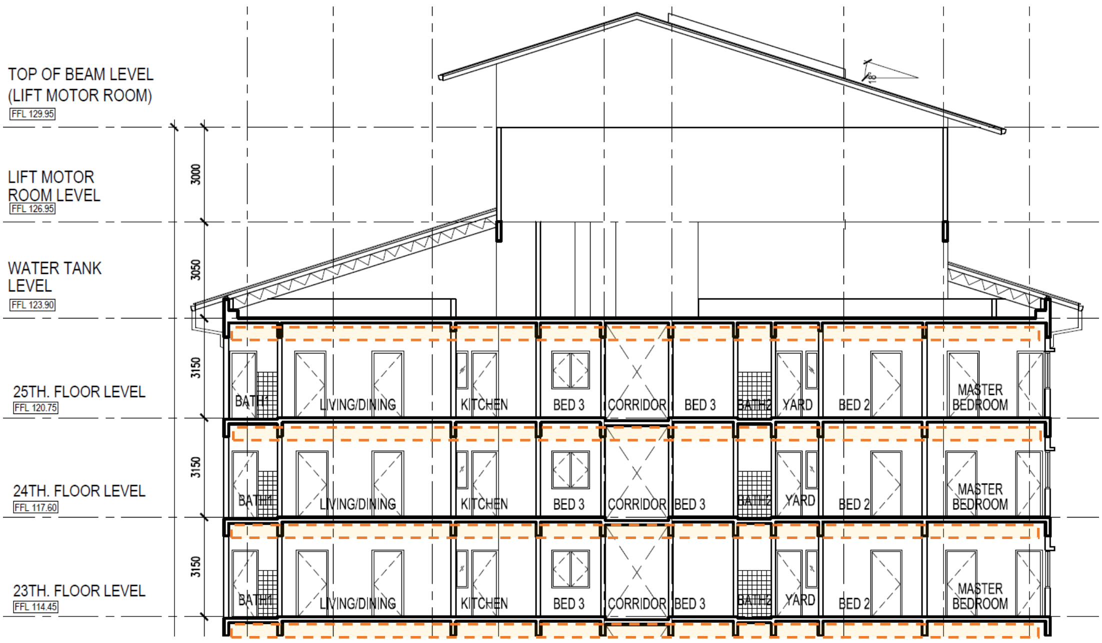


Figure 6.1: Typical section of PPR second-generation (Drawing courtesy from KPKT)

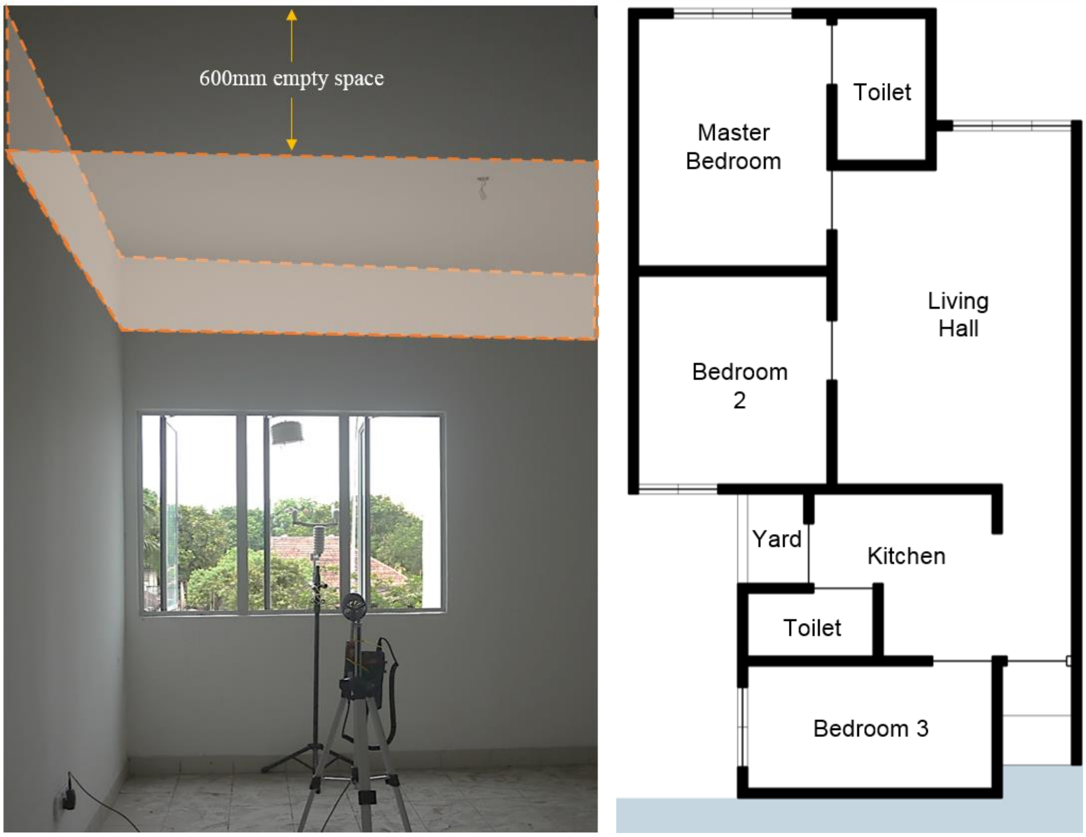


Figure 6.2: The empty space location and typical layout plan

In this social housing unit, there are four habitable rooms – living, dining hall, master bedroom, bedroom 2 and bedroom 3. There are also three supporting spaces such as kitchen, yard and bathrooms (Figure 6.2). Hence, the application of this system will only cater to the habitable rooms. The installation of the system starts with the placement of the DHCBC system. In the first stage, coil pipes, copper-plated aluminium plates, condensate water tray and condensate water pipe are installed and attached to the floor slab soffit.

Then, the DHAPC membrane, together with an activated carbon layer (on top of the membrane), will be placed. An aluminium perforated ceiling which could allow air flows through is used to hold the membrane and activated carbon layer. While the system is in operation, the housing unit shall be airtight to achieve the right results. Thus, the design of the windows shall be used in two situations – airtight, which means fully sealed and penetrable, which opens to airflow. Casement aluminium windows with side hung are suitable to be used in this system.

One of the important parts in this system is the coil pipes and copper-plated aluminium plates. These parts are important to create radiant cooling effects. The chilled water of 15°C will flow inside the coil pipes to collect the heat from the air inside the DHAPC compartment which is supplied by a fan. The copper-plated aluminium plates, at the same time, with its large accumulated surface areas will provide assistance on collecting the heat. The 15°C cold water flows (1.1 l/s) inside the coil pipes and passes through the aluminium plates to reduce the air temperature by convection and radiation from 35°C (maximum outside air temperature) to 25°C (designed indoor air temperature).

Table 6.2 lists the detail measurement of the coil pipes and aluminium plates required for each room to fulfil the cooling requirement. Using computational methods, for the master bedroom (A) with 37.8 m^3, it is recommended that the coil pipes length shall be approximately 10 metres with 20 mm diameter. The numbers of aluminium plates required are 150 pieces with dimension 0.2 x 0.2 m for each plate. This will create an area of 6.0 m^2 for radiant cooling. For bedroom 2 (B), to cool a space with 33.8 m^3, approximately 8.5 metres of coil pipe is needed and 136 pieces of aluminium plates. These aluminium plates, in the total surface, will create 5.5 m^2.

Table 6.2: Details of coil pipes and aluminium plates

Rooms	**Volumes** (m^3)	**Coil Pipe Length** (20mm Ø)	**Aluminium Plates Quantities** (200 x 200mm)	**Aluminium Plates Surface Areas** (m^2)
A) Master Bedroom	37.8	10.0 metres	150 pieces	6.0
B) Bedroom 2	33.8	8.5 metres	136 pieces	5.5
C) Living Room	57.9	15.0 metres	230 pieces	9.0
D) Bedroom 3	28.2	7.0 metres	114 pieces	4.5

The living room (C) is the largest space in the PPR second-generation unit with 57.9 m^3. Thus, it needs 15 m long of coil pipes and 230 pieces of aluminium plates. The plates create a 9.0 m^2 to absorbing heat and the coil pipes for radiant cooling. The smallest room in this unit is bedroom 3 (D) with 28.2 m^3. The requirement for radiant cooling purposes is 7 metres of coil pipes and 114 of aluminium plates that in total, create a 4.5 m^2 of absorption surface. Figure 6.3 shows the actual design of the coil pipes and aluminium plates for each room.

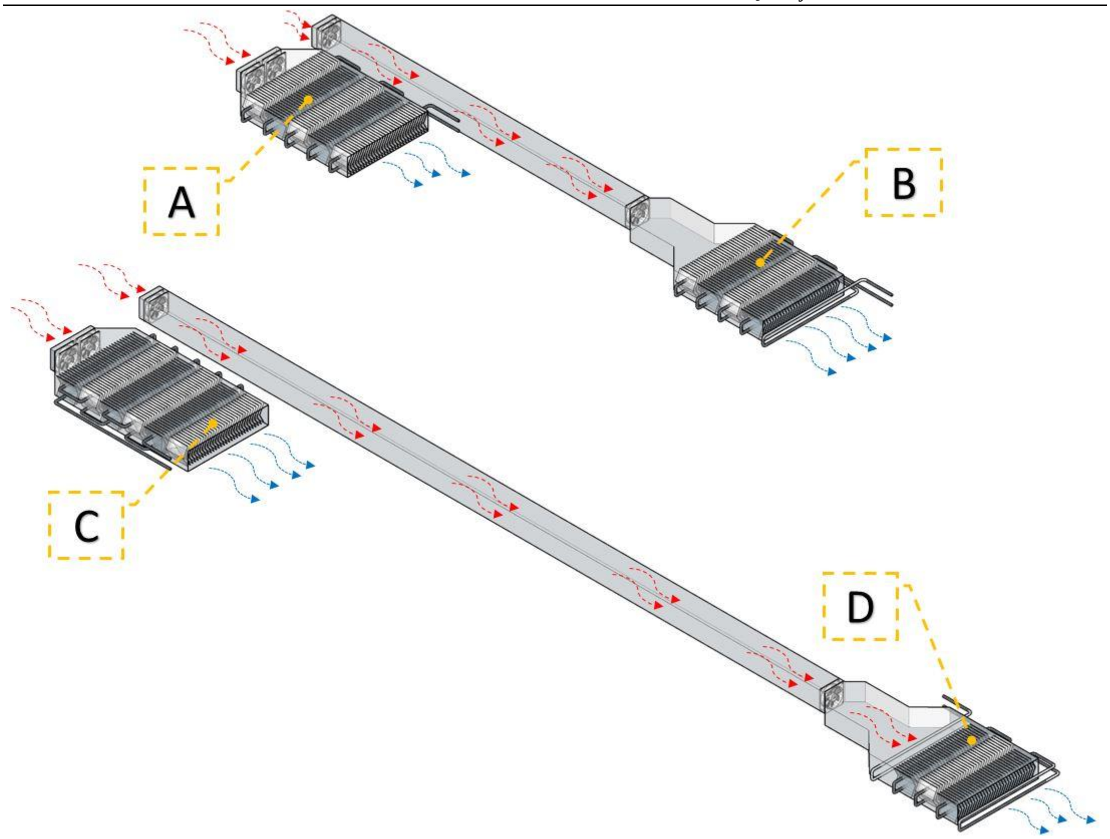


Figure 6.3: Design of the coil pipes and aluminium plates.

Figure 6.4 shows the arrangement of the coil pipes and aluminium plates. With the 'V' shape and compact arrangement of the plates, the air that flows through these parts will get maximum contact. Chilled water with low flow (1.1 l/s) inside the coil pipes maximising the radiant cooling effect.

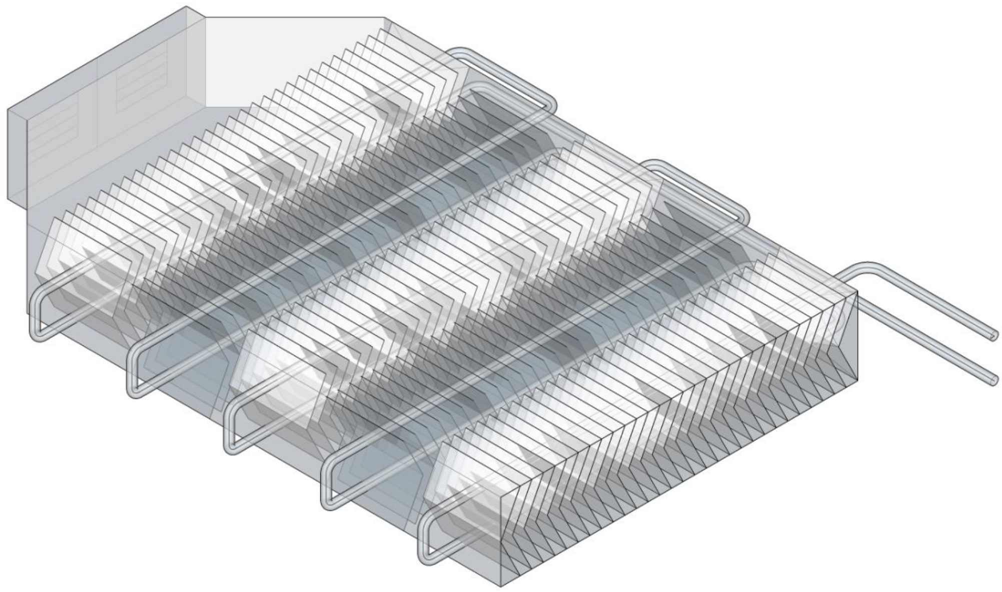


Figure 6.4: Close-up look of the coil pipes and aluminium plates design

As the cooling requirement for the air supply temperature is 25°C, chilled water at 15°C is circulated in the coil pipes to achieve the required temperature. This water is supplied from a central chiller unit located at rooftop level (Figure 6.5 and Figure 6.6). There is a temporary chilled water tank for every housing unit to regulate the water flow to the desired pressure before the water enters the coils.

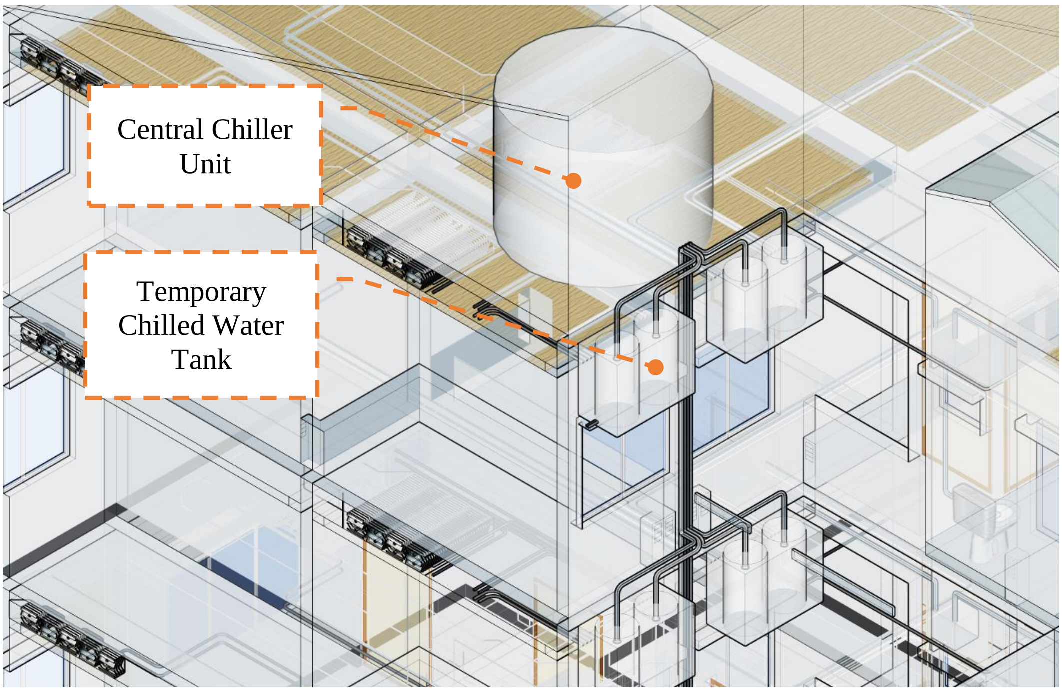


Figure 6.5: Location of the central chiller unit at rooftop level

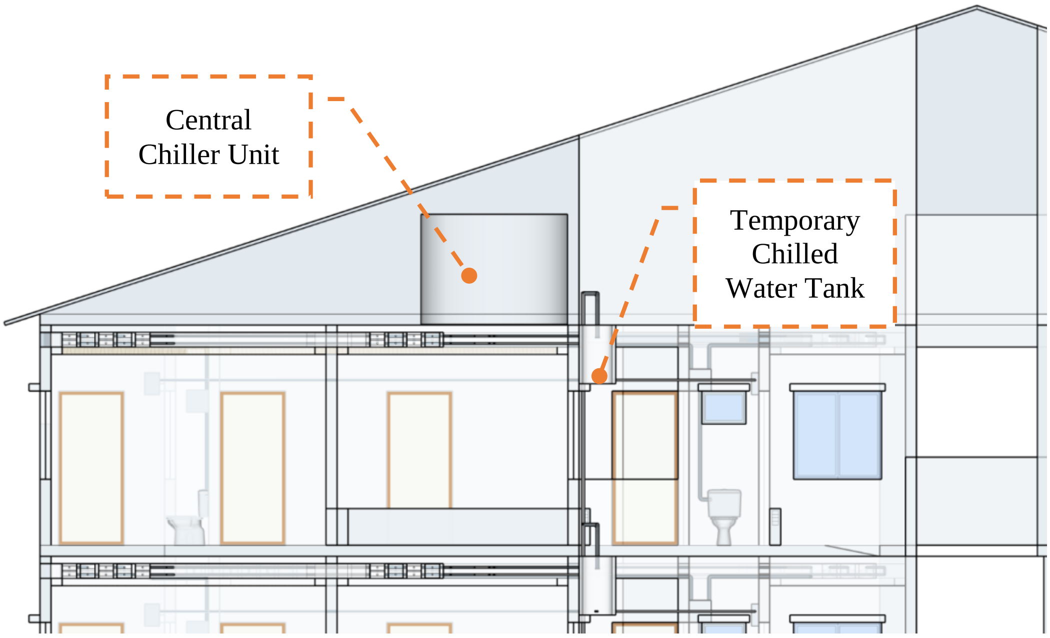


Figure 6.6: Location of the central chiller tank and temporary chilled water tank.

Figure 6.7 shows the location of the central chiller water tanks in PPR second generation block. Eight tanks will be located near the eight light-wells in this block. For energy efficiency, each tank will cater for 50 housing units only.

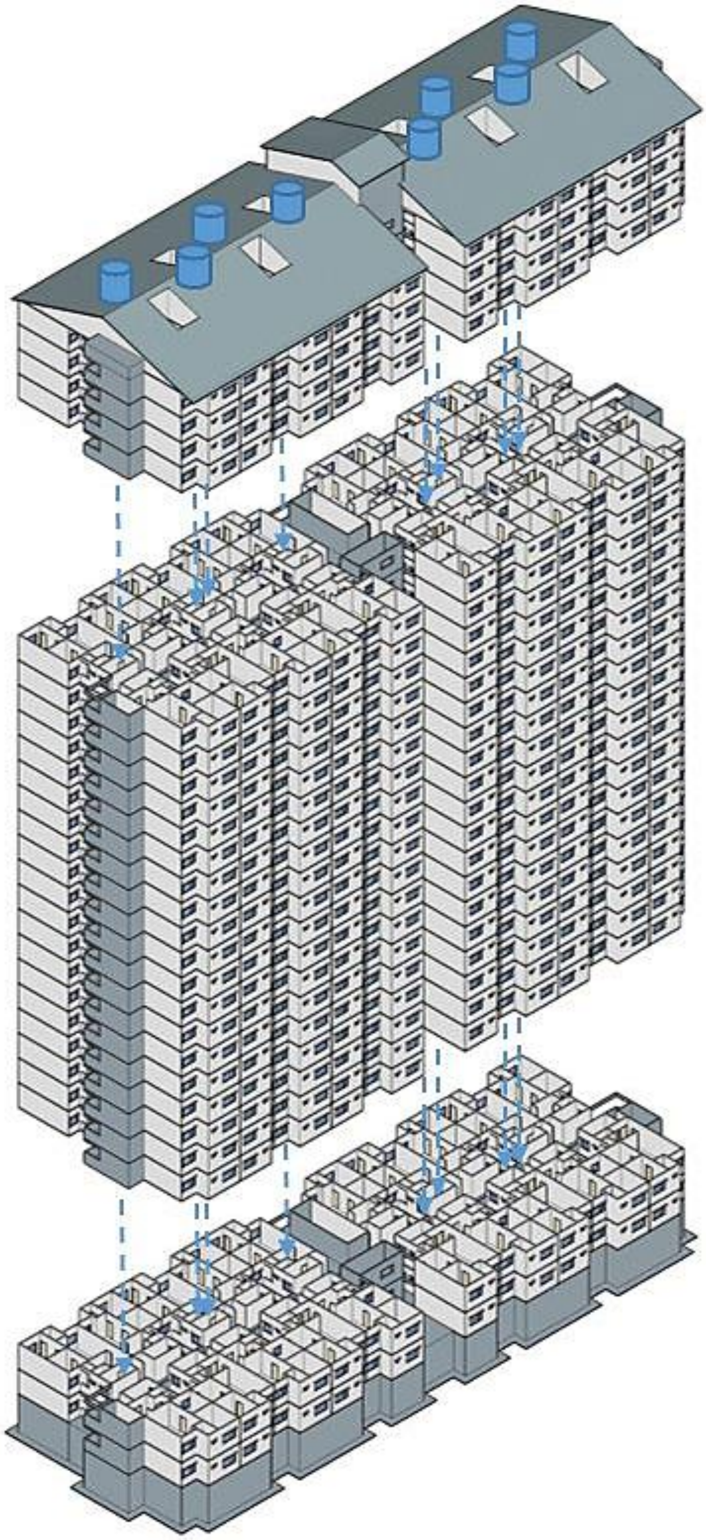


Figure 6.7: Location of central chiller water tanks in PPR second-generation block

As the finned pipes are below dew point temperature, the condensation is collected and channelled via the metal trays to the nearest drain outlet. In this case, the condensate water is re-used for flushing system. A temporary condensate tank will be located in the bathrooms before the water enters the cistern tank via the condensate pipe (Figure 6.8). All of these condensate parts – trays, pipes and tanks, are sealed properly to avoid insect breeding which will cause health problems. The warm return loop is upgraded by a heat pump to boost the domestic hot water temperatures. The heat recovered from the ambient air will be stored in a temporary warm water tank. The tank is located beside the temporary chilled water tank, supplying warm water to the water heater fitted inside the bathrooms (Figure 6.9).

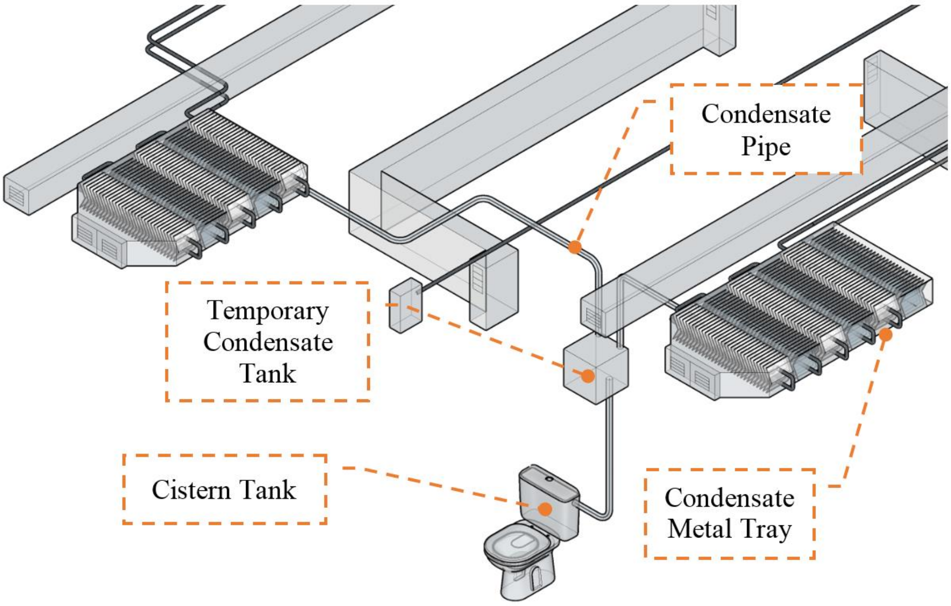


Figure 6.8: Condensate water for flushing system

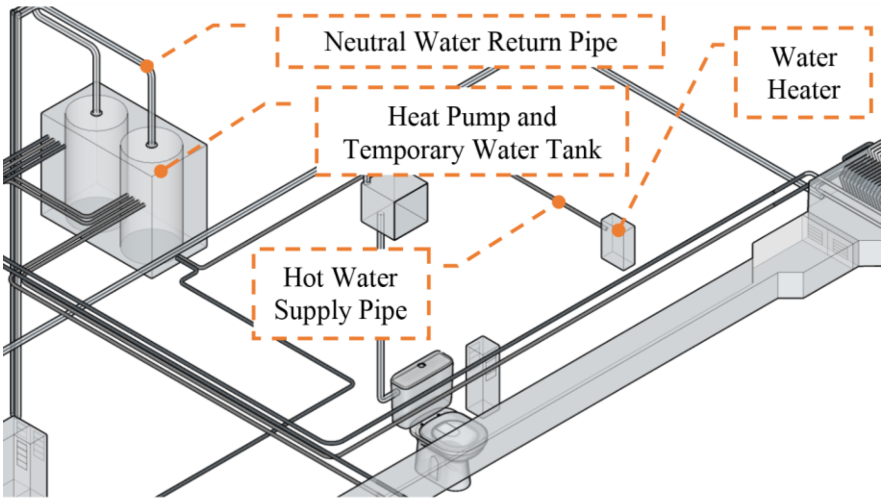


Figure 6.9: Warm return loop system

Figure 6.10 shows the overall application methods of DHCBC and DHAPC systems in the social housing unit of PPR second generation. This system – the DHAPC membrane together with an activated carbon layer, DHCBC coil pipes and aluminium plates, is designed to be fitted in a compact ceiling space (within 600 mm).

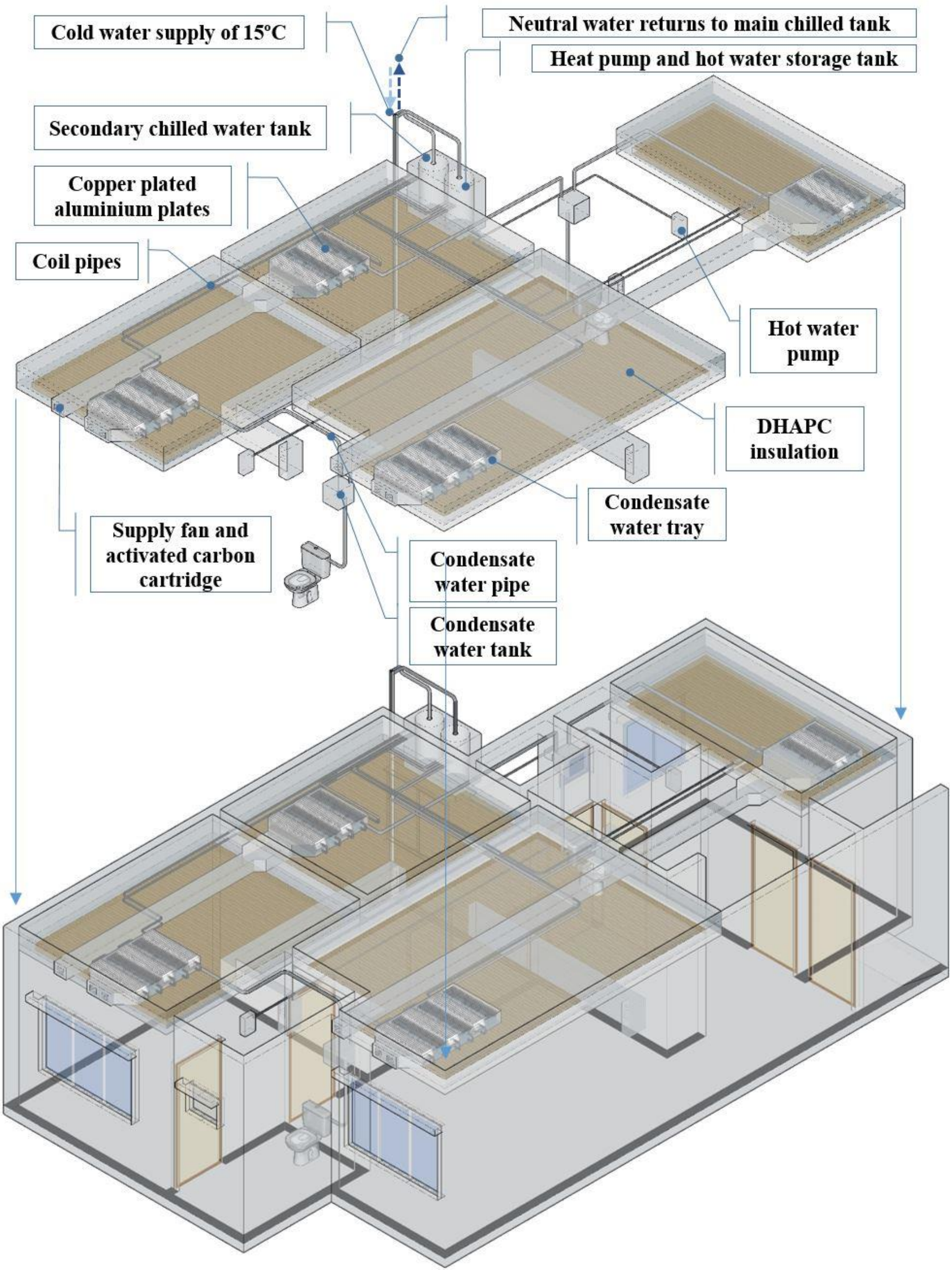


Figure 6.10: The application of DHAPC and DHCBC systems in the social housing unit

6.2.2 Application in New Buildings

For new buildings, regardless of the building forms (high, medium or low) – single or multiple storeys, this system only requires a minimum space of 600 mm at the ceiling space. As gazetted in the Malaysian building regulations – Uniform Building By-Law (UBBL), in clause 44(1a), the height of the living rooms and bedrooms should not be less than 2500 mm (UBBL, 2013). According to this and the application of the system in a multiple storey building, the minimum of 600 mm space should be allocated from the floor soffit to a level with a minimum of 2500 mm from the floor level (Figure 6.11). For a single-storey building, the same criteria are also recommended. However, as the roof is directly exposed and closes the indoor space, an additional aluminium sheet insulation should be placed on the system's compartment to prevent heat radiation to enter the system's compartment (Figure 6.12). This is crucial to provide an energy-efficient and high-performance system.

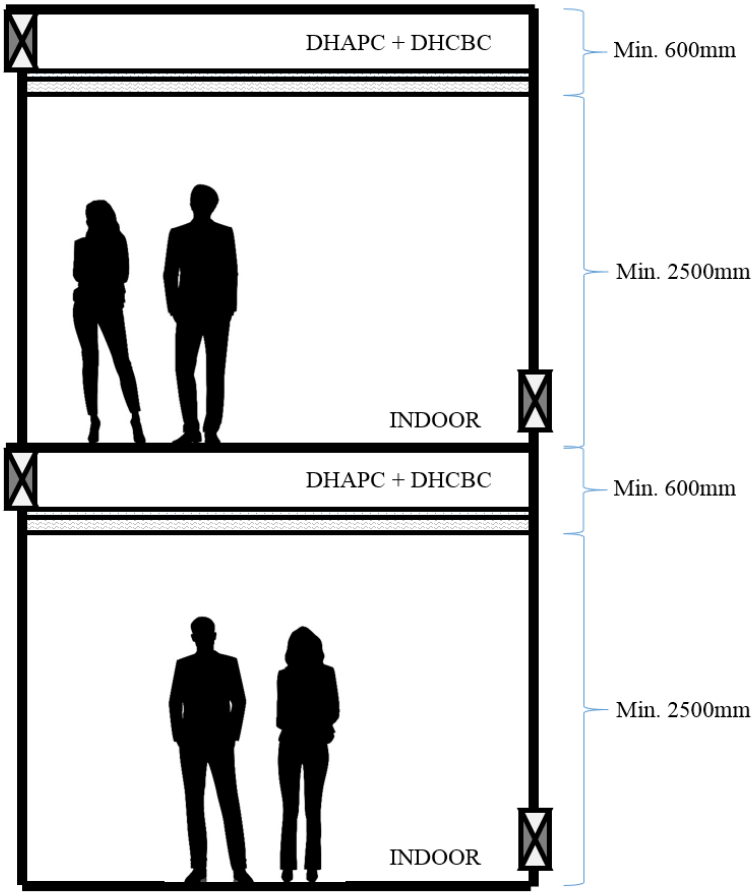


Figure 6.11: The schematic design of the system in a new multiple storey building

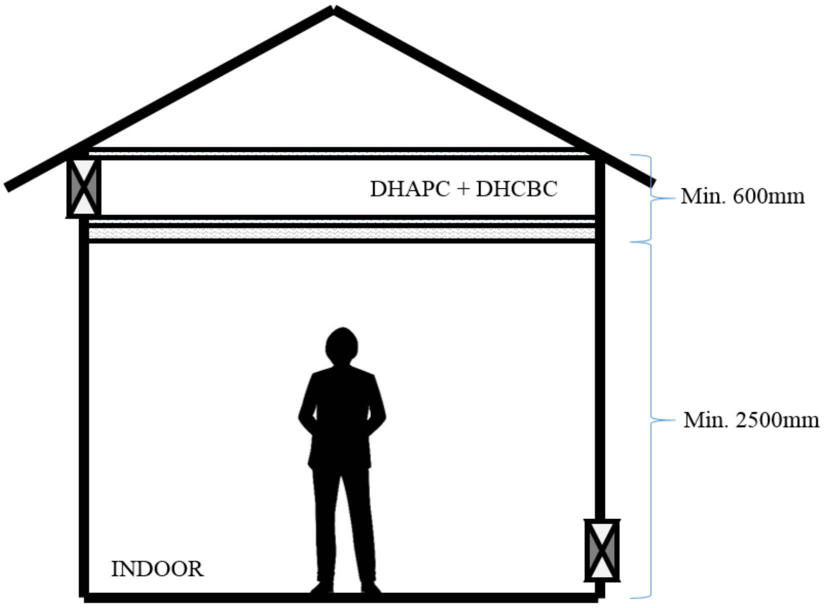


Figure 6.12: The schematic design of the system in a new single-storey building

For DHCBC system components, a set of design multipliers has been proposed as listed in Table 6.3. For every 1 m^3, the coil pipe length should be 0.25 mm with a diameter of 20 mm. For the aluminium plates, 4 pieces of 200 x 200 mm plates should be provided for every 1 m^3. These multipliers are defined using the total length of coil pipes and total aluminium quantities divide with the total floor areas as listed in Table 6.2. Therefore, in order to achieve an optimum building design that complies with the 'Airhouse' Concept, at the beginning of the design stage, these components shall be defined and designed concurrently.

Table 6.3: Design multipliers for the DHCBC system components

Rooms	**Volumes** (m^3)	**Coil Pipe Length** (20mm Ø)	**Aluminium Plates Quantities** (200 x 200 mm)
Habitable Space	1.0	0.25x	4.0x

Similar to the arrangement of the coil pipes and aluminium plates explained in the previous section, the 'V' shape and compact arrangement of the plates are recommended. The air flows when using these design elements will get the maximum contact with the pipes and plates. Chilled water with a low speed of 1.1 l/s is supplied into the coil pipes to create a radiant cooling effect. This water comes from the central chiller water tank located at the rooftop level in multiple or single-storey building. Another smaller temporary chilled water tank shall be provided at every housing unit to regulate the water flow to the desired pressure before the water enters the coils.

6.3 Other Issues to Be Considered

6.3.1 Fire Control Mechanism

The current building regulations in Malaysia (UBBL) were implemented in 1984 and these are based on the recommendations provided by the United Kingdom's Building Research Station (BRS), which is currently known as the Building Research Establishment (BRE). The recommendations were previously applied in Kuala Lumpur and Singapore, both being the British colonies until 1957 (Mohd Sahabuddin & Gonzalez-Longo, 2017; Said, 2011). As mentioned in Chapter 2, the UBBL does not fully consider the Malaysia's hot-humid climate and the issues concerning carbon emissions (Mohd Sahabuddin & Gonzalez-Longo, 2015). For ventilation purposes, the regulations establish that the minimum size of openings for natural ventilation purposes in residential buildings should not be less than 10% of the total floor area of the room (UBBL, 2013), a requirement which has remained unchanged for 33 years.

For fire control requirement, UBBL has gazetted a few strategies from passive to active, with several of them particularly addressing the high-rise buildings. One of the passive strategies in controlling the spread of fire from the point of origin is by using a compartmentation concept – UBBL Clauses 137, 138(b), 148(1b) and 148(4). Clauses 137 and 138(b) explain that any building which exceeds 30 metres in height shall be constructed as compartment walls and floors (UBBL, 2013). Special requirements for the walls and floors in compartment floors are listed in Clause 148(1b and 1c). This regulation suggests that no opening shall be made in any compartment walls and floors with the exception of an opening such as an opening in the protected shaft (1b) and an opening for a ventilation duct (1c) (UBBL, 2013).

Vertical stacks are great to promote air change rates, but they also promote the spread of fire and smoke (Passe & Battaglia, 2015). *Vertical fire and smoke spread in particular needs to be restricted, which poses a conflict in vertically connected spaces needed for stack effect ventilation. Smoke exhausts, as well as movable fire blankets or walls, are usually required* (Passe & Battaglia, 2015). This study has suggested that the housing unit in PPR second generation should implement the 'Airhouse' Concept criteria – implementing passive air filtering technique, hybrid ventilation system and chilled beam ceiling in order to achieve indoor comfort and good air quality conditions in a tropical climate.

The concept requires exhaust fans in each room for sucking out the polluted and hot air inside the rooms to the depressurised light-wells. Using exhaust fans will eliminate ceiling fans (currently being used by the majority of the occupants) which will also reduce the spreading of fire and smoke (X. Chen & Wang, 2019). According to a study, the wind force from the ceiling fans will spread the smoke out to the entire space which later will reduce the visibility of the occupants for evacuation during fire events (X. Chen & Wang, 2019). Thus, the system is in-line with these regulations, allowing to have some openings for ventilation ducts on compartment walls adjacent to the light-wells. The walls are also fire-retarded, and the openings are equipped with louvres that open by direct airflow only. This louvres design will prevent backflow air movement from the light-wells (Figure 6.13). For the active approach in fire safety regulations, the UBBL through Clause 202 suggests that all of the spaces that have a height of more than 45.75 metres (i.e. staircases), shall be provided with an adequate ventilation with a basic system of pressurisation (UBBL, 2013). In addition, in its sub-clause of 202(a), the capacity of the fan(s) shall be sufficient to maintain an airflow of not less than 60 metres per minute (UBBL, 2013). This mechanical system is designed to create the negative pressure inside the space to prevent smoke from re-entering the indoor space.

In the same way, through this study, it is suggested that light-wells are transformed as pressurised spaces using exhaust fan. Currently, at the moment, these light-wells are built as naturally ventilated spaces which solely rely on stack effect (UBBL, 2013). However, through the fieldworks, naturally ventilated light-wells are deemed to create a short-circuit of airflow which contributes to high moisture at its lower level (Mohd Sahabuddin & Gonzalez-Longo, 2018). As exhaust fans will be located at the top of the light-wells to create pressurisation effect, this technique could also assist in channelling the smoke out of the building efficiently (Figure 6.13). Given the above arguments, the 'Airhouse' Concept is highly capable to fulfil the purpose of the fire control mechanism. Its application that uses compartment walls with ventilation ducts and pressurised light-wells could allow for smoke and heat to be promptly channelled out from the housing unit to the pressurised light-well and to the outside of the building, lowering the potential of accumulated smoke and heat during a fire event.

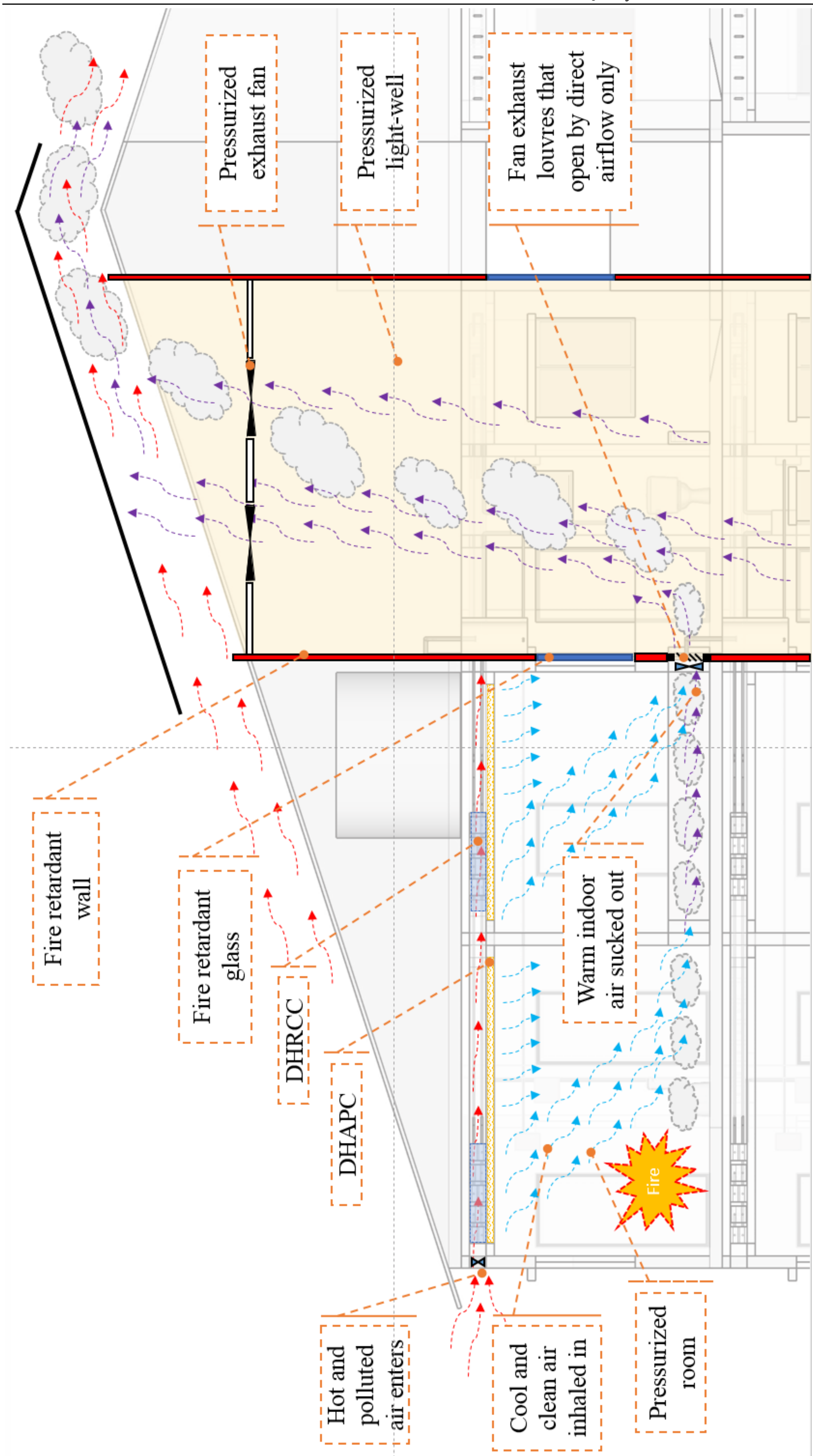


Figure 6.13: 'Airhouse' as a fire control mechanism

6.3.2 Maintenance Aspects

This system is proposed to have low maintenance requirements as possible. As mentioned in Chapter 5, the integration of DHAPC and DHCBC systems have formed the final concept called ‘Airhouse’. This concept, at its best performance, requires both DHAPC and DHCBC systems to work in tandem. However, it is also possible to run these systems separately according to the occupant’s needs because DHAPC alone can reduce approximately 16% of heat and moisture as well as 90% of airborne particles with a constant airflow rate. Therefore, activating the DHCBC system is optional, which could only add another 10% to 20% of heat and moisture reductions. Therefore, it is recommended that this system should be activated during the hottest hours only.

Given the above recommendations, it could be seen that DHAPC system requires more maintenance than DHCBC system. Even though the system is partially active, there are still three components that need to be maintained – the system’s fans, ducts and filter membranes. Fans which have a long lifespan, require more frequent maintenance such as blades cleaning to ensure its efficiency in supplying or exhausting the air (Figure 6.14). As the ambient air conditions in urban areas in Kuala Lumpur are heavily polluted, fan blades are easier to trap impurities, especially in high humid condition. It is suggested that the cleaning may need to be scheduled for every six months.

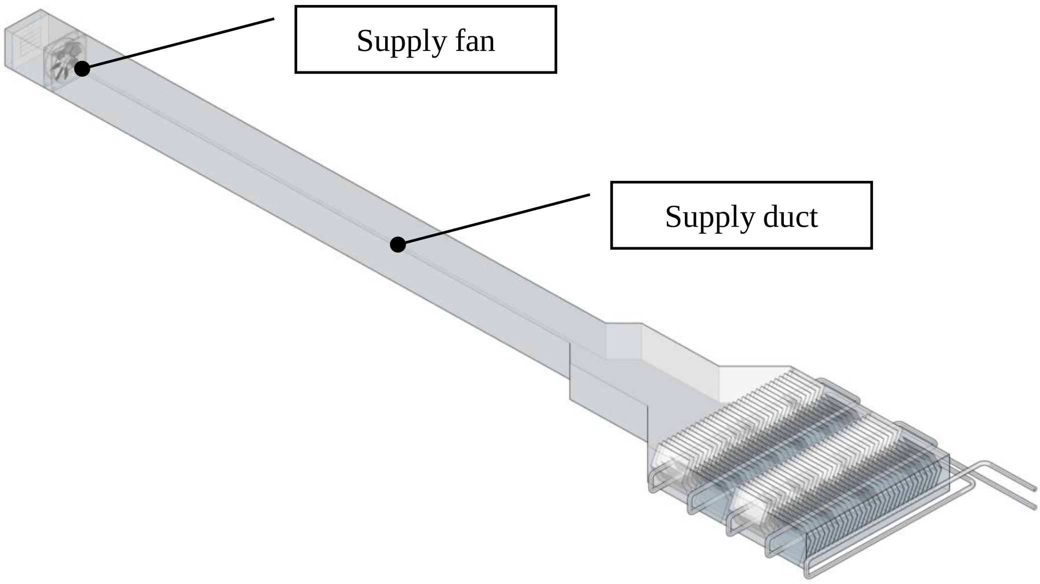


Figure 6.14: Supply fan and supply duct in the ‘Airhouse’ Concept

Ducts are one of the important elements in this system, and need to be cleaned periodically to ensure its hygienic level. Longer ducts will have more potential of contaminants that will attach onto its inner surfaces. For supply ducts, outdoor contaminants including moisture will directly enter the ducts together with outdoor air intake. Similarly, in exhaust ducts, the contaminants attach onto its inner surfaces are produced by the occupant's activities such as cooking, washing and smoking. If the humidity level in the housing unit is high, the contaminants could easily be attached to the duct's inner surfaces and reduced its hygienic level. Therefore, these supply and exhaust ducts are recommended to be cleaned once a year.

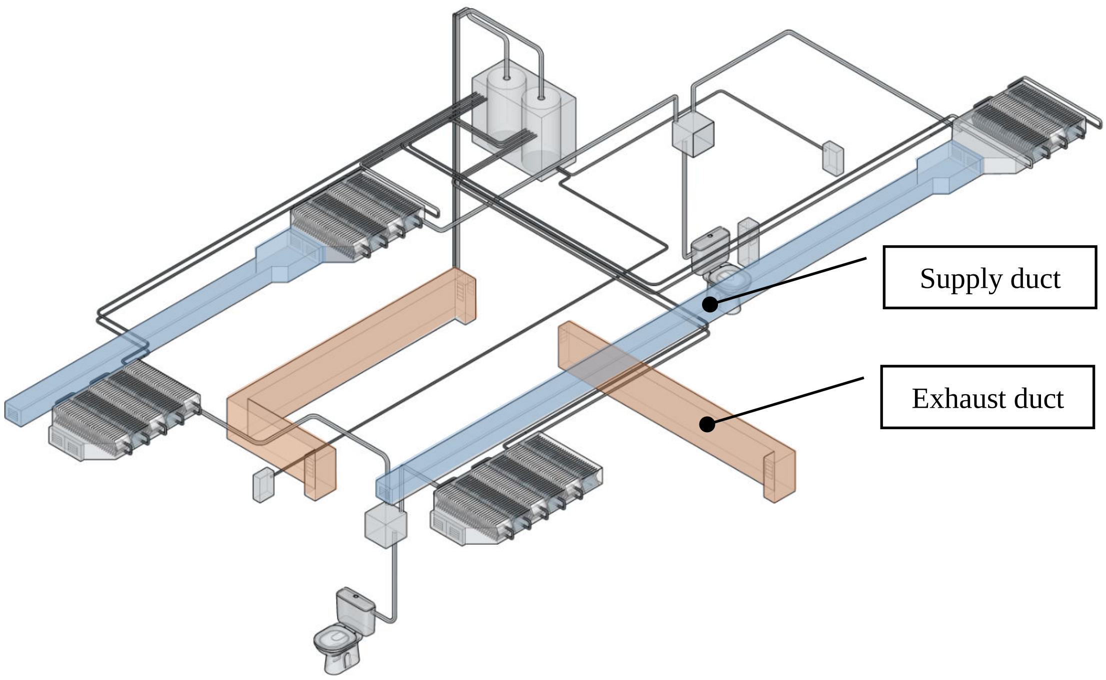


Figure 6.15: The supply and exhaust ducts in the 'Airhouse' Concept

The filter membrane is the most crucial component in this system. Without it, the system is not able to filter the three main factors of indoor discomfort and air pollution – heat, moisture and contaminants. One of the reasons why this system is applied on almost 100% of ceiling area is because of its large surface area that can ensure the membrane could sustain the insurmountable amount of contaminants in a very long period before another change of membrane is needed. It could be deduced that this filter membrane is the least maintenance component in this system. Considering that the size of contaminants that are in microgram (μg) scale while the filter membrane is in tens of square metres (m^2) (Figure 6.16), it would take tens of years for the membrane to get inefficient.

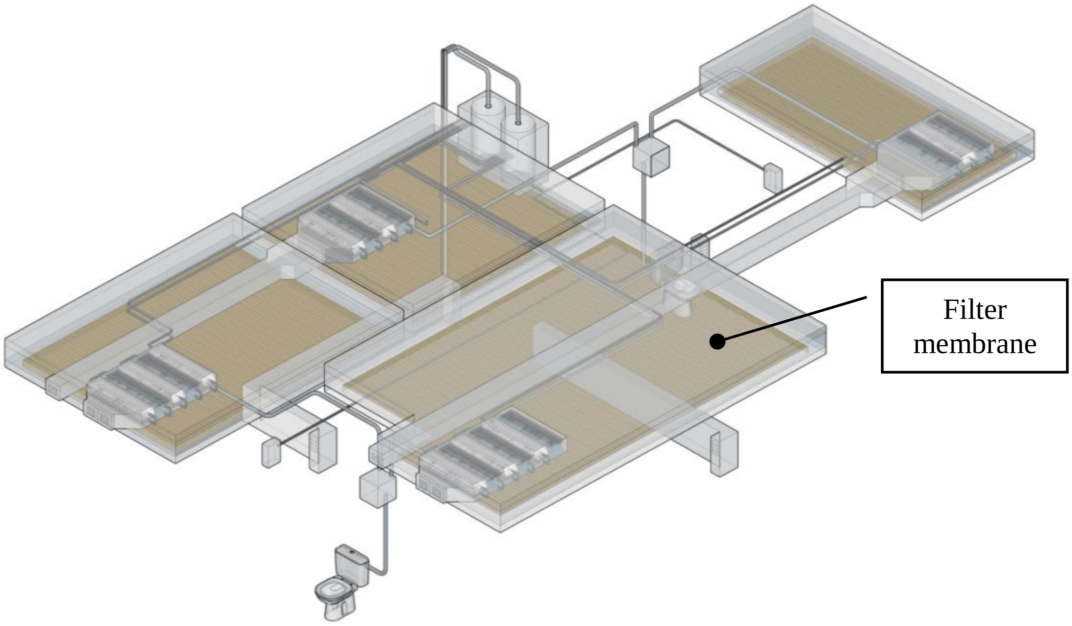


Figure 6.16: The filter membrane surfaces in the 'Airhouse' Concept

As an additional system to support the main system (DHAPC), DHCBC system has lesser maintenance works compared to the main system. The system's piping works – mostly from the main chilled water tank to the temporary chilled water tank and from the temporary chilled water tank to the entire ceiling areas, are maintenance-free components. The only component that needs a regular maintenance schedule is the central chiller unit. This unit requires a series of periodic inspection to ensure it is in good working order.

It could be concluded that the 'Airhouse' Concept is an easy-to-maintain system. The two systems (DHAPC and DHCBC) in the concept can be activated separately according to the occupant's needs. Relying on the DHAPC system alone can achieve the right indoor comfort and air quality conditions as set by the established international and local standards. Activating the DHCBC system in tandem could further improve the performance of the thermal conditions. As mentioned in Chapter 5, this concept requires a very low energy consumption which is 66% less than the conventional air-conditioning system (Mohd Sahabuddin & Howieson, 2019). Thus, it is proven that this concept could solve the problems of indoor discomfort and air pollution in high-rise residential buildings with energy-efficient, low carbon emissions and low-maintenance.

7 CHAPTER 7: Conclusion, Recommendations and Limitations

7.1 Conclusion

Indoor discomfort and air pollution have negative impacts on the urban population in many developing countries. The ongoing high-rise housing programs, particularly in Kuala Lumpur, are not addressing these issues in full. As household incomes rise, residents are resorting to retro-fitting wall mounted split, air conditioning units; a strategy that is neither cost nor carbon effective. The high air temperature and humidity in these buildings are caused by two factors: 1) external factors such as local climate, urban fabrics and building envelope materials; and 2) internal factors such as plan layout, human behaviour and ventilation approach.

The external factors have very limited options to adapt to changes. The local climate and the current situation with the challenges from urbanisation and industrialisation that cause global warming and transboundary air pollution make these issues even more critical. Yet, urban fabrics are also not offering any better options, the scarcity of urban land areas makes buildings squeezed and stuck in a very limited land area. Air pockets in between tall buildings prohibit the most influential element of indoor comfort: adequate ventilation. Heavyweight construction with concrete panels or brickwork without insulation which at the moment are the common construction methods in Malaysia, will store heat and release it at night, giving no option for the occupants except to use mechanically air-conditioning systems to achieve thermal comfort. These active systems require high energy consumption.

The plan layout that is built as a part of the building leaves the occupants with a very limited option to change it. Human behaviour and ventilation approach are two factors that still could be controlled by the end-users. It was observed that at the side facing the corridor the occupants tend to install curtains, blinds and shut their windows at all times due to privacy reasons. Even though the windows that face open areas were left opened (with the opening areas reduced by the curtains and blinds), the airflow rate was still inadequate to remove the heat, moisture and particles away from the internal spaces. Resulting in these factors and as discussed in Chapter 3, the PM_{10} and

$PM_{2.5}$ concentrations in indoor spaces in the high-rise social housing were recorded high (53.5 µg/m^3 and 44.2 µg/m^3, respectively) and surpassed the WHO 24-hour limits.

Since being created 33 years ago, the building regulations in Malaysia, which only regulate the sizes of openings (Clause 39) and light well requirements (Clause 40), have not been reviewed and further researched in accordance with the local climate and evolving environmental conditions. Although the current standards and green rating tools have proposed a number of thermal comfort strategies, they have not been able to completely acknowledge the current and future climatic conditions of Kuala Lumpur. At the same time, they are not able to address the required improvements in the occupant's health and comfort as well as the reduction of carbon emissions. New strategies and systems are required to deal with these issues of indoor discomfort in urban areas. The building regulations need to be revised in accordance with more appropriate set of indoor comfort conditions in residential buildings in Malaysia.

In the absence of local standards for indoor comfort design in Malaysia, this research has referred to several international standards to define the suitable conditions for this country. Even though they were developed primarily in North America and the European countries, the indoor comfort temperatures suggested are in line with the average lowest and highest temperatures established in ten previous studies conducted in Kuala Lumpur, Bangkok, Singapore and Jakarta (refer Section 2.3.1 - Table 2.2). Referring to ASHRAE Standard 55 and CIBSE Guide A, the comfort criteria in Kuala Lumpur for operative temperature is between 24°C and 28°C, for relative humidity is between 40% and 70% RH and for airspeed is between 0.15 m/s and 0.50 m/s. For air quality, WHO has set the annual limits for PM_{10} and $PM_{2.5}$ which should not be more than 20 µg/m^3 and 10 µg/m^3 respectively. For 24-hour period, the limit for PM_{10} is 50 µg/m^3 and $PM_{2.5}$ is 25 µg/m^3 (refer Section 2.3.2 - Table 2.4). These are the reference values for thermal and air quality conditions that have been used in this research.

According to the research key findings, the current study was satisfactorily and sufficiently answered the research leading questions that raised at the beginning of this thesis and emphasized the research hypothesis. These answered questions are summarized as follows:

Question 1: What is the existing level of thermal comfort and indoor air quality in high-rise social housing buildings in Kuala Lumpur?

This question was extensively answered in Chapter 3 with the objective of carrying out an in-situ data gathering to evaluate the performance of the existing, recently built, high-rise social housing blocks in Kuala Lumpur. Two fieldwork campaigns have been conducted to evaluate the actual comfort and health conditions in two types of development in the city. It was started with a preliminary study on ten high-rise social housing developments across Kuala Lumpur. It was observed that these buildings show signs of thermal discomfort and three common additional elements (awnings, fans and air-conditioning systems) were installed by the occupants to deal with the indoor discomfort issues (refer Section 2.4.3).

The first fieldwork study assessed the thermal comfort and found that the operative temperature (above 29°C) and the relative humidity (above 70%) in the case studies have firmly surpassed the limits set by the established standards. Among the contributing factors was the presence of human activities and closed-environment setup (using curtains, blinds, etc.) that also significantly reduced the airflow rate in the house samples. Without using fans, the average internal airspeeds recorded were very low, almost no air movement at all. Considering that the standard flat layout is single-sided, with cross-ventilation driven by ambient air movement, it is not a particularly effective technique for providing ceiling fans to enhance evaporative cooling. Different façade-facing obstructions proposed different indoor thermal and air quality conditions (Figure 3.31). This scenario proposes that the current building regulations (Clause 39 and 40) in Malaysia could not provide indoor comfort conditions by natural means in these buildings.

The second fieldwork evaluated the indoor air quality and found that the average PM_{10} and $PM_{2.5}$ concentrations in indoor spaces in PPR second-generation were high (53.5 µg/m^3 and 44.2 µg/m^3, respectively). These values surpass the WHO 24-hour limits. This is due to the compact plan layout in the building, as it includes light-wells. This layout decreases the air movement in comparison with PPR first-generation which has a more open layout with two large atriums, substantially reducing the PM_{10} concentrations. The CO_2 concentrations were still below the limit of 1000 ppm set by DOSH Malaysia. It suggests that the CO_2 concentrations in indoor spaces in both PPR generations were at good levels (circa 500 ppm) confirming that there were signs of adequate ventilation in these buildings.

Question 2: What are the key environmental problems to indoor discomfort and air pollution in Kuala Lumpur?

The answer to this question was indicated in Chapter 3 where two fieldwork campaigns have successfully identified the actual indoor comfort problems in high-rise social housing in Kuala Lumpur. They have allowed fulfilling the second objective of the research which was to analyse the data and evaluate the results to identify the main problems in providing comfort and health to the occupants. By allowing outside air, it is obviously permitting the hot and polluted air into the indoor spaces. The fieldwork studies have allowed identifying the four issues that need to be addressed in achieving indoor comfort in high-rise social housing buildings in Kuala Lumpur: 1) to reduce air temperature, 2) to reduce humidity, 3) to filter airborne particles, and 4) to provide adequate and constant air movement.

Question 3: What is the optimum strategy or system that could be applied for reducing indoor discomfort and air pollution?

The answer to this question was stated in Chapter 2 with the objective of identifying the most suitable system to be used in addressing these four issues. Dynamic insulation (DI) was identified to have a great potential in solving these four issues, as it allows constant air stream being delivered through an insulation matrix above an air-permeable ceiling (Mohd Sahabuddin & Howieson, 2019). DI also has the additional advantage of providing a large volumetric filter membrane that can filter air pollution (B. J. Taylor et al., 1998) and heat and moisture at the same time (Craig & Grinham, 2017; Halliday, 1997).

As explained in Chapter 3, the ceiling was identified as the most suitable element to integrate the system due to the availability of ample unused surface which could be fully used for placing ventilation devices. These large surface areas contribute to better air distribution and reduce clog problems of the filter membrane. In advance application using directional airflow, so far DI has been implemented mainly in healthcare and electronic facilities known as 'cleanrooms'. As the application of this system in residential buildings especially in a tropical climate is still largely unexplored, this research has investigated its potential application in high-rise social housing buildings in Kuala Lumpur.

The idea of permeable buildings is common in traditional vernacular Malay houses which have been used for hundreds of years in Malaysia, achieving thermal comfort in the tropical environment (Mohd Sahabuddin & Gonzalez-Longo, 2015). The four design strategies to adapt to the climatic contexts of tropical climate are: 1) built on stilts for promoting stack effect, 2) full-length windows at body level for cross ventilation, 3) double roof concept for exhausting hot air, and 4) using lightweight materials for reducing heat radiation at night. These design strategies have been referred and were modelled in the initial 'Airhouse' Concept study done in 2012 (Mohd Sahabuddin, 2012), based on the application of these traditional values into a modern high-rise social housing in Kuala Lumpur. This new research has further developed this 'Airhouse' Concept by using DI together with hybrid ventilation located in the ceiling compartment. Three tests using a physical model were carried out to evaluate the new proposed DI system, called the 'Dynamic Hybrid Air Permeable Ceiling' (DHAPC).

Question 4: How feasible is the proposed system to reduce heat, humidity and air pollution as well as provide constant air movement?

As explained in Chapter 3, to test this DHAPC system in a high-rise building, a one-fifth (1:5) physical model of the master bedroom in PPR second-generation was constructed. The testing series by using this scaled-model were conducted in three tests using four different ventilation protocols consisting fully passive ventilation, hybrid ventilation and fully mechanical ventilation. The basic concept of the system is by supplying hot and polluted air into the ceiling compartment of the housing units. The air is sucked into the ceiling compartment by a supply fan. It was then filtered by a filter membrane and dispersed equally throughout the depressurised indoor spaces before the air was taken out to the depressurised light-well using an extraction fan.

Using three different synthetic insulation materials, Test 1 achieved better reduction rates in all four parameters (air temperature, humidity, PM_{10} and $PM_{2.5}$) when passive ventilation was applied. However, this ventilation approach solely depended on wind buoyancy pressure which in Kuala Lumpur, is unreliable and inconsistent (Mohd Sahabuddin & Gonzalez-Longo, 2017). Meanwhile, the full mechanical ventilation recorded the least reduction rates for most of the parameters except humidity. The hybrid ventilation protocols, however, recorded similarities on filtering $PM_{2.5}$ and PM_{10} particles including air temperature and humidity. Based on these findings, both passive and mechanical ventilation protocols were not considered in the next tests. In terms of airspeed performance, lower airspeeds produced better reduction rates. Based on the test 1 results, the hybrid ventilation protocols with low airspeed have fulfilled three out of four parameters' requirements set by ASHRAE Standard 55 and WHO's air quality guidelines. Thus, they are considered as suitable options that should be studied in Test 2.

In Test 2, recycled insulation materials and activated carbon (AC) cartridge were added and tested in the system. Using these elements, the air temperature and humidity reduction rates were circa 14% and for $PM_{2.5}$ and PM_{10}, the reduction rates were circa 90%. It can be deduced that the lower airspeed of 0.125 m/s is proven to produce better results than the higher airspeeds. Moreover, other remarkable results that this material produced were the reduction rates for air temperature and relative humidity, especially when applying hybrid ventilation with recycled glass material. The reduction rates were approximately 18% and 16%, respectively. AC cartridge, in this test, added approximately 10% to 30% reduction rates for PM_{10} and $PM_{2.5}$.

In test 3, using hybrid ventilation protocols together with recycled glass material and AC applications (cartridge and loose-fill), three types of gases (CO, benzene and SO_2) and three sizes of particulate matter (PM_1, $PM_{2.5}$ and PM_{10}) were analysed. For CO, the average reduction rate without AC applications was 50%. However, when AC applications (cartridge and loose-fill) were introduced, the rates improved by 50% and 15.4% respectively. Similarly, for benzene, the baseline reduction rate without AC was 59.8% and improved to 93.9% and 86.8% when AC cartridge and AC loose-fill were applied, approximately at 30% improvement. Much lower rates were achieved for SO_2 which the baseline was 38.9% and slight improvements of 20 to 25% when AC techniques were used. For the particulate matter of PM_1, $PM_{2.5}$ and PM_{10}, the baseline rates were circa 50%. Meanwhile, when using

AC cartridge, the improvements were between 65 to 70% and with AC loose-fill, it improved up to 88%.

Given the above outcomes obtained from the three tests, the DHAPC system appears as the best option in providing air filtration for all sources of pollution and meets the challenges of modern air pollution. However, in tests 1 and 2, due to the geographical location of the test site which was in a temperate climate, the reduction rates for heat and humidity seemed lower (circa 14%) than expected (circa 20%). It is believed that the reduction rates could be more significant if the tests were conducted in the actual hot and humid climate conditions. In fulfilling the fourth objective, this research developed an energy-efficient system that can reduce air temperature and humidity as well as providing adequate airflow rate to achieve thermal comfort in high-rise social housing in Kuala Lumpur. The additional system called DHCBC has been integrated with the main DHAPC system. The selection of this DHCBC system was based on three factors: 1) smaller space requirements, 2) thermal comfort and air quality performance, and 3) energy savings potential.

To further assess the DHCBC system, two computational modellings were analysed. The basic concept of this system was by introducing coil pipes and aluminium plates into the ceiling void to reduce the average operative temperature to be below 28°C while suppressing humidity below 65%. Considering that the maximum outdoor air temperature in Kuala Lumpur is 35°C, chilled water at 15°C is required and circulated in the coil pipes to reduce the air temperature to meet the cooling requirement for the air supply temperature of 25°C.

Question 5: What are the most effective design configurations of the proposed system for achieving best results of thermal comfort and indoor air quality?

As explained in detail in Chapter 5, the most effective configuration appears to be 20°C of supply air temperature at 30 l/s of airflow rate. This combination can significantly reduce the average results of the operative temperature and humidity to the lower threshold of the proposed comfort zone. When both systems (DHAPC and DHCBC) were combined, they produced the maximum reduction rates for operative temperature and humidity up to 20%. This protocol can be delivered with an average power consumption of 1.86 kW that equates to 680 kWh/year. According to a study (Kubota et al., 2011), the annual energy consumption for cooling (air-conditioning and ceiling fans) in Malaysian housing is 1,973.6 kWh/year (29% of total consumption). If this outcome can be delivered in practice it would represent an overall saving of circa 66% in power consumption for cooling purposes.

The fifth objective of the research, which to evaluate the outcomes and suitability to address the problems of indoor discomfort and indoor air pollution in high-rise social housing was fulfilled through the physical model tests and computer model simulations. It was proven that DHAPC and DHCBC systems, if combined, had successfully addressed the issues of indoor discomfort and air pollution in high-rise residential building in Kuala Lumpur. These systems are required to be implemented in the 1:1 scale. However, the initial data suggested that such an approach, could make a major contribution to improving indoor thermal comfort and air quality with a much-reduced carbon penalty. Therefore, these systems are designed to be fitted in a compact ceiling space in an existing high-rise social housing unit in Malaysia. These systems can be fitted not only in new buildings but also existing buildings, regardless of the building forms (high, medium or low) – single or multiple storeys. It only requires a minimum space of 600 mm at the ceiling space. In addition, as explained in Sections 6.3.1 and 6.3.2, these systems have the capabilities to tackle the issues of fire control mechanism as well as having low maintenance aspects.

Question 6: How can the results contribute to the development of the 'Airhouse' Concept and how the research should continue?

The research findings have answered the question by fulfilling the sixth objective of the research which was to refine the initial 'Airhouse' Concept in order to impose this integrated strategy in the Malaysian construction industry with energy-efficient ventilation protocol, low-energy air cooling system and passive air filtering technique. The integration of DHAPC and DHCBC systems can reduce the air temperature, humidity, airborne particle and gases as well as provide a constant airflow rate. This will allow introducing new design criteria for 'Airhouse' Concept.

Concerning the thermal comfort conditions of the new proposed 'Airhouse' Concept, the recommendation for air temperature was set between 23 to 24°C; the previous proposed value was 25°C to 27°C. The air temperature requirement was set to be in the lowest threshold, considering other factors that might raise the temperature indoors. For humidity, an additional 5% reduction was suggested from below 60% RH to below 55% RH and for air movement, the minimum of 0.125 m/s should be constantly supplied throughout the indoor space which also fulfilled the minimum airflow rate set by ASHRAE Standard 62.2. Two additional criteria for indoor air quality were added for PM_{10} and $PM_{2.5}$; it should be no more than 1.2 µg/m^3 and 1.0 µg/m^3 respectively. For energy consumption and carbon emissions, the new values were set much lower than the initial figures which should be less than 700 kWh/year and 200 kgCO_2/year respectively. Finally, while the initial version of the concept emphasised on natural ventilation with passive openings strategy, the new refined concept introduced a hybrid ventilation approach with active light-well in tandem to provide health and comfort in habitable spaces. These 'Airhouse' Concept requirements should be implemented in the Malaysian construction industry especially for residential buildings, and perhaps, in other countries with the same climatic conditions.

The research works have contributed to establish the actual baseline thermal comfort and IAQ conditions for high-rise social housing in Kuala Lumpur. The findings suggested different indoor comfort conditions for different façade conditions. However, after being occupied, the conditions changed to be uniform without external factors and contexts. This situation has created a different perception on natural ventilation as the main ventilation approach in designing residential buildings in Malaysia and its tropical region. The investigations in two naturally ventilated high-rise social housing in Kuala Lumpur found that both indoor comfort criteria – thermal and health, were not at satisfying levels. The high temperature and humidity in these spaces were caused by external factors such as local climate, urban fabrics and building envelope materials; and internal factors such as plan layout, human behaviour and ventilation approach.

The internal factors are more into the adaptability of the occupants with its thermal conditions. Given the above findings, it was contributed from the research that the ventilation approach for these housing units which currently naturally ventilated is not suitable with local climatic conditions, ambient air quality levels, passive building designs and construction materials as well as the habitual use of space by the users. Therefore, in order to achieve indoor comfort, the perception of natural ventilation approach in high-rise residential building in urban areas should be given a new insight.

Through this research, permitting outside air is likely to allow hot, humid and polluted air in. As located near the equator line, air movement in this city was recorded insufficient and unreliable. Thus, through this research, depending solely on natural ventilation approach is considered as an obsolete approach. Designers have to explore new ways of ventilating residential buildings. It requires significant changes on high-rise building design that can control indoor comfort as a whole and continuously.

Through this research, it was learnt that there are other design strategies that could be potentially included in high-rise social housing design, such as DHAPC and DHCBC systems. However, providing shading device or/and double façade on all exposed windows and walls should be incorporated in the first place to reduce direct and indirect solar radiations. This strategy can directly reduce indoor air temperature and integrating this strategy with the systems could further reduce the demand of energy consumption.

7.2 Recommendations

7.2.1 General Recommendations

In order to achieve indoor comfort, the residential buildings (new and existing) in Malaysia should be given a new incentive. Through this research, designers have to explore new ways of designing residential buildings. It requires a significant change in building design to ensure building owners, end-users and occupants can control their indoor comfort as a whole. To achieve that aspiration, the following recommendations are intended for the decision-makers, architects, engineers, and building owners:

a) Review and update building regulations in Malaysia to insert thermal comfort and indoor air quality requirements to the building design.
b) Imposing new policies and regulations in the building sector to promote energy-efficient houses in Malaysia that can also provide indoor comfort benefits.
c) Support new initiative such as implementing passive filtering and hybrid cooling strategies in residential buildings with financial support.
d) Implement the established thermal comfort and indoor air quality standards to control the indoor comfort of future residential buildings.

e) Raise public awareness on the negative impacts of indoor discomfort and poor air quality in residential buildings.
f) Educate the public on the benefits of energy-efficient technologies and its positive impacts on the long-term economic effect.
g) Encourage more research on passive filtering and hybrid cooling strategies in residential buildings and support the developments with grant aid.

7.2.2 Revision on Building Regulations

Building regulations in Malaysia, especially for high-rise residential buildings, only emphasise natural ventilation strategies. They are only concerned about the proportion of windows (Clause 39) and size of light-wells (Clause 40) and also do not specifying any regulations on achieving health and comfort living in residential buildings. Likewise, the Malaysian standard and green rating tools in Malaysia also need to be revised following the recommendations on the building regulations. The revisions on the standard and green rating tools should also take the critical conditions into consideration, which allow for passive and low-energy strategies to constantly provide air movement, reduce the airborne particulate matter, operative temperature and humidity levels in indoor spaces. Therefore, if the proposed system is to be implemented, three addendums for Clause 39 and 40 need to be added in the building regulations. These clauses are in dire need of change and improvement in order to ensure the occupants' comfort and health.

a) Clause 39 (Addendum 1) – Other opening(s) that are equipped with a mechanism (active or passive strategy) must be provided at the ceiling level for supplying cool, clean and constant air into indoor spaces.
b) Clause 39 (Addendum 2) – The conditions of the supply air temperature, humidity, cleanliness and airflow rate shall follow the recommendations set by the established standards.
c) Clause 40 (Addendum 3) – A mechanism that could assist in removing the air efficiently inside the light-well, either by active or passive strategy should be provided.

7.2.3 Design and Construction Methods

One of the challenges in determining the effectiveness of 'Airhouse' Concept is the construction quality of the whole building envelope. It means that this concept requires a high construction quality especially the jointing sections of the building components – walls, ceilings, roofs, floors, doors and windows. This compliance requires very neat supervision during construction. Based on the precedent cases and results obtained from this research, one of the main issues of this system is the buildability aspects that need to be met during the construction works. Some general recommendations to overcome the issues are:

a) In the design process, it is very useful if the prefix design work takes into consideration the work from different background experts including physicists, to observe the airflow pattern, and chemists, to advice on the suitable materials in ensuring indoor comfort performance.
b) Taking into consideration the advantages and disadvantages of existing on-site elements and site contexts for utilising renewable energy generation and minimising the negative impacts of surroundings elements.

The specific recommendations to address the buildability issues are:

a) Fully wind-proof outer skin to protect the porous building surfaces from the outside that could permeate into the indoor spaces and create pressure fluctuations.
b) Proper seal along the jointing is mandatory to prevent the air leakage along with jointing in between building components, especially at the ceiling compartment. This is to ensure the supply air flows through the insulation properly and to avoid the risk of condensation.
c) For low rise buildings, loft airtightness is absolutely compulsory. This aspect is the most important as pre-cooled loft could sufficiently cool-down the habitable spaces.
d) Avoiding air leakage in the building fabric and ceiling compartment which will short-circuit the airflow.
e) As the indoor spaces are in constant pressurised and depressurised conditions, the door-slam effect will occur which could cause injury to the occupants, thus, door-slam-stoppers are recommended to be installed on all doors.

7.3 Future Research

7.3.1 Generic Suggestions

This research is only the first commencement in looking for solutions to produce more sustainable buildings. The proposal of dynamic insulation combining chilled beam system had here is only an initial evaluation of its potential to reduce the air temperature, humidity and airborne particles as well as to provide a constant airflow rate in a typical social housing unit in tandem with active light-wells. More research need to be carried out. There are still other factors that should be focused in the future to implement the system in more practical and realistic situations. Even though this research has combined both the physical and computer modelling, the validation of the system should be done using a full-scale prototype in existing and new buildings in the actual hot-humid climatic context. This pilot trials or similar systems should be the main priority of the construction industry in Malaysia.

Further investigations also need to be carried out using different filtering or cooling approaches with different schematic designs. For example, the development of DHAPC and DHCBC systems can be integrated with other building components (floors, roofs, walls, columns and beams) while the cooling method of the DHCBC system can be used as cold water or cold air by taking the advantage of the ground cooling and night cooling effects to cool the water or air by convection and supply it into the coil pipes in the system. Based on hot-humid climatic patterns, other passive cooling systems either evaporative or ventilative can also be incorporated in future studies. Potential future studies could also focus on zero energy and carbon emission buildings by replacing the conventional energy sources of the proposed systems with renewable energy sources such as photovoltaic solar panels or water turbine.

In dealing with the effects of climate change and urbanisation, building designers have to establish more explicit designs in providing both thermal comfort and air pollution reduction. It is also very relevant to do research on non-domestic building types regardless of their forms – low-rise, medium-rise, individual or linked buildings. Thus, the future research direction is to ensure the implementation of an energy-efficient residential design initiative within the Malaysian housing sector (and building industry) with reference to thermal comfort and indoor air quality. This initiative requires cooperative research and studies with organisations associated with the construction industry and academic institutions in Malaysia such as the Ministry of Works, the Ministry of Urban Wellbeing, Housing and Local Government, the Ministry of Energy, Science, Technology, Environment & Climate Change, engineering consultants, construction companies and local universities. The key recommendations for future researchers from the industries and academics are summarised as follows:

a) Broadening the investigation on the full energy consumption performance of the proposed systems not only in residential but also other types of buildings.
b) Implementing different design parameters of the proposed systems to optimise its performance.
c) Developing new materials from local raw sources that have higher filtration with lower density to reduce pressure drops.
d) Incorporating various renewable energy systems such as photovoltaic panels and water turbine in considering the abundant sources of solar energy and rainwater harvesting.
e) Interrogating the proposed systems in different climatic conditions.
f) Analysing the performance and life cycle cost (LCC) of the proposed systems.

Since the proposed ‘Airhouse’ Concept has significantly achieved the criteria of low-carbon and low energy performance in ensuring the highest standard of the proposed systems could offer, it is recommended for future research to upgrade the achievement to as high as zero energy and CO_2 emissions in the future.

7.3.2 Specific Suggestions

Research on ‘Hybrid-Negative vs Hybrid-Positive’ for Physicist

In this research, two ventilation protocols had been tested in test 2 and test 3. The hybrid-positive (F-B) configuration is where the supply fan was active and the exhaust fan was inactive during the test. While the hybrid-negative (B-F) configuration is where the supply fan was inactive and the exhaust fan was active. It was observed that these two ventilation configurations have significantly given different effects in reducing air pollution from petrol and diesel engines. The F-B configuration, for instance, produced higher reduction rates on particles. This was due to the repulsion force that makes more ‘larger’ airborne particles trapped inside the membrane. While the B-F configuration which dominantly powered by suction pressure, dragged and released more particles from insulation membrane but not gases. It seems that more adsorption process occurred when B-F was used. For example, F-B configuration recorded circa 15% more reduction on airborne particles than B-F configuration. Whereas, B-F configuration filtered circa 15% more gases molecules than F-B configuration. These scenarios need to be further studied by a physicist to explain why such conditions could happen.

Research on ‘AC Cartridge vs AC Loose-fill’ for Chemist

In this research, two activated carbon (AC) approaches were tested – AC cartridge and AC loose-fill. The AC cartridge is where the AC was filled in a box made from polystyrene while AC loose-fill is where the AC was flattened on the DHAPC membrane top surface. The first option had a compressed box while the second option had an uncompressed surface. Polluted air was introduced and passed through the compressed box and the uncompressed surface. It was observed that different profiles of air quality variables (carbon monoxide, benzene and sulfur dioxide, PM1, PM2.5 and PM10) were observed when AC cartridge and AC loose-fill were applied. AC cartridge produced better results for filtering gases while AC loose-fill filtered airborne particles better than AC cartridge. For example, AC cartridge filtered almost 35% more carbon monoxide than AC loose-fill but AC loose-fill filtered almost 25% more particulate matter than AC cartridge. These scenarios need to be further studied by a chemist to explain why such conditions could happen.

7.4 Research Limitations

This research has been conducted with several specific limitations that need to be considered in future research. It also has been carried out using a limited amount of data and tests. Even though, specific systems have been tested, many other options on the building design and fabric can also be used to address the issues.

First, this research was totally conducted in the UK climate conditions except for the fieldwork studies. It was believed that the physical model experiments might be affected by the temperate climate conditions. However, by knowing this limitations, this research has taken into consideration all of these barriers and every effort has been made in realising the tropical conditions in the UK climate. It was found that the UK local ambient humidity has lower range, offering little margin, makes the reduction rates for humidity seemed insignificant and if the actual Kuala Lumpur's humidity condition was applied, the results could be more significant. Therefore, for future research, the physical model experiments should be conducted in the actual conditions of Kuala Lumpur's outdoor environment.

Second, two different hand-held anemometers were used for measuring the outdoor and indoor air velocities in the social housing units (Fieldwork 1). These instruments may have different sensors sensitivity and the recorded air velocities might produce different values. Besides, the recorded air velocities at different locations may be influenced by different external wind conditions depending on the site contexts. Furthermore, the value of 0.0 m/s that has been recorded might be because of the anemometers' limitation which could have a minimum air speed before they will start rotating and logging. For future research, it is suggested that similar equipment should be used in order to get more accurate data.

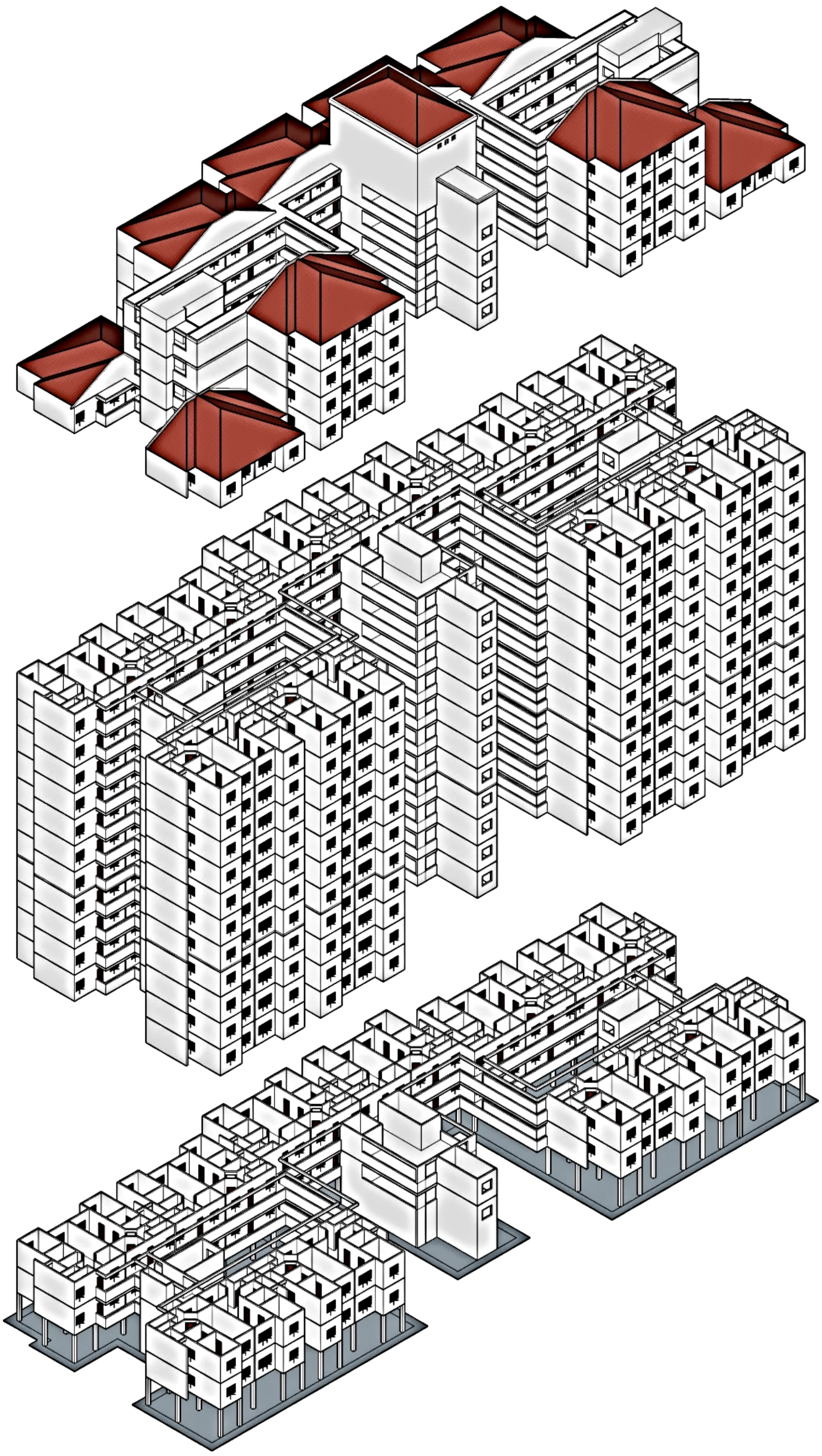
Third, computer simulations are proven as one of the popular methodologies that have been used by many researchers. This method can analyse a full-scale building in a short period with a more realistic weather background. However, different software has different ability and for this research, the software itself has limitations such as material properties that are not completely similar while translating the actual building properties into the IES simulation model. Therefore, in this research, the most similar properties of construction elements and local environment were assigned and adapted in the simulation models. Furthermore, the IES software can measure for thermal comfort conditions and energy consumptions only. It worthwhile to be considered in future research to use a simulating software that can measure both thermal and indoor air quality parameters (especially particles and toxic gases).

Fourth, it should be noted that the energy savings obtained in Chapter 5 when employing different configurations of the proposed air cooling system were simply estimated by calculating the electricity consumption of a chilled water loop system with supply and extract fans employed in a number of rooms only. A very detailed analysis of the electricity consumption and its potential savings requires a very significant task, given the enormous number of variables involved, this task was considered beyond the scope of this study. Therefore, for future research, a detail consideration on electricity consumption should be studied and compared with other systems.

Fifth, physical modelling was one of the key methodologies in this research. The physical model built for this research was airtight and made of closed-cell extruded polystyrene foam. The results show a modest reduction in temperature and humidity. However, this is likely to be due to the boundary conditions and possible hygroscopicity (the capacity of a product to react to the moisture content of the air by absorbing or releasing water vapour) of the insulation material that would just be a temporal effect. To minimize the effect, in future research, it is advisable to model the most accurate materials used in real buildings. If all these constraints can be minimized, the investigating of the new standard will be more neat and accurate.

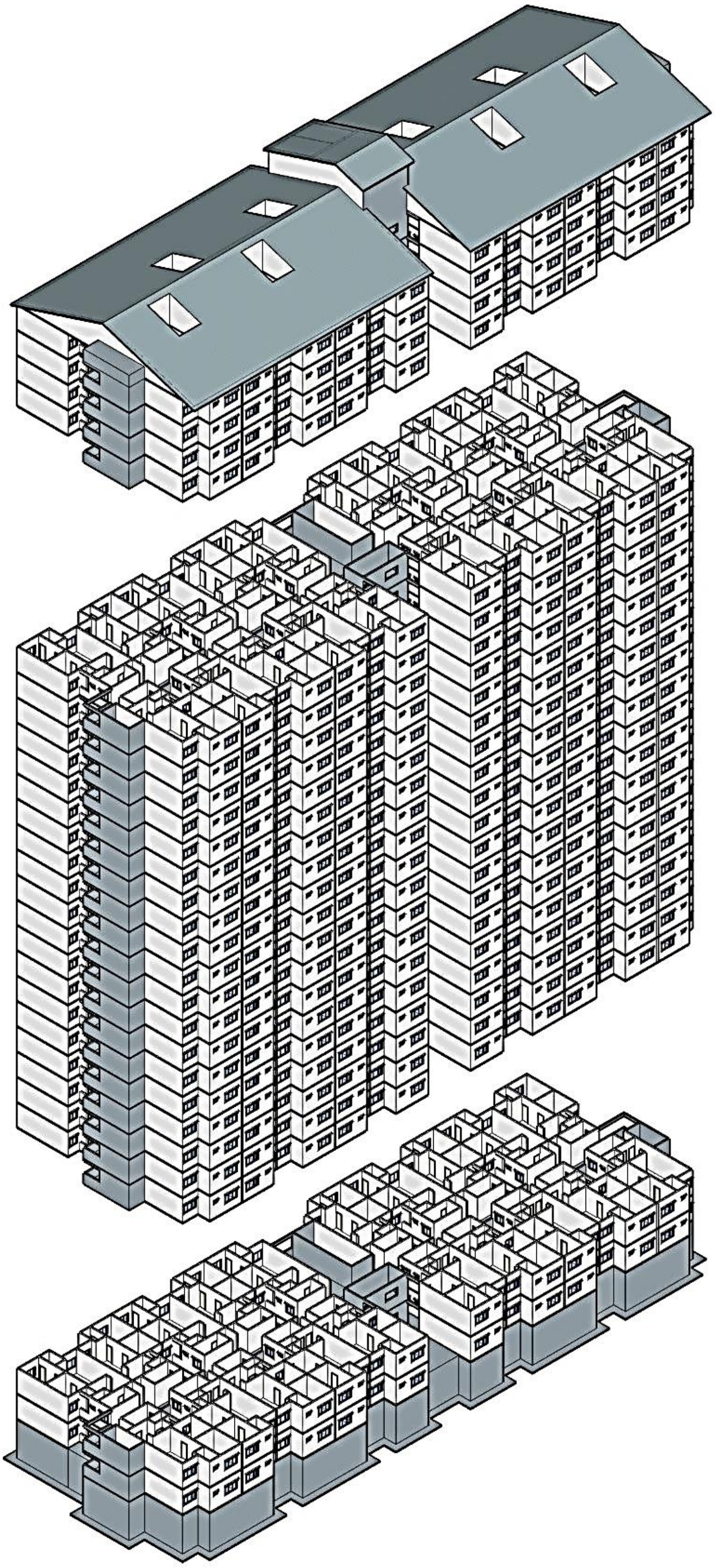
Appendices

Appendix 1A



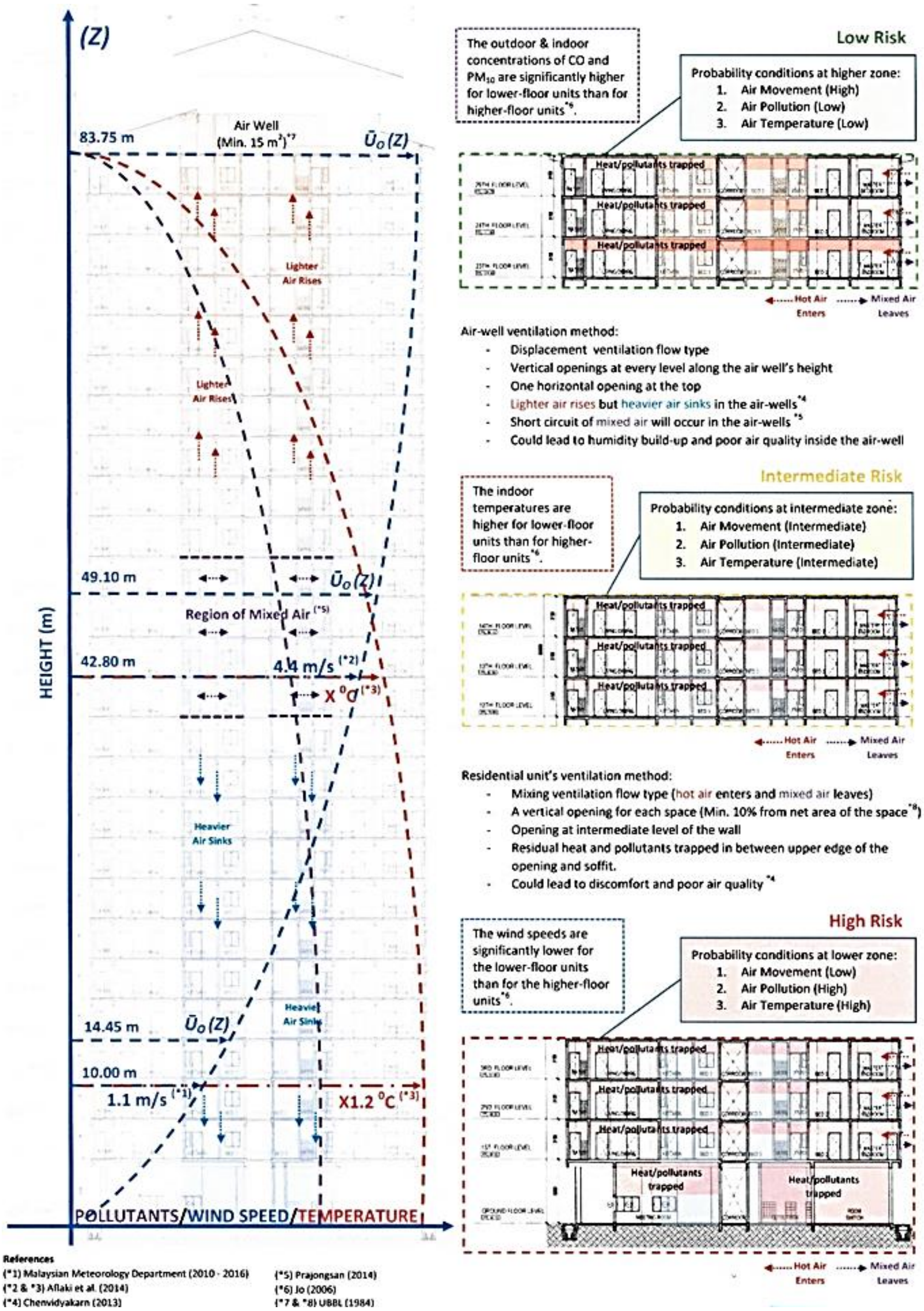
The arrangement of the housing units (layout plan) in PPR first-generation

Appendix 1B



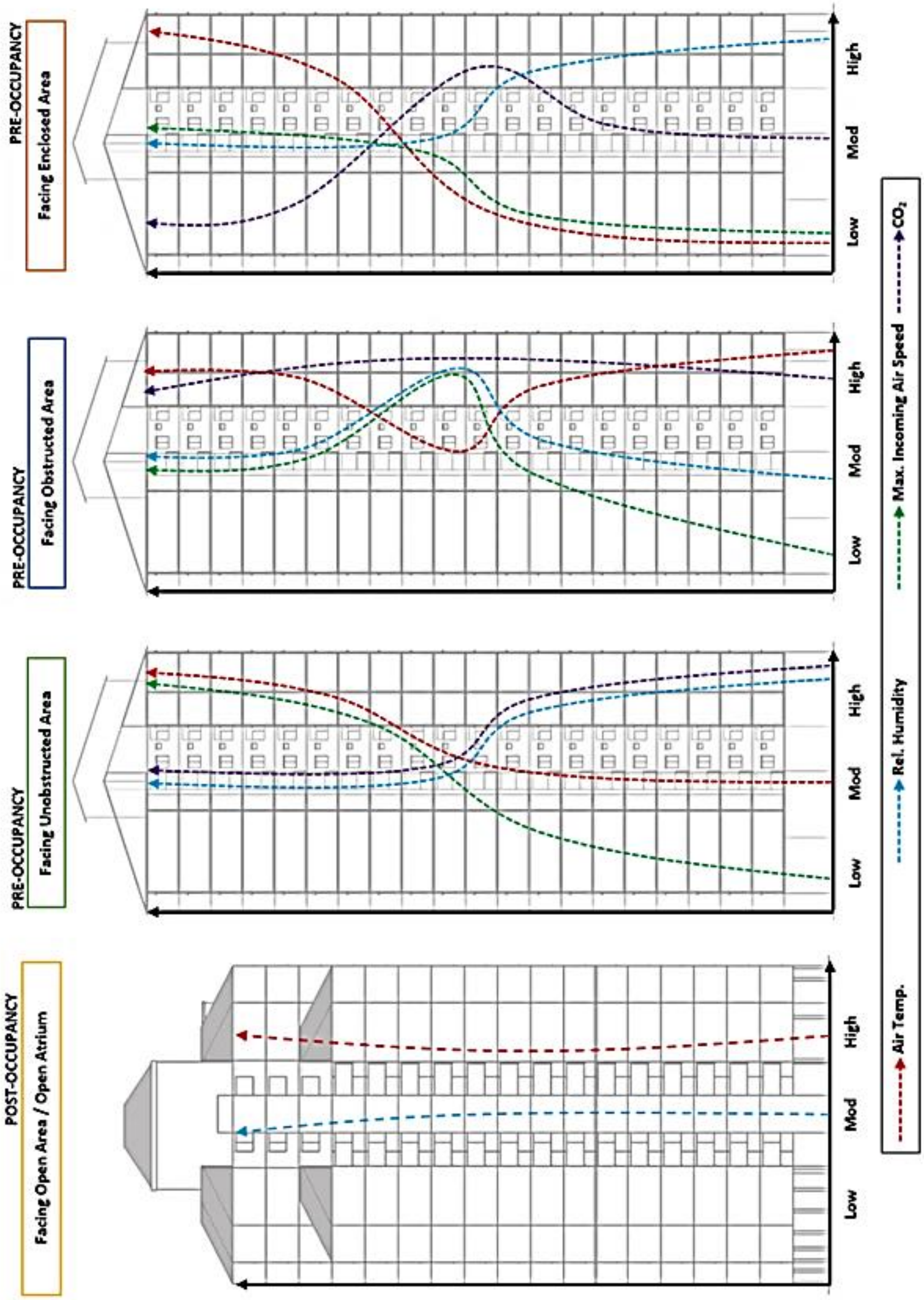
The arrangement of the housing units (layout plan) in PPR second-generation

Appendix 1C



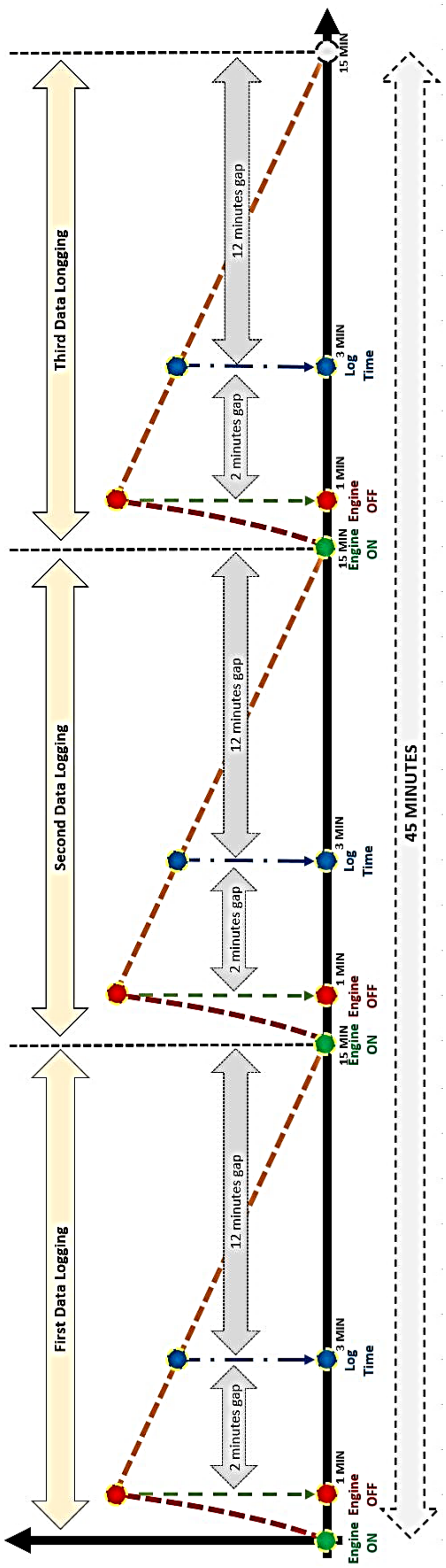
Probabilities of air temperature, wind speed and pollutants concentration in high-rise residential building

Appendix 1D



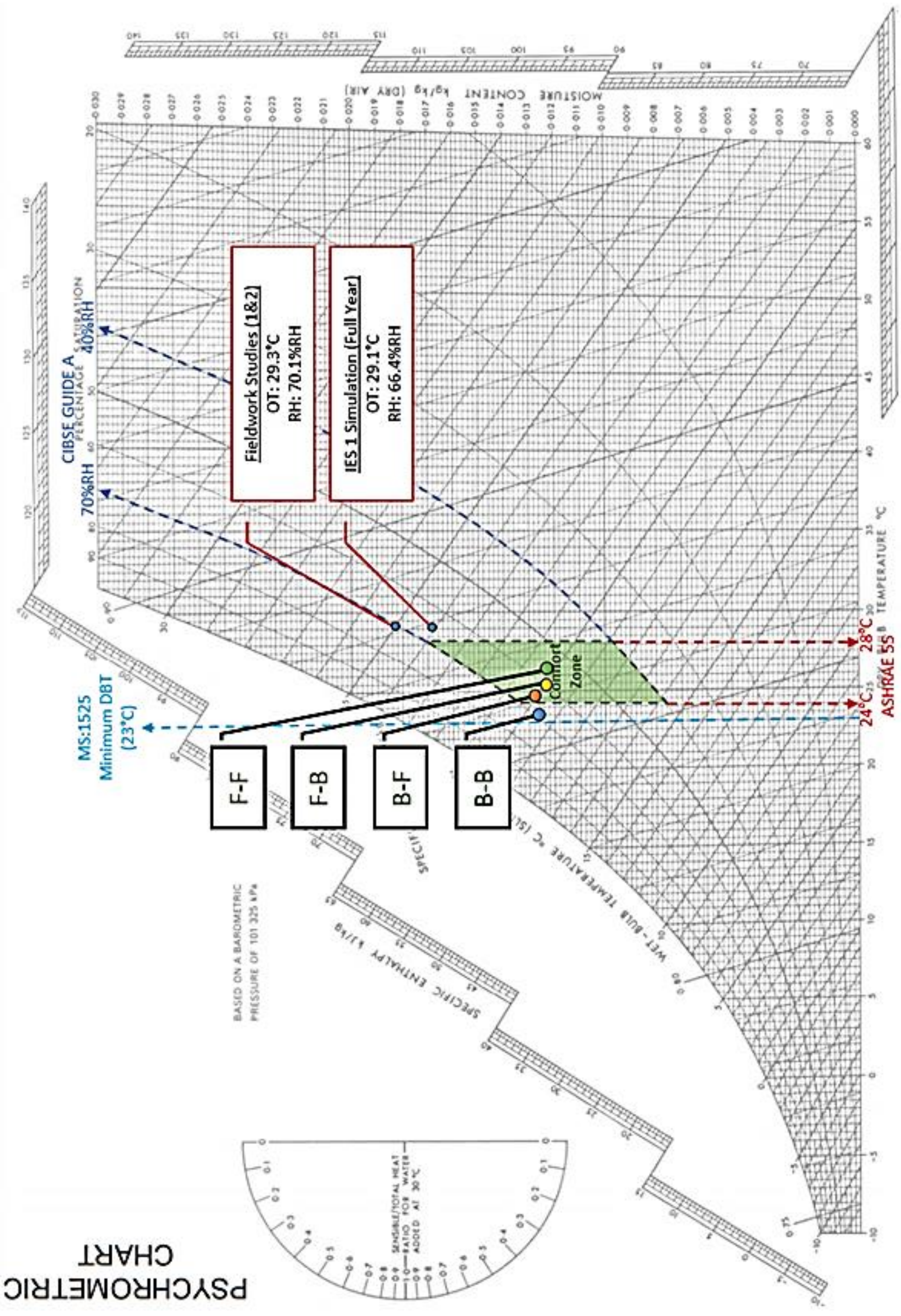
The identified four different environmental conditions zones in PPR Seri Aman and PPR Beringin

Appendix 1E



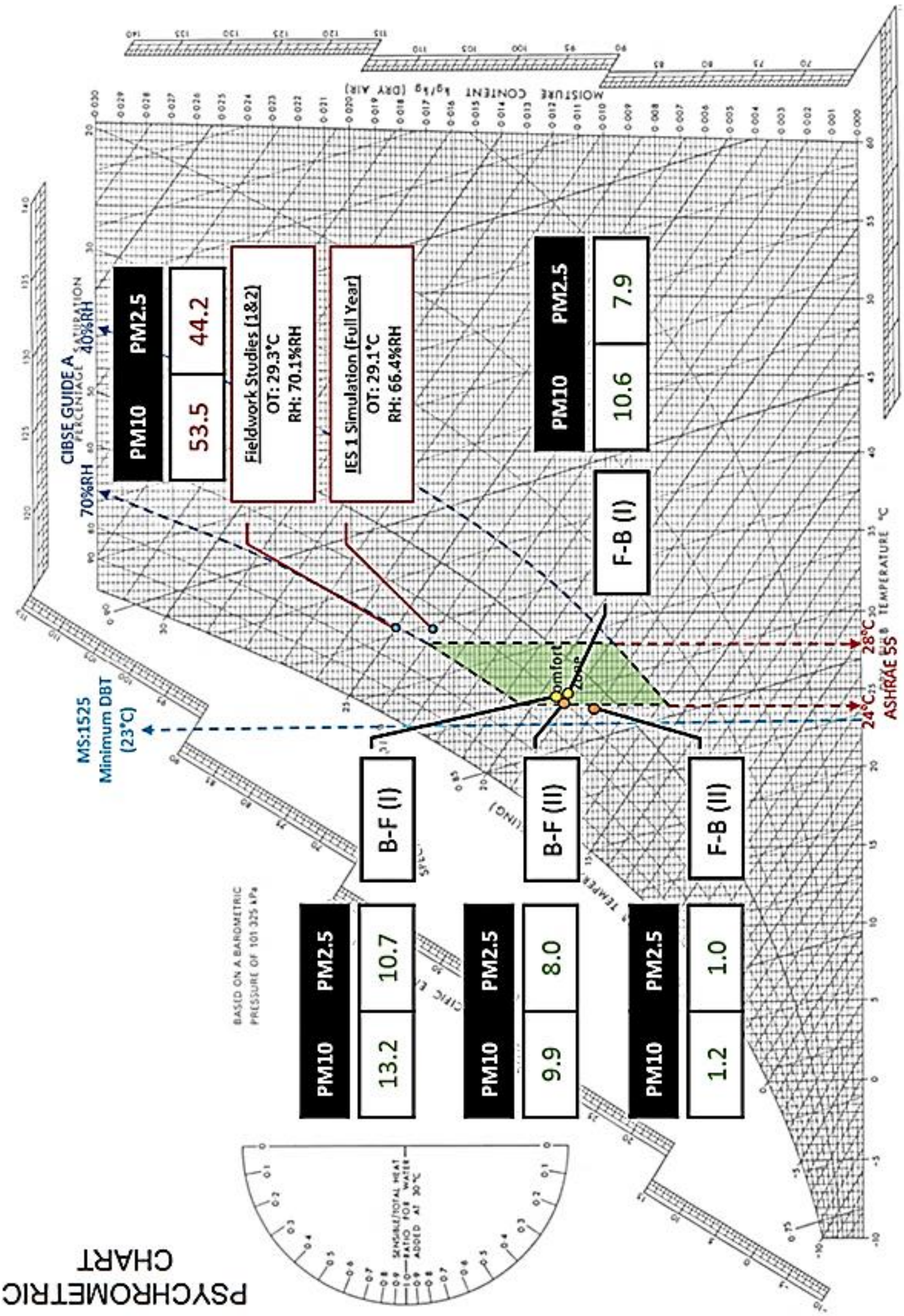
Measurement methods timeline

Appendix 1F



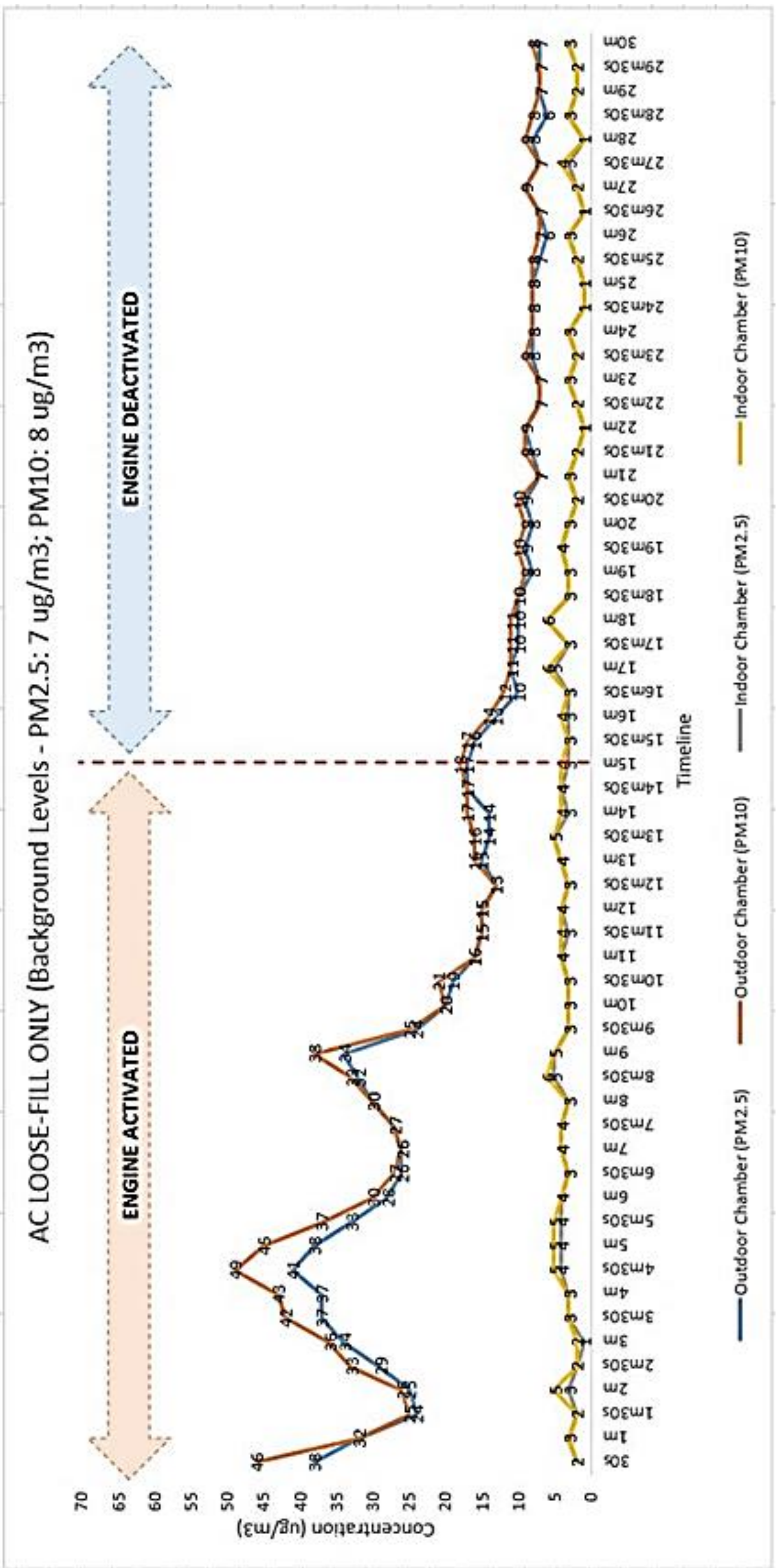
Tabulation of ventilation protocol results on Psychrometric Chart

Appendix 1G



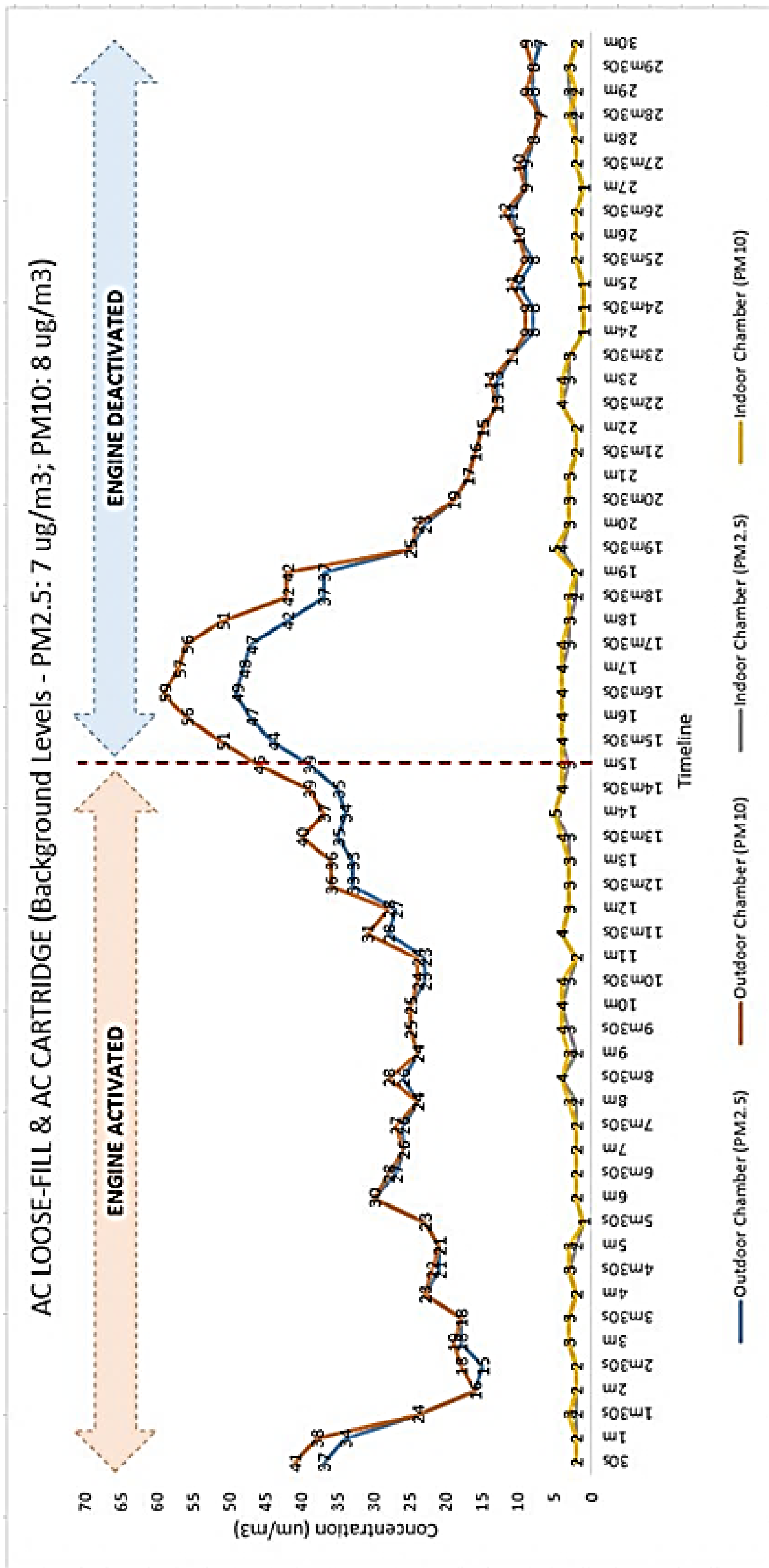
Tabulation of B-F and F-B results using 0.125 m/s and recycled glass with AC on a psychrometric chart

Appendix 1H-1



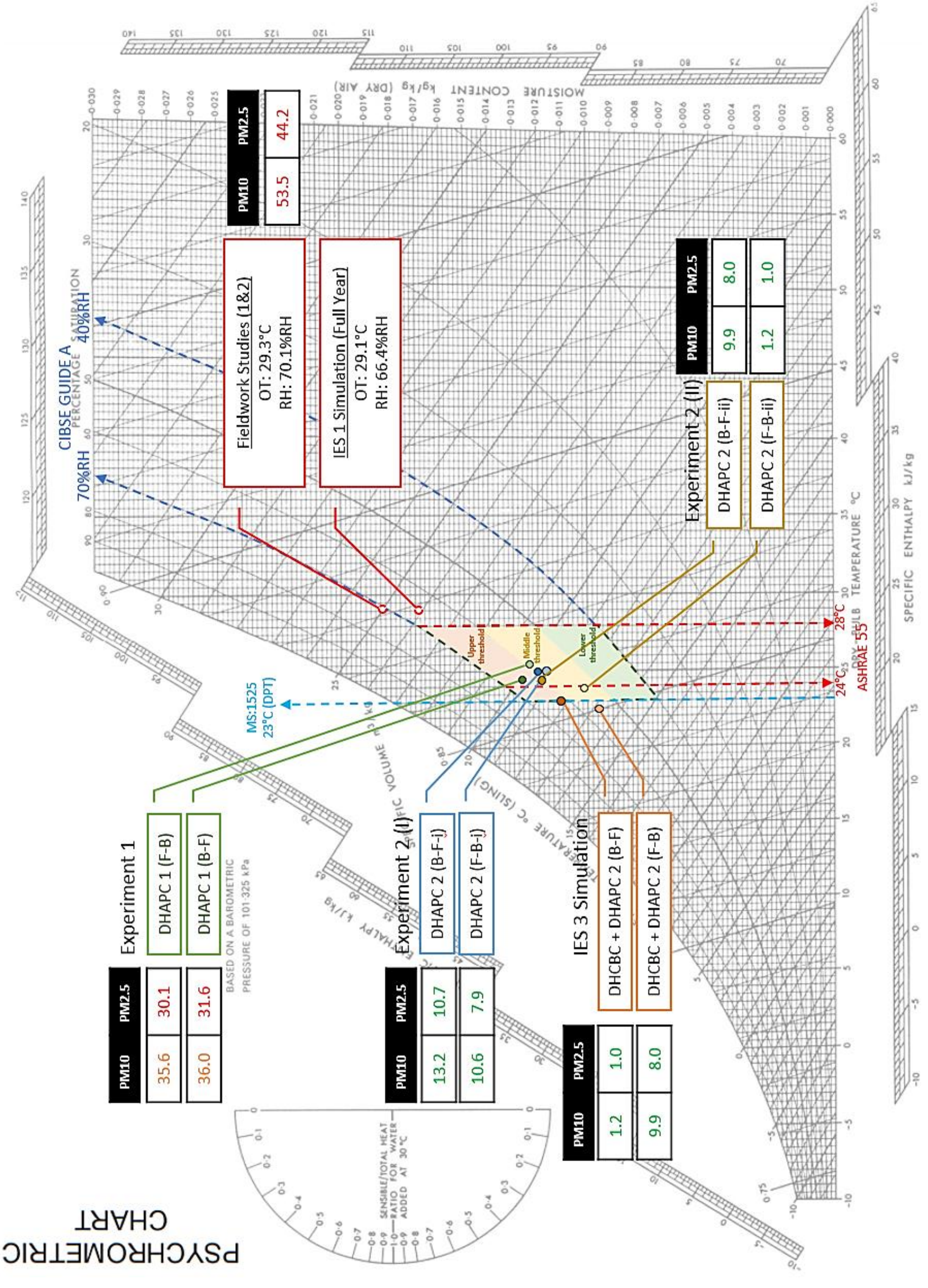
Logged values and concentration patterns of PM in the tests

Appendix 1H-2



Logged values and concentration patterns of PM in the tests

Appendix 1J



The tabulation of all results from fieldwork studies, physical tests and IES simulations on the psychometric chart

References

Abd Manaf, I., Durrani, F., & Eftekhari, M. (2018a). *Investigating performance of solid desiccant dehumidification in an evaporative cooling system*. Paper presented at the CIBSE Technical Symposium 2018., London South Bank University.

Abd Manaf, I., Durrani, F., & Eftekhari, M. (2018b). A review of desiccant evaporative cooling systems in hot and humid climates. *Advances in Building Energy Research*, 1-42.

Acuff, J. W. S. (1943). Insulation: Google Patents.

ADB, A. D. B.-. (2019). *The Links Between Climate Change, Disasters, Migration, and Social Resilience in Asia: A Literature Review*. Retrieved from Manila, Philippines: https://www.adb.org/publications/climate-change-disasters-migration-social-resilience-asia

Aflaki, A., Mahyuddin, N., Al-Cheikh Mahmoud, Z., & Baharum, M. R. (2015). A review on natural ventilation applications through building façade components and ventilation openings in tropical climates. *Energy and buildings, 101*, 153-162. doi:10.1016/j.enbuild.2015.04.033

Aflaki, A., Mahyuddin, N., & Baharum, M. R. (2016). The influence of single-sided ventilation towards the indoor thermal performance of high-rise residential building: A field study. *Energy and buildings, 126*, 146-158. doi:10.1016/j.enbuild.2016.05.017

Aflaki, A., Mahyuddin, N., Manteghi, G., & Baharum, M. R. (2014). Building Height Effects on Indoor Air Temperature And Velocity in High Rise Residential Buildings in Tropical Climate. *OIDA International Journal of Sustainable Development, 7*(7), 39-48.

Aldossary, A., Ali, Z., & Summ, W. M. (2016, 11-13 July 2016). *To Do Away With Air Conditioning - Comfort With Natural Ventilation in Tropical High Rise.* Paper presented at the PLEA2016 - The 32nd Conference on Passive and Low Energy Architecture, Los Angeles, USA.

Ali, Z. F. (2007). *2007 On Site Review Report: No 1 Moulmein Rise, Singapore*. Retrieved from Singapore:

Alongi, A., & Mazzarella, L. (2015). Characterization of fibrous insulating materials in their application in Dynamic Insulation technology. *Energy Procedia, 78*, 537-542.

AlQdah, K. S., & AlGrafi, M. (2013). *Utilizing the waste polystyrene to enhance the thermal insulation of the local buildings.* Paper presented at the Advanced Materials Research.

Alung'at, I. (2017). Might Your Building Be Making You Sick? Retrieved from http://www.nation.co.ke/lifestyle/DN2/Might-your-building-be-making-you-sick/957860-3787496-goh1vfz/

ASHRAE. (2007). Standard 52.2-2007–Method of testing general ventilation air-cleaning devices for removal efficiency by particle size (ANSI/ASHRAE Approved). *Am. Soc. Heat. Refrig. Air-Cond. Eng*.

ASHRAE. (2013). Standard 55-2013:"Thermal Environmental Conditions for Human Occupancy"; ASHRAE *Atlanta USA.*

ASHRAE. (2016a). Standard 62.1-2016, Ventilation for Acceptable Indoor Air Quality. *American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, GA.*

ASHRAE. (2016b). Standard 62.2-2016. Ventilation for acceptable indoor air quality in low rise residential buildings, in *American Society of Heating, Refrigerating, and Air Conditioning Engineers, Inc, Atlanta, GA*.

Awbi, H. B. (2002). *Ventilation of buildings*: Routledge.

Azad, A. S., Rakshit, D., Wan, M. P., Babu, S., Sarvaiya, J. N., Kumar, D. K., . . . Gao, C. P. (2018). Evaluation of thermal comfort criteria of an active chilled beam system in tropical climate: a comparative study. *Building and Environment, 145*, 196-212.

Bean, R. (2010). Mean Radiant Temperature (MRT) - Part I. Retrieved from http://www.healthyheating.com/

BERNAMA. (2013, 14 June). 15 Modern PPR Projects are Being Built Throughout the Country Since 2010. *The Borneo Post Online*. Retrieved from http://www.theborneopost.com/2013/06/14/15-projek-ppr-moden-dibina-di-seluruh-negara-sejak-2010/

Bhatia, A. (2012a). A Basic Design Guide for Cleanroom Applications: PDH Center.

Bhatia, A. (2012b). HVAC Design for Cleanroom Facilities: Continuing Education and Development, Inc.

Bhattacharya, Y., & Milne, M. (2009). Psychrometric Chart Tutorial: A Tool For Understanding Human Thermal Comfort Conditions. *Dept. of Architecture and Urban Design, University of California Los Angeles*.

Cehlin, M., Karimipanah, T., Larsson, U., & Ameen, A. (2019). Comparing thermal comfort and air quality performance of two active chilled beam systems in an open-plan office. *Journal of Building Engineering, 22*, 56-65.

Cerini, M. (2016). Could This Smog-Eating Tower Solve China's Pollution Problem? *CNN Style Design.* Retrieved from http://edition.cnn.com/2016/09/29/design/smog-eating-tower/index.html

Chen, G. (2015, 17 April 2015). Government to Build One Million PPR Homes. *The Star*.

Chen, X., & Wang, F. (2019). *Use CFD Modeling Tool to Study Impact of Energy-saving HVLS Fans on Fire Safety in Large Space*. Paper presented at the ASHRAE Annual Conference, Kansas City, Missouri.

Chenvidyakarn, T. (2013). *Buoyancy effects on natural ventilation*: Cambridge University Press.

CHO, J., WOO, K., & KIM, S. (2019). Removal of Airborne Contamination in Airborne Infectious Isolation Rooms. *ASHRAE Journal, 61*(2).

Chung, L. P., Ahmad, M. H., Ossen, D. R., Hamid, M. B., & Baharvand, M. (2014). The Effects of Orientations on the Room's Thermal Performance in the Tropics. *Applied Mechanics and Materials, Vol. 567*, pp 631-636.

Churkina, G., Kuik, F., Bonn, B., Lauer, A., Grote, R. d., Tomiak, K., & Butler, T. M. (2017). Effect of VOC emissions from vegetation on air quality in Berlin during a heatwave. *Environmental science & technology, 51*(11), 6120-6130.

CIA, C. I. A.-. (2019). The World Factbook. Retrieved from https://www.cia.gov/library/Publications/the-world-factbook/geos/my.html

CIBSE. (2012). CIBSE Knowledge Series KS17: Indoor Air Quality and Ventilation. London: The Chartered Institution of Building Services Engineers (CIBSE).

CIBSE. (2015). Environmental Design. *The Chartered Institution of Building Services Engineers, London, 8th Edition*.

CIDB. (2016). MyCREST: A Reference Guide for Design Stage Certification. Kuala Lumpur: Construction Industry Development Board Malaysia (CIDB).

Cionita, T., Adam, N. M., Jalaludin, J., Mansor, M., & Siregar, J. (2014). *Measurement of Indoor Air Quality Parameters in Daycare Centres in Kuala Lumpur Malaysia.* Paper presented at the Applied Mechanics and Materials.

Colls, J. (1997). *Air Pollution - An Introduction*. London: E & FN Spon.

Craig, S., & Grinham, J. (2017). Breathing walls: The design of porous materials for heat exchange and decentralized ventilation. *Energy and buildings, 149*, 246-259.

Crawley, D. B., Hand, J. W., Kurnmert, M., & Griffith, B. T. (2008). Contrasting the capabilities of building energy performance simulation programs. *Building and Environment*, *43*(4), 661-673. doi:10.1016/j.buildenv.2006.10.027

Crockford, G., & Goudge, J. (1970). Dynamic insulation: an equation relating airflow, assembly thickness and conductance. *Proceedings of the Royal Society of Medicine, 63*(10), 1012.

CTBUH, C. o. T. B. a. U. H.-. (2019). The Skyscraper Center: The Global Tall Building Database of the CTBUH. *Compare Data.* Retrieved from http://skyscrapercenter.com/compare-data

d'Ambrosio Alfano, F. R., Bellia, L., Fragliasso, F., Palella, B. I., & Riccio, G. (2019). *Thermal comfort and visual interaction: a subjective survey*. Paper presented at the 51st AiCARR International Conference: The Human Dimension of Building Energy Performance, Venice, Italy.

Daghigh, R. (2015). Assessing the thermal comfort and ventilation in Malaysia and the surrounding regions. *Renewable and sustainable energy reviews, 48*, 681-691.

DBKL, K. L. C. H.-. (2019). *List of High Rise Social Housing (PPR) Under Supervision of DBKL*. Retrieved from: http://www.data.gov.my/

De Dear, R. J. (1998). A global database of thermal comfort field experiments. *ASHRAE transactions, 104*, 1141.

Di Giuseppe, E., D'Orazio, M., & Di Perna, C. (2015). Thermal and filtration performance assessment of a dynamic insulation system. *Energy Procedia, 78*, 513-518.

Ding, W., Hasemi, Y., & Yamada, T. (2004). Natural Ventilation Performance of a Double-Skin Facade with a Solar Chimney. *CTBUH 2004 Seoul Conference*.

Djamila, H., Chu, C.-M., & Kumaresan, S. (2014). Effect of Humidity on Thermal Comfort in the Humid Tropics. *Journal of Building Construction and Planning Research, 2*(02), 109.

DOE. (2013). *New Malaysia Ambient Air Quality Standard*. Retrieved from Putrajaya:

DOE. (2015). *CHAPTER 1: AIR QUALITY MONITORING*. Retrieved from Putrajaya:

DOE. (2016a). *CHAPTER 1: AIR QUALITY MONITORING* Retrieved from Putrajaya:

DOE. (2016b). *Chronology of Haze Episodes in Malaysia*. Retrieved from Putrajaya: https://www.doe.gov.my/portalv1/en/search/haze

DOE. (2016c). *Monthly Outdoor Air Quality in Kuala Lumpur*.

DOE. (2017). *CHAPTER 1: AIR QUALITY MONITORING* Retrieved from Putrajaya:

DOE, D. o. E.-. (2015). Indoor Air Quality. Putrajaya: Ministry of Natural Resources & Environment Malaysia.

DOSH, D. o. O. S. a. H.-. (2010). Industry Code of Practice on Indoor Air Quality, 2010. Putrajaya: Ministry of Human Resources Malaysia.

Elsarrag, E., Aboulnaga, M., Peacock, A., & Imbabi, M. S. (2006). *Dynamic insulation for energy conservation and improved indoor air quality in hot humid climates.* Paper presented at the Invited keynote paper, ASHRAE Emirates Falcon Chapter, 5th Chapters Regional Conference (CRC).

EN, C. (2012). EN 779-2012 Particle air filters for general ventilation-determination of filtration performance: Brussels: CEN.

Energy, D. W. (2016). Global Wind Atlas. Retrieved 29/11/2016, from Department of Wind Energy http://www.globalwindatlas.com/index.html

Environmental Health Directorate, H. P. B. (1995). Exposure Guidelines for Residential Indoor Air Quality. Ottawa, Canada: Minister of Supply and Services Canada.

ESRI. (2015). ArcGIS. Retrieved 01/12/2016 http://www.esri.com/software/arcgis/arcgisonline

Etheridge, D., & Zhang, J. (1998). Dynamic insulation and natural ventilation: feasibility study. *Building Services Engineering Research and Technology, 19*(4), 203-212.

Fanger, P. O. (1970). Thermal comfort. Analysis and applications in environmental engineering. *Thermal comfort. Analysis and applications in environmental engineering.*

Fuller, G. (2018). *The Invisible Killer - The Rising Global Threat of Air Pollution and How We Can Fight Back*. London: Melville House UK.

Fulton, L., Mejia, A., Arioli, M., Dematera, K., & Lah, O. (2017). Climate Change Mitigation Pathways for Southeast Asia: CO2 Emissions Reduction Policies for the Energy and Transport Sectors. *Sustainability, 9*(7), 16.

Gagge, A. P., Stolwijk, J., & Hardy, J. (1967). Comfort and thermal sensations and associated physiological responses at various ambient temperatures. *Environmental research, 1*(1), 1-20.

Givoni, B. (1994). *Passive low energy cooling of buildings*: John Wiley & Sons.

Gray, R. (2016, 10 February). The Building that 'Sucks Up' SMOG: Cement Absorbs Pollution from the Air and Turns It into Harmless Salt that Washes Off in the Rain. *Mail Online: Science.* Retrieved from http://www.dailymail.co.uk/sciencetech/article-3440356/The-buildings-suck-SMOG-Cement-absorbs-pollution-air-turns-harmless-salt-washes-rain.html#ixzz4Xu5XBPYP

Halawa, E., Ghaffarianhoseini, A., Ghaffarianhoseini, A., Trombley, J., Hassan, N., Baig, M., . . . Ismail, M. A. (2018). A review on energy conscious designs of building façades in hot and humid climates: Lessons for (and from) Kuala Lumpur and Darwin. *Renewable and sustainable energy reviews, 82*, 2147-2161.

Halliday, S. (1997). *Performance of Dynamic Insulation*. Paper presented at the CIBSE National Technical Conference, Edinburgh.

Halliday, S. (2000). *Dynamic Insulation - Guidance Note*. Retrieved from Edinburgh:

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.* (Ph.D), University of Strathclyde, Glasgow.

Imbabi, M., Campbell, J., & Lafougere, S. (2002). *Multi-Layer Dynamic Insulation Panels for Natural Ventilation and Filtration of Urban Air Pollution.* Paper presented at the World Renewable Energy Congress VII, Frankfurt–invited speaker.

Imbabi, M. S.-E. (2012). A passive–active dynamic insulation system for all climates. *International Journal of Sustainable Built Environment, 1*(2), 247-258.

Imbabi, M. S., & Peacock, A. (2003). *Smart breathing walls for integrated ventilation, heat exchange, energy efficiency and air filtration.* Paper presented at the Invited paper, joint ASHRAE/CIBSE conference, Edinburgh.

IPCC. (2018). *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* Retrieved from Geneva, Switzerland:

Ismail, F., Jabar, I. L., Janipha, N. A. I., & Razali, R. (2015). Measuring the quality of life in low cost residential environment. *Procedia-Social and Behavioral Sciences, 168*, 270-279.

ISO. (2015). Cleanrooms and Associated Controlled Environments - Part 1: Classification of Air Cleanliness by Particle Concentration. Switzerland: International Organization for Standardization Geneva.

Jamaludin, N., Mohammed, N. I., Khamidi, M. F., & Wahab, S. N. A. (2015). Thermal comfort of residential building in Malaysia at different micro-climates. *Procedia-Social and Behavioral Sciences, 170*, 613-623.

Jennette, J. P. (Producer). (2014, 12 February 2019). Directional Airflow - What, Where & When? [Presentation Material]

Jo, W.-K., & Lee, J.-Y. (2006). Indoor and outdoor levels of respirable particulates (PM 10) and carbon monoxide (CO) in high-rise apartment buildings. *Atmospheric Environment, 40*(32), 6067-6076.

Jonker, J., & Pennink, B. (2010). *The essence of research methodology: A concise guide for master and PhD students in management science*: Springer Science & Business Media.

JPN, N. H. D.-. (2016). *Statistics Report (3rd Quarter 2016)*. Retrieved from Putrajaya:

Keywood, M., Ayers, G., Gras, J., & Boers, C. (2003). Haze in the Klang valley of Malaysia. *Atmospheric Chemistry and Physics, 3*(3), 591-605.

Khan, F., Latif, M. T., Juneng, L., Amil, N., Mohd Nadzir, M. S., & Syedul Hoque, H. M. (2015). Physicochemical factors and sources of particulate matter at residential urban environment in Kuala Lumpur. *Journal of the Air & Waste Management Association, 65*(8), 958-969.

Kolenbrander, A., Perez, S., Yowell, J., Mach, N., Zarske, M. S., & Carlson, D. (2004a). Pollution Solutions: Cleaning Air With Electrostatic Precipitator. Retrieved from https://www.teachengineering.org/activities/view/cub_air_lesson10_activity1

Kolenbrander, A., Perez, S., Yowell, J., Mach, N., Zarske, M. S., & Carlson, D. (2004b). Pollution Solutions: Washing Air With Wet Scrubber. Retrieved from https://www.teachengineering.org/activities/view/cub_air_lesson10_activity1

Kotani, H., Satoh, R., & Yamanaka, T. (2003). Natural ventilation of light well in high-rise apartment building. *Energy and buildings, 35*(4), 427-434.

KPKT. (2017). JPN Statistic of People's Housing Program (PPR) in 2015 Retrieved 27 April 2017, from Ministry of Urban Wellbeing, Housing, and Local Government http://www.data.gov.my/

Kubota, T., Jeong, S., Toe, D. H. C., & Ossen, D. R. (2011). Energy consumption and air-conditioning usage in residential buildings of Malaysia. *Journal of international Development and Cooperation, 17*(3), 61-69.

Leary, C. A. (1979). Behavior of the wind field in the vicinity of a cloud cluster in the intertropical convergence zone. *Journal of the Atmospheric Sciences, 36*(4), 631-639.

Lechner, N. (2014). *Heating, cooling, lighting: Sustainable design methods for architects*: John wiley & sons.

Leh, O. L. H., Ahmad, S., Aiyub, K., Jani, Y. M., & Hwa, T. K. (2012). Urban air environmental health indicators for Kuala Lumpur city. *Sains Malaysiana, 41*(2), 179-191.

Lenchek, T., Mattock, C., & Raabe, J. (1987). *Superinsulated design and construction: A guide for building energy-efficient homes*: Van Nostrand Reinhold Company.

Lewis, A. (2018). Beware China's 'anti-smog tower' and other plans to pull pollution from the air. *Environment + Energy*. Retrieved from https://theconversation.com/beware-chinas-anti-smog-tower-and-other-plans-to-pull-pollution-from-the-air-90596

Li, N. (2015). *Comparison between three different CFD software and numerical simulation of an ambulance hall.* (Masters of Science Master's Dissertation), KTH School of Industrial Engineering and Management Energy Technology Stockholm. (EGI-2015-017 MSC Division of Energy Technology SE-100 44 STOCKHOLM)

Lubin, J. (2016). 'Humanizing the Megascale' - Case Study: Sky Habitat, Singapore. *CTBUH Journal 2016*(Issue 1), 12-18.

Lucon, O., Ürge-Vorsatz, D., Ahmed, A. Z., Akbari, H., Bertoldi, P., Cabeza, L. F., . . . Vilariño, M. V. (2014). *Buildings. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Retrieved from Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA:

MAMPU, M. A. M. a. M. P. U.-. (2016a). *JPN Statictic of People's Housing Programme (PPR) Rented by States, 2016*. Retrieved from: http://www.data.gov.my/data/en_US/dataset/jpn-statistik-program-perumahan-rakyat-ppr-disewa-mengikut-negeri-2016

MAMPU, M. A. M. a. M. P. U.-. (2016b). *JPN Statistical Status of the Implementation of the People's Housing Programme (PPR), 2016*. Retrieved from: http://www.data.gov.my/data/en_US/dataset/jpn-statistik-program-perumahan-rakyat-ppr-disewa-mengikut-negeri-2016

Marko Jarić, Nikola Budimir, Milica Pejanović, & Svetel, I. (2013). A Review of Energy Analysis Simulation Tools. *7th International Working Conference 'Total Quality Management–Advanced and Intelligent Approaches', 3rd – 7th June, 2013. Belgrade, Serbia*.

MECHON. (ND). Cleanrooms - A Guide to HVAC Systems Design. Retrieved from https://www.mechon.co.uk/cleanroom-hvac-system-design-guide/

Mediastika, C. E. (1999). *Design solutions for naturally ventilated houses in a hot humid region with reference to particulate matter and noise reduction.* University of Strathclyde.

Medinilha, T. A., & Labaki, L. C. (2016, 11-13 July 2016). *Let's Open These Windows! The Influence of Opening Design Parameters on Natural Ventilation.* Paper presented at the PLEA2016 - The 32nd Conference on Passive and Low Energy Architecture, Los Angeles, USA.

MET, M. M. D.-. (2009). *Climate Change Scenarios for Malaysia: 2001 - 2099*. Retrieved from Petaling Jaya:

MET, M. M. D.-. (2017a). *Annual Report 2017*. Retrieved from Petaling Jaya: http://www.met.gov.my/web/metmalaysia/publications/bulletinpreview/monthlyairquality

MET, M. M. D.-. (2017b). Monthly Weather Bulletin - July 2017. Retrieved from http://www.met.gov.my/web/metmalaysia/publications/bulletinpreview/monthlyweather

MET, M. M. D.-. (2019). Malaysia Climate. Retrieved from http://www.met.gov.my/pendidikan/iklim/iklimmalaysia

Meteorology, B. o. (2019). Global climate variability & change. *Climate change – trends and extremes.* Retrieved from http://www.bom.gov.au/climate/change/#tabs=Tracker&tracker=global-timeseries

MGBC, M. G. B. C.-. (2014). Design Reference Guide – Residential New Construction (Rnc). Kuala Lumpur: GreenBuildingIndex Sdn Bhd.

MGBC, M. G. B. C.-. (2017). Green Building Index: Executive Summary As 15 October 2015. Retrieved from http://www.greenbuildingindex.org/organisation-certified-buildings-Summary.html

Milne, M. (2016). Climate Consultant v6. 0. In U. D. o. Energy (Ed.). University of California, Los Angeles.

Ministry of Urban Wellbeing, H. a. L. G. K. (2015). *KPKT Annual Report 2015*. Retrieved from Putrajaya:

Ministry of Urban Wellbeing, H. a. L. G. K. (2016). *KPKT Annual Report 2016*. Retrieved from Putrajaya:

Mohamed Bin Yehmed, F., Abdullah, A. M., Zainal, Z., Zawawi, R. M., & Elawad, R. E. E. (2016). Trend and Status of SO2 Pollution as a Corrosive Agent at Four Different Monitoring Stations in the Klang Valley, Malaysia. *International Journal of Advanced Scientific and Technical Research, 3*(6), 17.

Mohd Sahabuddin, M. F. (2012). *Traditional values and their adaptation in social housing design: Towards a new typology and establishment of 'Air House'standard in Malaysia.* (MSc. Advanced Sustainable Design Dissertation), University of Edinburgh, Edinburgh.

Mohd Sahabuddin, M. F., & Gonzalez-Longo, C. (2015). Traditional values and their adaptation in social housing design: Towards a new typology and establishment of 'Air House'standard in Malaysia. *International Journal of Architectural Research: ArchNet-IJAR, 9*(2), 31-44.

Mohd Sahabuddin, M. F., & Gonzalez-Longo, C. (2017, 3rd - 5th July). *Natural Ventilation Potential in Kuala Lumpur: Assumptions, Realities and Future.* Paper presented at the Passive Low Energy Architecture : Design to Thrive, Edinburgh.

Mohd Sahabuddin, M. F., & Gonzalez-Longo, C. (2018). *Assessing the Indoor Comfort and Carbon Dioxide Concentration in High-Rise Residential Buildings in Kuala Lumpur: The People's Housing Programme*. Paper presented at the CIBSE Technical Symposium 2018 - Stretching the Envelope, London South Bank University.

Mohd Sahabuddin, M. F., & Gonzalez-Longo, C. (2019). Achieving Health and Comfort in High-Rise Residential Buildings by Using Dynamic-Hybrid Air

Permeable Ceiling (DHAPC). *American Society of Heating Refrigerating and Air Conditioning Engineers (ASHRAE) Transactions, 125*(2), 15.

Mohd Sahabuddin, M. F., & Gonzalez-Longo, C. (2019). *Balancing Comfort and Indoor Air Quality in High-Riser Buildings for Social Housing in Kuala Lumpur: From Regulations to Construction*. Paper presented at the 51st AiCARR International Conference: The Human Dimension of Building Energy Performance, Venice, Italy.

Mohd Sahabuddin, M. F., & Howieson, S. (2019). Improving Indoor Air Quality Using Dynamic Insulation and Activated Carbon in an Air Permeable Ceiling. *Building Services Engineering Research and Technology*.

Moreno-Rangel, A., Sharpe, T., Musau, F., & McGill, G. (2018). Field evaluation of a low-cost indoor air quality monitor to quantify exposure to pollutants in residential environments. *Journal of Sensors and Sensor Systems, 7*(1), 373.

MS1525, M. S.-. (2014). MS 1525:2014 Energy Efficiency and Use of Renewable Energy for Non-Residential Buildings - Code of Practice *Air-Conditioning and Mechanical Ventilation (ACMV) System* (pp. 38-51). Cyberjaya, Selangor: SIRIM.

Myers, P. (2018). Activated Carbon Air Filters: Everything You Need to Know. *Air Purifier Technology*. Retrieved from https://molekule.com/blog/activated-carbon-air-filter/

Nave, C. R. (2012). HyperPhysics. *Department of Physics and Astronomy, Georgia State University. Retrieved January, 16, 2017*.

Nicol, J. F., & Humphreys, M. A. (2002). Adaptive thermal comfort and sustainable thermal standards for buildings. *Energy and buildings, 34*(6), 563-572.

Olmsted, R. N. (2008). Pilot study of directional airflow and containment of airborne particles in the size of Mycobacterium tuberculosis in an operating room. *American journal of infection control, 36*(4), 260-267.

Osseiran, N., & Lindmeier, C. (Producer). (2018, 2 May 2018). 9 out of 10 people worldwide breathe polluted air, but more countries are taking action. Retrieved from https://www.who.int/news-room/detail/02-05-2018-9-out-of-10-people-worldwide-breathe-polluted-air-but-more-countries-are-taking-action

Oswald, F., & Riewe, R. (2013). Residential High-Rises without the usage of Air-Conditioning in Tropical Regions - A Case Study of the MET in Bangkok. *SB13 Graz - Sustainable Building Conference 2013*, 768-778.

Passe, U., & Battaglia, F. (2015). *Designing Spaces for Natural Ventilation: An Architect's Guide*: Routledge.

Payus, C., Abdullah, N., & Sulaiman, N. (2013). Airborne particulate matter and meteorological interactions during the haze period in Malaysia. *International Journal of Environmental Science and Development, 4*(4), 398.

Pigliautile, I., Casaccia, S., Calvaresi, A., Morresi, N., Arnesano, M., Pisello, A. L., & Revel, G. M. (2019). *A comprehensive human comfort assess-ment protocol based on multidomain meas-urements and surveys*. Paper presented at the 51st AiCARR International Conference: The Human Dimension of Building Energy Performance, Venice, Italy.

Pistore, L., Cappelletti, F., & Romagnoni, P. (2019). *Indoor Environmental Quality, individual attitudes and group dynamics in shared environments: investigation of users' behavior in school classrooms through a multi-level holistic approach*. Paper presented at the 51st AiCARR International Conference: The Human Dimension of Building Energy Performance, Venice, Italy.

Prajongsan, P. (2014). *Natural ventilation strategies to enhance human comfort in high-rise residential buildings in Thailand.* University of Liverpool.

Rahman, H. A. (2013, 28-29 September). *Haze phenomenon in Malaysia: Domestic or transboudry factor.* Paper presented at the 3rd International Journal Conference on Chemical Engineering and its Applications (ICCEA'13), Phuket, Thailand.

Rahman, S. A., Hamzah, M. S., Elias, M. S., Salim, N. A. A., Hashim, A., Shukor, S., . . . Wood, A. K. (2015). A long term study on characterization and source apportionment of particulate pollution in Klang Valley, Kuala Lumpur. *Aerosol and Air Quality Research, 15*(6), 2291-2304.

REHDA. (2015). Design Reference Guide – Residential Building & Landed Home. Petaling Jaya: GreenRE.

Roaf, S. (2012). Innovative approaches to the natural ventilation of buildings: the imperative for change. *Architectural Science Review, 55*(1), 1-3.

Roth, K., Dieckmann, J., Zogg, R., & Brodrick, J. (2007). Chilled beam cooling. *ASHRAE Journal, 49*(9), 84.

Rumsey, P., & Weale, J. (2007). Chilled beams in labs: eliminating reheat & saving energy on a budget. *ASHRAE Journal, 49*(1), 18.

Safarik, D. (2016). The Other Side of Tall Buildings: The Urban Habitat. *CTBUH Journal, 2016*(I), 20-25.

Said, B. H. M. (2011). An overview of the Uniform Building By-Laws, 1984 & the Amendments 2007 [Part 3/5]. Retrieved from http://badrulhishamarchitect.blogspot.co.uk/2011/03/overview-of-uniform-building-by-laws_963.html

Salmond, J. A., Tadaki, M., Vardoulakis, S., Arbuthnott, K., Coutts, A., Demuzere, M., . . . Macintyre, H. (2016). Health and climate related ecosystem services provided by street trees in the urban environment. *Environmental Health, 15*(1), S36.

Samad, D., Zainon, N., Rahim, F. A. M., Lou, E., & Karim, S. B. A. (2016). *Malaysian Affordability Housing Policies Revisited.* Paper presented at the MATEC Web of Conferences.

Sapian, A. R., Majid, A., Hanita, N., & Hokoi, S. (2012). Natural ventilation around open round floors with pilotis in high-rise residential buildings in tropical areas: harmonization of modern and traditional housing in tropical areas.

Singer, B. C., & Delp, W. W. (2018). Response of consumer and research grade indoor air quality monitors to residential sources of fine particles. *Indoor air*.

Sousa, J. (2012). Energy Simulation Software for Buildings: Review and Comparison. *Proceedings of the international workshop on information technology for energy applications (IT4ENERGY 2012), Lisbon, Portugal*.

Starke, M. (2012). Building Cleanrooms - Regulations, Air-Handling, Design & Construction. Germany: Solution and Handling GmbH.

Strimling, W. E. (1966). Dynamic insulating systems: Google Patents.

Sujatmiko, W., Dipojono, H. K., Soelami, F. X. N., & Soegijanto. (2015). Natural ventilation and temperature conditions in some high-rise building flats in

Bandung and Jakarta in perspective of adaptive thermal comfort. In A. Trihartono & B. McLellan (Eds.), *5th Sustainable Future for Human Security* (Vol. 28, pp. 360-369).

Tahir, M. M., Zain, M. F. M., Sopian, K., Usman, I. M. S., Surat, M., Abdullah, N. A. G., . . . Che-Ani, A. I. (2010). *The Development of A Sustainably Responsive Ultra Low Energy Terrace Housing For The Tropics Incorporating The Raised Floor Innovation*.

Tang, C. K., & Chin, N. (2013). Building energy efficiency technical guideline for passive design. *Malaysia Building Sector Energy Efficiency Project (BSEEP)*.

Taylor, B., & Imbabi, M. (1998). The application of dynamic insulation in buildings. *Renewable energy, 15*(1-4), 377-382.

Taylor, B. J., & Imbabi, M. S. (1997). The effect of air film thermal resistance on the behaviour of dynamic insulation. *Building and Environment, 32*(5), 397-404.

Taylor, B. J., & Imbabi, M. S. (1999). Dynamic insulation in multistorey buildings. *Building Services Engineering Research and Technology, 20*(4), 179-184.

Taylor, B. J., & Imbabi, M. S. (2000). Environmental design using dynamic insulation. *ASHRAE Transactions 106 (1)*.

Taylor, B. J., Webster, R., & Imbabi, M. S. (1998). The building envelope as an air filter. *Building and Environment, 34*(3), 353-361.

Tominaga, Y., Akabayashi, S., Kitahara, T., & Arinami, Y. (2015). Air flow around isolated gable-roof buildings with different roof pitches: Wind tunnel experiments and CFD simulations. *Building and Environment, 84*, 204-213. doi:10.1016/j.buildenv.2014.11.012

Laws of Malaysia (Act 133): Uniform Building By-Law 1984 (UBBL), (2013).

UNFCCC, U. N. F. C. o. C. C. (2017). UN Climate Change: Paris Agreement. Retrieved from http://newsroom.unfccc.int/paris-agreement/

Walliman, N. (2017). *Research methods: The basics*: Routledge.

Watkins, L. (1991). *Air Pollution from Road Vehicles*. London: HMSO Publications Centre.

WHO, W. H. O.-. (2006). WHO Air quality guidelines for particulate matter, ozone, nitrogen dioxide and sulfur dioxide-Global update 2005-Summary of risk assessment, 2006. *Geneva: WHO*.

WHO, W. H. O.-. (2010). WHO guidelines for indoor air quality: selected pollutants.

WHO, W. H. O.-. (2011). *Methods for Monitoring Indoor Air Quality in Schools*. Retrieved from Copenhagen, Denmark:

WHO, W. H. O.-. (2018a). Air Pollution. Retrieved from http://www.who.int/airpollution/en/

WHO, W. H. O.-. (2018b). Exposure to ambient air pollution from particulate matter for 2016 (Report). Retrieved 19 November 2018, from World Health Organization (WHO) http://www.who.int/airpollution/data/AAP_exposure_Apr2018_final.pdf?ua=1

WHO, W. H. O.-. (2019). About WHO. Retrieved from https://www.who.int/about

WHO, W. H. O.-., & UNAIDS. (2006). *Air quality guidelines: global update 2005*: World Health Organization.

Wong, M. S., & Hassell, R. (2009). Tall Building in Southeast Asia – A Humanist Approach to Tropical High-Rise. *CTBUH Journal*(3).

Wong, M. S., & Hassell, R. (2012). Case Study: The Hansar, Bangkok. *CTBUH Journal*(1).

Yang, F., Qian, F., & Lau, S. S. Y. (2013). Urban form and density as indicators for summertime outdoor ventilation potential: A case study on high-rise housing in Shanghai. *Building and Environment, 70*, 122-137. doi:10.1016/j.buildenv.2013.08.019

Yuan, C., & Ng, E. (2012). Building porosity for better urban ventilation in high-density cities - A computational parametric study. *Building and Environment, 50*, 176-189. doi:10.1016/j.buildenv.2011.10.023

Yusuf, Y. A., Pradhan, B., & Idrees, M. O. (2014). Spatio-temporal assessment of urban heat island effects in Kuala Lumpur metropolitan city using Landsat images. *Journal of the Indian Society of Remote Sensing, 42*(4), 829-837.

Zaid, N., & Graham, P. (2011). Low-cost housing in Malaysia: A contribution to sustainable development? *Proc., Energy, Environment and Sustainability*, 82-87.

Zaid, S. M. (2015). Measuring Operational Affordability of Public Low-Cost Housing in Kuala Lumpur. Case study of People's Housing Programme

Public Low-Cost Housing in Kuala Lumpur. *International Journal of Social Sciences, 4*(4), 54-74.

Zain, Z. M., Taib, M. N., & Baki, S. M. S. (2007). Hot and humid climate: prospect for thermal comfort in residential building. *Desalination, 209*(1-3), 261-268.