Design for Fire Safety Onboard Passenger Ships

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Summary

The importance of this research work comes from the fact that fire accidents have always been considered among the greatest hazards threatening safety onboard ships beside collision, grounding and hull structural failure. On the other hand, the introduction of Regulation 17 of the performance-based design in Chapter II-2 of SOLAS convention and more importantly the incapability of the current prescriptive regulations to cover all aspects in marine fire safety raised the challenge in using the state-of-the-art tools to quantify and assess fire risks in the early stages of a design in order to reduce or even prevent them. This illustrates the shift in ship design from the reactive approach based on prescriptive rules and triggered by disasters to the proactive approach based on design performance and driven by technology and tools development.

The research undertaken in this thesis is an attempt to handle fire safety onboard passenger ships in a performance-based approach. For this purpose the thesis entails: review of the whole concept of the new design philosophy based on assessing the design's performance by quantifying and evaluating risk; collection and analysis of a number of significant fire incidents data to preliminary indentify the most hazardous areas onboard for further studies; investigation of the capabilities of relevant simulations codes and performing further sensitivity studies for the selected models; setting computational methods for the quantification of the effects of human exposure to fire effluents; Integration of the aforementioned models and methods in a platform capable of assessing the fire safety performance of a design in form of life loss (injuries and fatalities); comparison of the final outcomes of the different fire model types used in the study; undertaking a design case study in form of a demonstrative fire scenario for a novel design to illustrate the usability of the fire safety performance-based approach proposed in this thesis.

By defining the problems encountered in shipboard fire safety and by offering an integrated platform of computer-simulated programs and an approach to evaluate the

fire safety performance of a novel design deviating from prescriptive rules, this thesis is made a new contribution to the field of shipboard fire safety in particular and safety of life at sea in general.

On the other hand, due to the novelty of the field and time limitation of this research, there remains lots of work to be done including among others: proper utilisation of the historical data, performing experimental tests of shipboard fires, further development of the relevant simulation tools, widening the range of the model applicability to involve different aspects and spaces onboard.

Finally, it can be said that this thesis work can be considered as an important step in the achievement of a holistic approach in ship safety based on risk quantification and evaluation of design performance rather than complying with prescriptive rules.

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1 Introduction

1.1 Introductory Remarks

This introductory chapter will present the background of the problems encountered in handling fire safety onboard passenger ships. Thereafter, the problems at hand will be formulated as statements for clear understanding of the standing issues in shipboard fire safety. Moreover, the main concept of the thesis focus will be revealed briefly in this chapter. Finally, the structure of the thesis with a short description of every chapter will be presented to facilitate the following of the subsequent ideas and actions carried out during this thesis.

1.2 Background

Fires onboard ships have always been considered among the most serious hazards that might encounter ships at sea. Many disasters have been reported to occur in the maritime field as a result of fire incidents. Several risk analysis studies reported fire onboard ships as one of the greatest hazards threatening safety beside collision, grounding and hull structural failure [Konovessis and Vassalos, 2007] [Vanem and Skjong, 2004]. Additionally, the new ship design development led to construction of passenger ships with an increasing passenger's carrying capacity. The increase in number of lives onboard implies that any serious shipboard accident has the potential for disastrous consequences. On the other hand, fires onboard ships are known to be much more difficult to put off than onshore fires. This difficulty is obvious as the access to fire location can be complicated due to the complex nature of ship geometry. Wind speed and direction can have significant effects on fire development and propagation, where for instance wind played an important role in fire propagation onboard *Star Princess* which resulted in severe consequences including the loss of a life and many injuries from the human life safety viewpoint (See Appendix A). In addition, great care should be taken in the use of fire fighting equipment especially extinguishing water and its drainage in order to keep the ship's side list under control. Inappropriate use of fire fighting systems can result in very severe consequences which was the case when *Al-Salam Boccaccio* sank as a result of water accumulation on a vehicle deck taking more than 1000 lives with her (See Appendix A).

Ships were always protected against fire hazards by a reactive approach through SOLAS regulations which were updated repeatedly in the light of every fire disaster and the resulting growing experience. However, these rules have always been found unable to protect all aspects onboard ship. For instance the latest fire aboard *Star Princess* was ignited on a balcony which was considered an open deck area according to the prescriptive regulations and minor fire restrictions were applied to this space category [SOLAS, 2004] [MAIB, 2006]. The international regulations related to fire safety onboard ships are cited and further discussed in the literature review in Chapter 3. The implementation of fire safety regulations as design constrains started to change by the introduction of Regulation 17 of the alternative design and arrangements in Chapter II-2 of SOLAS convention. Also, the rising calls for the new design philosophy; "Design for Safety" adopting the Risk-Based approach favours the consideration of safety as a goal and not just a constraint for ship design [Vassalos et al., 2006; 2005; 2003]. Thus, safety in design is no longer just a straight forward application of rules. Safety approach in ship design is changing from reactive where regulations are enhanced in response to new disasters to a proactive approach where hazards are measured before they happen in order to reduce or even prevent them. Novel designs which are rather based on their performance than on complying with regulations initiate the full use of the state-of-the-art tools. Fire and smoke development prediction and evacuation models, consist the core of the tools used to assess safety performance of novel designs. The main advantage of simulation tools is their capability to predict the safety level of a design in its early stage of construction.

1.3 Formulating the Problem

From the preceding section, it was clear that the current prescriptive regulations were shown to be incompetent in protecting all aspects of the ship regarding fire safety. Even though SOLAS (Reg II-2 / 17) introduced the equivalency approach into ship design and the calls were rising for the adoption of a performance based approach in ship design, the application of these approaches in the marine sector were still limited. The reasons for the limited utilisation of the performance based approach are mainly the simplicity in using prescriptive approach design which is straightforward and requires less effort to accomplish and approve. As well, the major difficulty facing the utilisation of the novel approach based on design performance is the need for the expertise use of the fire engineering tools, their integration, applicability and proper deployment in order to assess the performance of a design. In addition, as far as passenger ships are concerned, the applicability of these tools is primarily crucial in the most critical places shown to have higher life loss potential than others. A design safety performance can be broken in three main categories; human life safety, damage to property and environmental damage. This study will mainly consider the hazards associated with fires that have impact on human life safety, thus the relevant parameters (such as smoke density, toxicity, temperature and heat flux) should be predicted in a reasonable accuracy as required for the life safety assessment conducted in the critical spaces identified. The fire resulting conditions should be properly integrated to evacuation models and exposure effects quantification methods to assess the fire safety performance of a design in terms of well defined final consequences criteria.

The research conducted in this thesis will mainly focus on the identification of the most vulnerable spaces onboard passenger ships regarding the impact of fire on human life safety. Thereafter, the development of the fire safety assessment tool by integration of the appropriate simulation models will be illustrated. The final outcome of the tool will be in form of life loss. In addition, the proper utilisation of the developed tool in the critical spaces identified will be demonstrated and analysed. Moreover, the assessment suite will be used to evaluate the performance of a design deviating from the prescriptive rules and interpret the resulting predictions. The next section in this chapter will provide more details about the whole structure of the thesis.

1.4 Structure of the Thesis

The thesis is structured in 14 chapters in addition to appendices. A brief outline of the chapters is given below:

Chapter 1 **(Introduction)**: This chapter outlines the background of the study describing and formulating the problems encountered in marine fire safety. It initiates the research conducted in this thesis.

Chapter 2 (**Aim and Objectives**): This chapter describes the main aim and specific objectives to be achieved in this research.

Chapter 3 (**Literature Review**): This chapter reviews the key elements relevant for this study including safety regulations, design concepts and the essentials in fire safety engineering.

Chapter 4 (**Approach Adopted**): This chapter defines the problem at hand and present the approach adopted in this thesis. It also presents the main concepts of tools utilised to achieve the approach.

Chapter 5 (**Shipboard Fire Incidents**): This chapter presents the collected data about fire incidents onboard passengers ships and identifies the most hazardous shipboard spaces for further considerations.

Chapter 6 (**Application of Fire Models**): This chapter represents the benchmarking of fire models against experimental test data to select the most suitable models for this study and then the application of selected fire models to critical ship geometries, particularly in the accommodation areas.

Chapter 7 (**Integration of Fire and Evacuation Models**): This chapter illustrates the integration of fire models with the evacuation model and the associated quantification methods to assess the effects of passenger's exposure to fire products.

Chapter 8 (**Design Case Studies**): This chapter demonstrates the use of the computer software-suite in assessing the safety performance of a novel design violating the prescriptive rules and compare the outcomes to the performance of a design complying with the regulations.

Chapter 9 (**Discussion**): This chapter outlines the developments, findings and main contributions of this research to the field and provides recommendation for future work.

Chapter 10 (**Conclusions**): This chapter summarises the main conclusions of this research study.

Chapter 11 (**References**): This chapter lists all the references used in this thesis.

1.5 Concluding Remarks

During this introductory chapter, the background and other considerations that initiated the undertaking of this research were presented and explained. The main gaps in addressing fire safety onboard passenger ships and the recent calls for change were put forward. The problems at hand were formulated and presented, and the main concept of the thesis focus was also revealed.

In this respect the current thesis work will focus on the integration of an assessment tool capable of reasonably predicting the consequences of a design fire scenario in terms of life loss. The applicability of this tool to spaces of interest onboard passenger ships is also considered in this study. The following chapter will clearly state the aim of the research and set of objectives to be achieved.

2 Aim and Objectives

The main aim of this thesis is to integrate different engineering approaches in order to develop a methodology that can be used to quantify fire safety performance of a novel design violating the prescriptive rules. The development and implementation of the quantification approach incorporates the philosophy of performance-based design and show its applicability to passenger ships.

To achieve this aim, the following specific objectives should be fulfilled:

- To review the current regulations governing fire safety onboard passenger ships, the new ship design concept of risk-based approach and the state-of-the-art tools used in fire safety engineering. Also, data of fire incidents onboard passenger ships was collected and analysed to screen ship spaces in order to prioritise the scenarios with higher risks

- To apply fire models to critical ship geometries, particularly the accommodation areas, to analyse the applicability, functionality and limitations of these models. Benchmark these models against experimental data when available and compare the predictions of the utilised models.

- To consolidate the selected fire and evacuation models along with the quantification methods to assess the effects of human exposure to fire effluents in form of fatalities and injuries.

- To implement the collection of computer programs in the assessment of the fire safety performance of a novel design violating the prescriptive regulations and compare the final consequences to the ones of a rules complying design. Based on the analysis and interpretation of the case study, means are suggested to improve the novel design.

3 Literature Review

3.1 Introductory Remarks

In this chapter the literature covering the main aspects of the study are reviewed. The review starts by looking at the regulations that govern and enforce fire safety onboard ships, considering the procedure of development for these regulations over time. Thereafter, deriving from the review of regulations, the need, introduction and development of the new safety concept based on risk assessment are reviewed here. In addition, the review went over fire safety engineering, covering the sides which were found mainly useful for the current study knowing that fire engineering topic is a very wide one. Previous surveys of simulation tools were reviewed as well. In the last part of the review, relative fire research studies dealing with fire safety with focus on the marine sector were reviewed. This all has been done in order to identify the missing efforts needed to close further the gaps in shipboard fire safety research.

3.2 Shipboard Fire Safety Regulations

Ships are protected against fire hazards through the regulations of the International Convention for the Safety of Life at Sea of the International Maritime Organization [SOLAS, 2004]. A convention is a treaty between states who accept responsibility for implementing its regulations on their ships [Cowley, 2006]. The first version of SOLAS convention was founded in 1914 in response to the *Titanic* disaster in 1912. The main purpose of the convention was to settle minimum requirements for safety. The consecutive convention versions were amended continuously in the light of every major accident drawing the attention to new safety aspects onboard. When changes to the regulations are deemed necessary (usually after accidents), proposals are submitted to the IMO's Maritime Safety Committee (MSC). If the majority of delegates agree on the proposal, the issue will be on the schedule of the Fire Protection (FP) Sub-committee which calls for papers on the subject. After considering the submitted papers, proposed changes (draft amendments) are reported to the MSC and then circulated to all participating countries where at least six months should elapse before adoption. After adoption the contracting governments have the opportunity for objection within two years before the amendments enter into force six month after acceptance or whatever date the MSC decided at time of adoption [Cowley, 2006]. The amendments procedure proved to be slow. As a result a completely new convention of SOLAS was adopted in 1974. This convention is still used until the date of writing this thesis and was amended on numerous occasions.

In particular, Chapter II-2 of SOLAS governs fire safety onboard. The regulations provide all fire safety provisions starting with division and separation by thermal and structural boundaries, continuing in restriction of combustible materials and detection of fire in place of origin. Thereafter, in the case of a fire incident, the regulations cover the containment and extinction procedures in place of fire origin. Then the means of escape or fire-fighting are protected through special provisions which extend to ensure the availability of fire-extinguishing appliances and minimize the possibility of ignition. Chapter II-2 was majorly amended on several occasions up to date of the time of writing this thesis [SOLAS, 2004] [IMO-webpage]. Following, are some brief highlights of these amendments:

In 1981, the chapter was re-arranged to strengthen the fire safety requirement for cargo and passenger ships.

In 1989, the amendments adopted improved fixed fire-extinguishing and smoke detection systems in addition to location and separation of spaces among other several regulations.

In 1991, 1992 and 1994, additional improvements were made to the fire safety chapter.

In 1996, considerable modifications were done to chapter II-2 and a new International Code for Application of Fire Test Procedures was introduced for products approval.

In 2000, a revised chapter which was made clear and user-friendly, and a new International Code for Fire Safety Systems which includes detailed specifications for fire safety systems were adopted.

In December 2002, the International Maritime Dangerous Goods Code was adopted.

In May 2006, requirements for testing and approving of water mist nozzles and new arrangements for flammable oils were employed.

In December 2006, radical amendments were adopted emphasising casualty occurrence in the first place then improving survivability for safe return to port in case of casualty. The amendments also provided the flexibility to ship designers to meet future safety challenges by providing the alternative designs and arrangements. In addition the new regulations covered safe areas to return to port, fire detection and alarm systems, enhancing fire safety of atrium and means of escape and time for orderly evacuation and abandonment. The amendments to SOLAS chapter II-2 and the International FSS code were developed to strengthen fire safety of cabin balconies in response to the fire onboard *Star Princess* in March 2006. The aim was to apply the existing regulations to the balconies as well. These regulations cover the primary deck covering, ceiling and linings, use of combustible materials and smoke generation potential and toxicity. For existing passenger ships, the provisions require the furniture on balconies to be of restricted fire load unless fixed water spraying systems, fixed fire detection and fire alarm systems are fitted and partitions between balconies are made of non-combustible materials.

As seen above, the rules were updated repeatedly in the light of every novel fire incident and the resulting growing experience. However, each new accident shows the incapability of regulations to protect all aspects of the ship. The introduction of Part F (Regulation 17) of “Alternative design and arrangements” amendments sets out a methodology for approving novel or alternative designs. Besides, the Maritime Safety Committee approved the guidelines on alternative design and arrangements for fire safety to provide further guidance for application of fire safety engineering design. The alternative design should prove to achieve at least a safety performance level equivalent to the performance of a design complying with the prescriptive rules. This demonstration can be carried out through a risk-based fire engineering analysis according to the guidelines. The alternative designs are evaluated to approve their safety performance. The evaluation process may differ depending on the level of evaluation necessary (based on the scope defined during the preliminary analysis), but should generally follow the process in Figure 3-1 [IMO, 2001].

On the other hand, the rising calls for the design philosophy “Design for Safety” favour the consideration of safety as a goal and not just a restriction into the ship design process [Vassalos, 1999; 2006; 2000]. Thus, safety in design is no longer just straight forward application of the rules. Recent designs are rather based on the performance of the novel design which initiates the full use of the state-of-the-art tools to assess the associated hazards. The next section will provide a review over the need, introduction and development of the new safety design concept based on risk assessment.

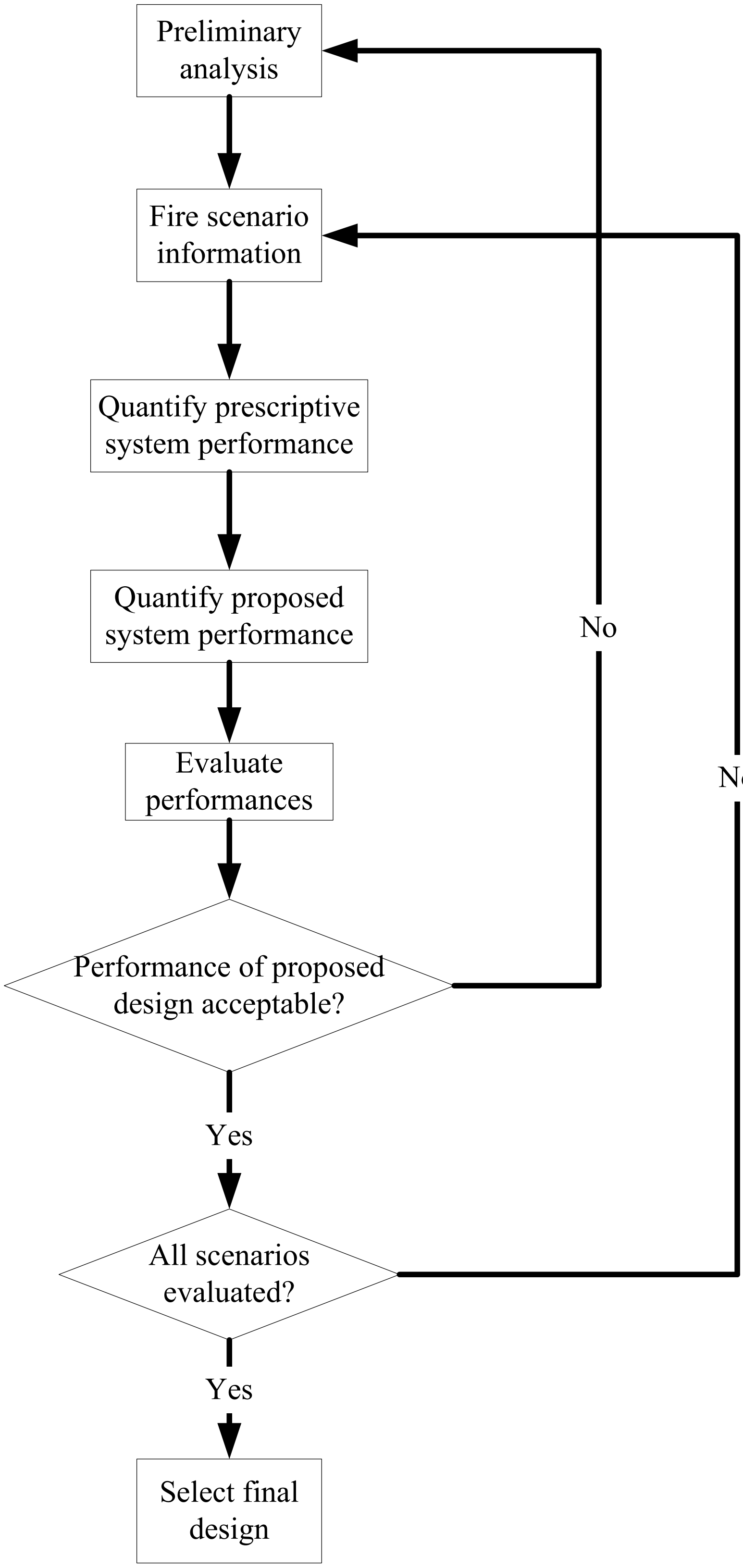

Figure 3-1: Alternative design and arrangements process flowchart [IMO, 2001].

3.3 The Risk-Based Approach for Ship Design

3.3.1 The Conventional Ship Design Approach and the Need for a New Design Concept

As reviewed in the previous section, safety in ship design has been dealt with, traditionally, by application of prescriptive rules and regulations and thus treated as a constraint to the design process. User requirements and technology in ship design were developing faster than safety knowledge which was relying on rules updated according to the gained experience after each marine disaster. The lack of a holistic approach that embraces all safety aspects of a ship left many uncovered gaps in safety onboard ships. The consecutive disasters in the marine sector drew more attention to the safety approach adopted in ship design. This increased the appreciation of risk quantification in the marine industry and the necessity of a holistic risk-based approach capable of addressing all risks faced onboard in a cost-effective way throughout the entire life of the vessel. This resulted in a tendency to move from prescriptive to performance-based approaches where safety is a central objective of the design and dealt with as a target rather than a simple compliance with the rules. Calls for the application of this novel approach in ship design and developments of its methodology were introduced in several publications [Vassalos], [SAFER-EURORO] and [SSRC]. A different design philosophy was introduced under the theme of “Design for Safety” which treats safety as a design objective rather than a constraint; this design is presented and described in [Vassalos et al., 2000] [Hormann, 2003] [Bakker et al., 2000]. Although ship designers always account for safety, this is done by compliance with rules and not addressed optimally. The “Design for Safety” approach aims to treat safety at the heart of design rather than treated as to be in conflict with ship production and operation, and isolated from other ship design factors. In the new methodology, safety is maximized by being treated as a design objective with the support of advanced safety performance prediction tools, in a holistic systematic approach considering all factors of safety onboard for the whole life-cycle of a ship.

Vassalos [1999] identified the deficiencies of safety handling in the conventional ship design approaches as, on one hand safety is treated as a global concept and the fragmented attempts to improve safety were found incomplete and not satisfactorily effective. On the other hand, the conventional approach lacks a systematic and all-embracing approach to ship safety which can make use of the information and knowledge cumulated during the years of research and development.

Sames [2004] cited the main drivers behind the switch from prescriptive based design to a risk based approach:

- Societal drivers for maritime safety: the society expectations for higher safety levels always exert a continuous driving force to improve the safety of waterborne transport

- Maritime safety regulations: the proposals and papers submitted by different parties drive the International Maritime Organization to develop new regulatory regimes

- Market drivers for innovative ship designs: the growth of market for different types of ships drives the innovation in design beyond the regulatory constrains

- Ship design as competitive advantage: advanced and integrated tools can provide the necessary knowledge for optimization in early stages of the design

- Design for Safety: all research activities related to design for safety are coordinated through projects towards a full risk based approach

The aim of ship design is in general to deliver a vessel design that performs in accordance with the expectations defined by the owner’s operational and functional requirements while complying with the statutory rules and regulations as well as ensuring that the construction process keeps to budget and schedule [Vassalos et al., 2006]. A possible generic and high-level representation of the ship design process is illustrated in Figure 3-2.

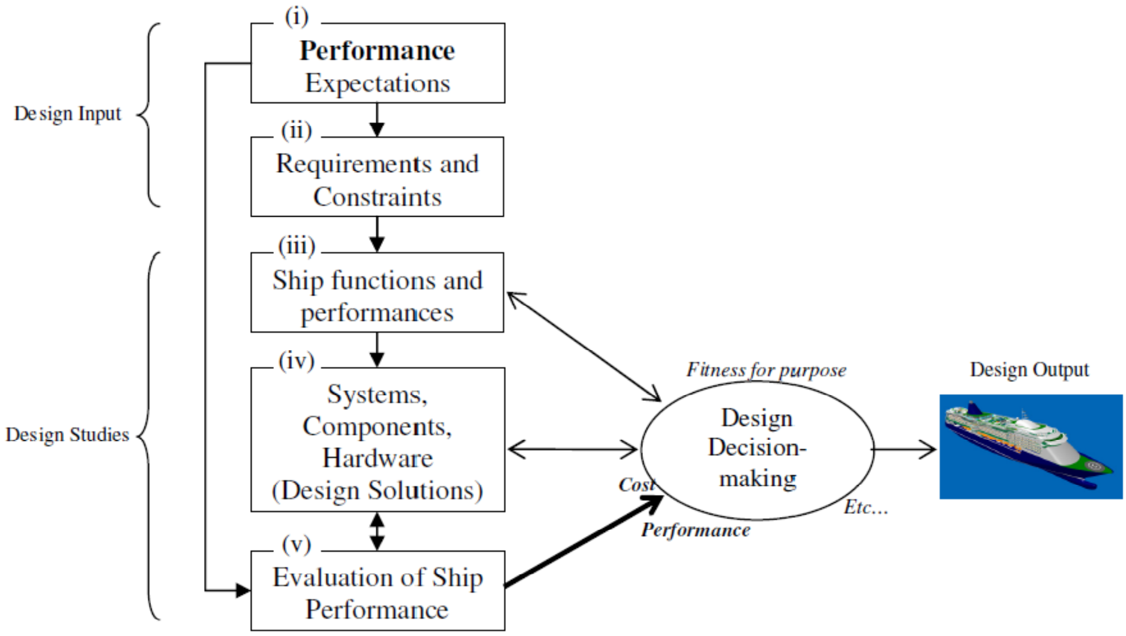

Figure 3-2: High level conventional design process [Vassalos et al., 2006]

The design input is divided in two categories; "performance expectations" and "requirements and constraints". These are derived from the ship owner's market, business and logistics analysis as well as from other stakeholders' expectations like general public opinion, charterers, customers, etc. The shipyard plays the essential role in defining requirements and constraints like building cost and time. The design studies involve design optimisation by managing many factors including safe operation, technical performance, preferences, cost logistics, etc. In this approach, safety is considered at the same level as other design factors; however it is limited to rule compliance and hence treated as a design constraint and not a design goal.

According to this conventional definition of ship design some innovative designs are not allowed to progress because they cannot comply with one or some of the safety regulations. Compliance with the prescriptive safety rules implies that the minimum level of safety performance according to the regulating authorities is attended.

Identification of the positive and negative sides of the rule compliance approach resulted in a list which can be summarised as follows [Vassalos et al., 2006]:

- Rules are minimum requirements that reflect average safety, hence may not be appropriate, consistent, and/or optimal in all cases.
- Most rules are developed in the wake of major accidents; as such, they are targeting to reduce consequences to appease public outrage; in some cases, emphasis or even relevance to design is all but lost.
- If the evaluated design is not encompassed or does not correspond to the data set used to derive the rules, then the design may be unnecessarily penalised or its safety performance might not be optimal or it might even be unsafe.
- In a rule-based regime "there is no chance to beat the competitors", as advances in technology are conveyed to others by the (prescriptive) rules. On the other hand, with safety imposed as a constraint to the design process, the transfer of knowledge between the design, production and operational phases is hindered (rule evolution is too slow).
- By specifying minimum requirement, a design that fulfils the requirement by far is considered as of the same safety level as a design that just "passes" the requirement – this is the major point where designers do not usually achieve a balance "best compromise" and the reason for the conclusion that "safety costs" or at best "safety does not pay".
- Rules are however easier to fulfil and facilitate class/flag changes (desirable). They are easy to apply and easy to check for the unskilled (which is rather undesirable).

With all the aforementioned, it became clear that there is a need to develop and adopt a different design approach. A new integrated approach that links safety performance prediction, risk assessment and design in a way that allows for interaction and iteration. The philosophy of a design for safety concept is illustrated as an iterative process in Figure 3-3.

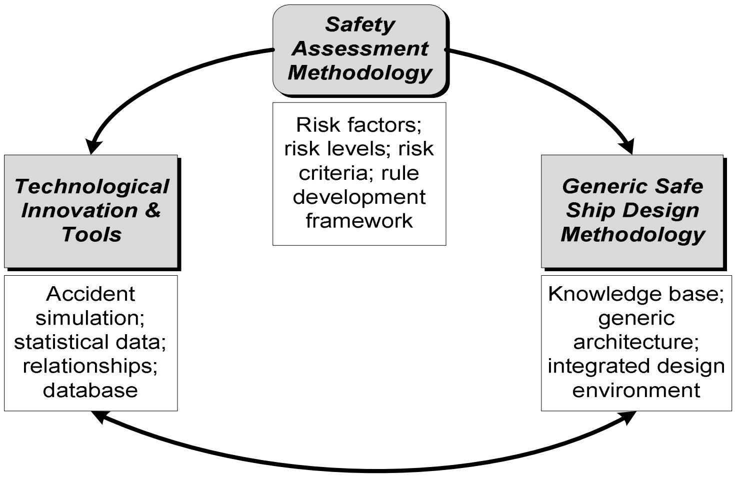

Figure 3-3: Iterative process of the design for safety philosophy [Vassalos, 1999].

The main differences between the conventional ship design approach and the new approach "design for safety" are summarised in Table 3.1 below; noting that the list is indicative rather than exhaustive.

Table 3.1: the list of differences between the conventional ship design approach and the new ship safety approach; reproduced from [Vassalos, 1999]

Conventional	New
Reactive	Pro-active
Prescriptive	Goal-setting
Regulation	Self-regulation
Deterministic	Probabilistic (risk-based)
Conformance-based	Performance-based
Compulsory	Safety Culture
Discipline-oriented (sectorial)	Total (integrated)
Experimental	First principles (calculation/simulation)
Hardware focus	Balance of safety elements
Short-term	Life-cycle
Irrational (subjective/emotional/political)	Rational (scientific/cost-benefit analysis)

Hadjisophocleous [1998] identified in more detail the advantages and disadvantages of the prescriptive based design and the performance based design. These are presented in the table below:

Table 3.2: The main advantages and disadvantages of prescriptive and performance based design codes [Hadjisophocleous et al., 1998]

Code Type	Advantages	Disadvantages
Prescriptive codes	• Straightforward evaluation of compliance with established requirements • No requirements for high level of engineering expertise	• Requirements specified without statement of objectives • Complexity of the structure of codes • No promotion of cost-effective designs • Very little flexibility for innovation • Presumption that there is only one way of providing the level of safety
Performance codes	• Establishment of clear safety goals and leaving the means of achieving those goals to the designer • Permit innovative design solutions that meet the performance requirements • Eliminate technical barriers to trade for a smooth flow of products • Facilitate harmonization of international regulation systems • Facilitate use of new knowledge when available • Allow for cost-effectiveness and flexibility in design • Non complex documents • Permit the prompt introduction of new technologies to the market place	• Difficult to define quantitative levels of safety (performance criteria) • Need for education because of understanding especially during first stages of application • Difficult to evaluate compliance with established requirements • Need of computer models for evaluating performance

3.3.2 The "Design for Safety" Concept – A Risk-Based Approach

The "design for safety" concept in ship design aims to account for safety more effectively in a rational way. *"If something cannot be measured it cannot be improved"* as stated in [Vassalos, 1999]; therefore a consistent measure of safety must be employed and a corresponding method of quantification must be adopted. The measure of safety is risk and the quantification method is the quantitative risk analysis. The risk quantification method should be integrated to the design process in a way that allows the designer to tackle safety issues systematically and rationally beside other design objectives related to performance, cost and earnings. This integration of safety in the optimization procedure of ship design necessitates the use of first-principles frequency estimation and consequences analysis tools for novel design cases. In addition it would be essential to investigate trade-offs between safety and other factors by utilising overlaps between functionality, performance and safety at parameter level. The new risk-based design approach implies three simple points; firstly it is a formalised design methodology; secondly it accounts explicitly for safety in the design procedure; and thirdly it adopts a rational decision making process based on cost-effectiveness to address safety. Therefore, in the risk-based design approach, an additional set of criteria has to be fulfilled in the optimization process in order to achieve the required safety standards cost-effectively, and hence safety is treated as another design objective which must be satisfied [Vassalos et al., 2005].

Bakker [2000] presented a risk assessment approach accounting for the accident scenarios that could impair the safety of the ship considered and assessed. The schematic presentation of the approach is illustrated in Figure 3-4

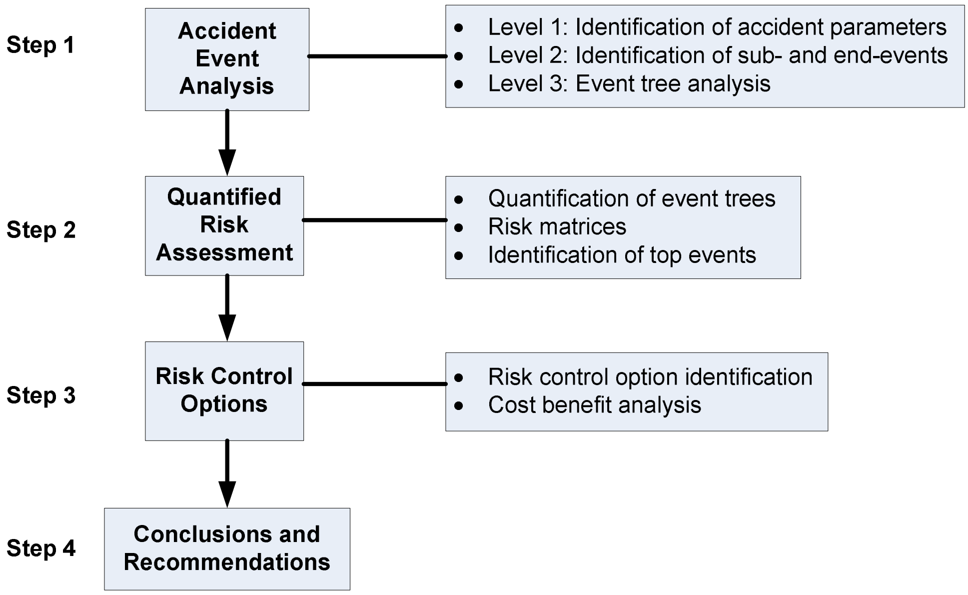

Figure 3-4: Flow diagram of the risk assessment approach; [Bakker et al., 2000]

Traditional ship design methodologies tended to examine the performance criteria of a ship extensively, without giving much attention to safety related factors particularly at the initial stages of a design. Ship safety can be influenced by several factors over time and it is apparent that to reach an acceptable and practicable solution optimally all such factors should be considered in a balanced and formalised manner over the life-cycle of the ship. But more importantly during the early stages as the cost of design changes increases significantly as the design process progresses. The design for safety philosophy consolidated within the risk-based design framework will form the basis for developing a software suite to integrate ship design knowledge, first-principle methods, state-of-the-art simulation tools, systematic risk analysis and decision making procedures to facilitate safety considerations cost-effectively through the whole design process [Vassalos et al., 2005]. This can be illustrated in Figure 3-5, which provide a general idea of the relation between risk analysis and the design process.

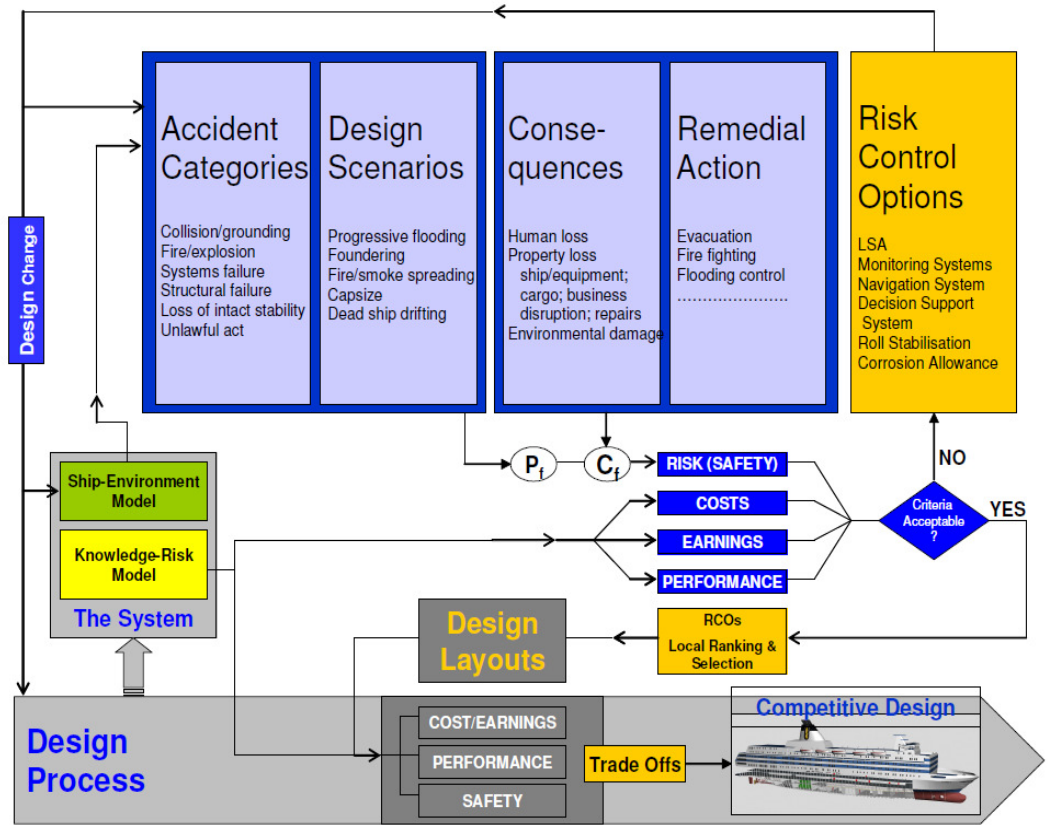

Figure 3-5: Overview of risk-based design (b); reproduced from [Vassalos et al., 2005]

The risk-based design can be seen as a "design for safety" application which provides the capability to achieve a competitive design within a specific area when the effects of a risk contributor are taken into account. At this level of the design, the input parameters required involves the following [Konovessis, 2001]:

- Design parameters and characteristics relevant to the specific events and themes
- Generic information for the specific risks
- Local design and operational preferences
- Design and risk evaluation criteria
- Relevant risk control options

The different steps and logical sequence of the procedure are illustrated in Figure 3-6 below. The steps comprised in the procedure can be summarized as follows [Vassalos et al., 2005]:

- Selection of risk acceptance criteria, as well as other design criteria
- Estimation of the frequency of an incident occuring
- Estimation of the cost of consequences
- Estimation of the implied risk level and categorisation according to the severtiy of the consequences
- Consideration of safey-enhancing measures to improve undesirable risk levels (these involves using both the available risk control options as well as those resulting from undertaking parametric studies)
- Setting up of the optimisation problem and consideration of an objective function appropriate to performing trade-offs among the specified societal and techno-economic targets (criteria)
- All necessary iterations

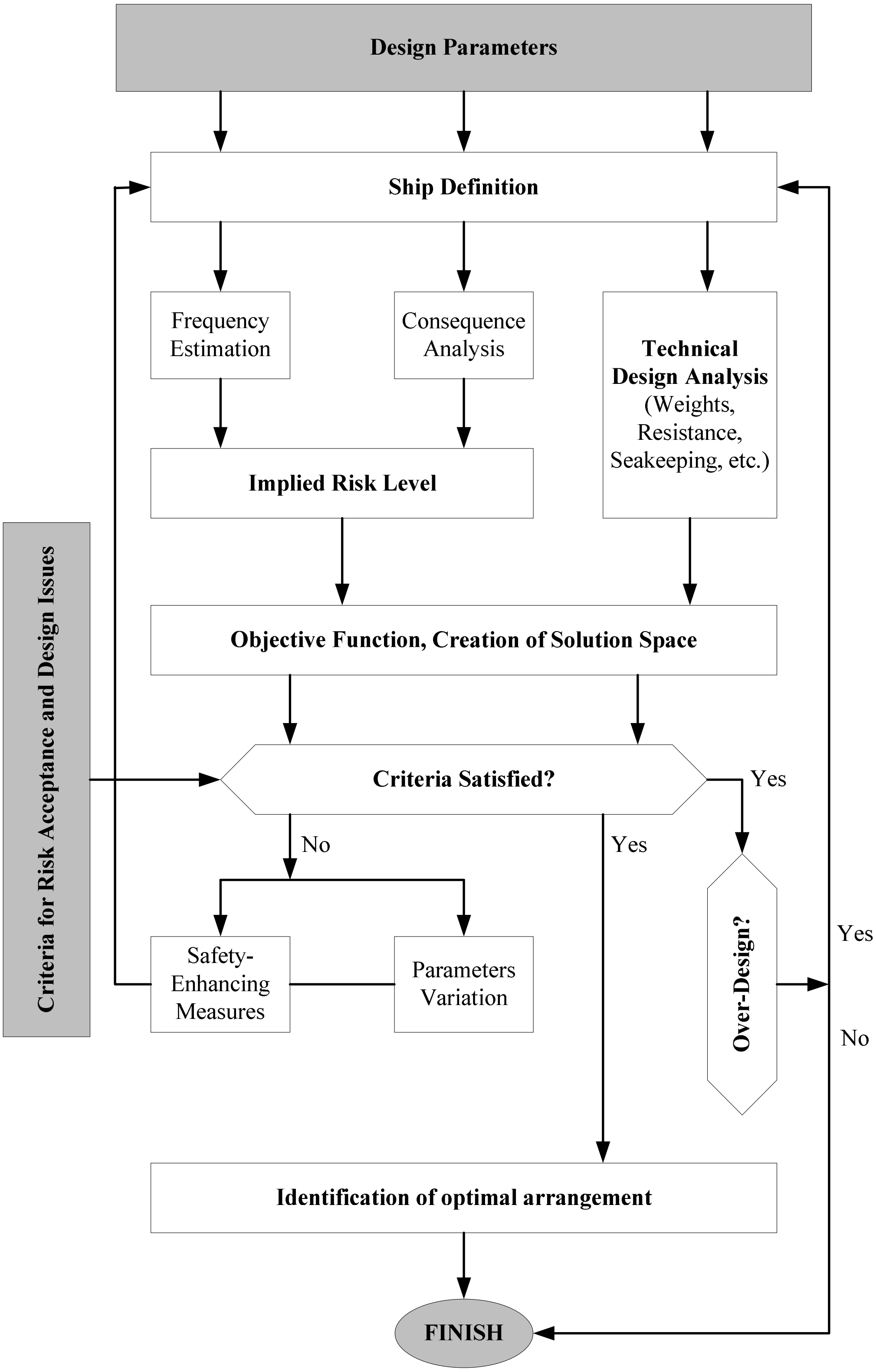

Figure 3-6: Risk-Based design framework; reproduced from [Konovessis, 2001]

3.3.3 The Risk-Based Approach and Risk Acceptance Criteria

In the past years the rules served to maintain the safety objectives required by authorities but most changes and improvements were resulted as reactions to accidents and disasters. However, it was seen that rather than waiting for every accident to happen in order to update the rules that may or may not improve safety, the new risk-based methodology proposed that all the knowledge resulting from the accidents are analysed and stored to be used as early as possible in the design process. Unlike prescriptive rules which treat safety of the ship implicitly with other design factors, risk-based design methodology addresses safety explicitly. Explicit consideration of safety is equivalent to evaluating risk during the design. As aforementioned safety need to be measured in order to be improved and risk can be considered the currency of safety. Vassalos [2006] defined the risk-based design as: "*Risk-based design is a formalised methodology that integrates systematically risk assessment in the design process with prevention/reduction of risk (to life, property and the environment) embedded as a design objective, alongside conventional design objectives such as speed, capacity, etc*".

Depicted in Figure 3-7 below, is a possible high level framework of a risk-based design. The safety assessment procedure in the risk-based design in Figure 3-7 is a systematic risk assessment process which can be conducted in a variety of ways. The suitable approach should be selected taking into account issues such as the stage of the design, major hazard potential and risk decision context, etc. The safety goals in the safety assessment are related to the ship's mission and purpose. Explicit safety goals are already a part of the design input. To achieve the safety objectives required more specific functional requirements should be defined and attained. The identification of the functional requirements should be based on rational assessments to identify the hazards that can obstruct the achievement of safety goals. Hazard identification techniques are usually qualitative based on expert judgements where the methods change depending on the purpose and level of design knowledge available.

The different hazard identification techniques include [HSE and DNV, 2002] [Bakker et al., 2000]:

- Preliminary Hazard Analysis (PHA)
- HAZard IDentification analysis (HAZID)
- Failure Modes, Effects and Criticality Analysis (FMEA)
- HAZard and OPerability study (HAZOP)
- Structured What-IF checklist Technique (SWIFT)
- Fault and Event Tree Analysis (FTA/ETA)
- Cause-Consequences Analysis (CCA)

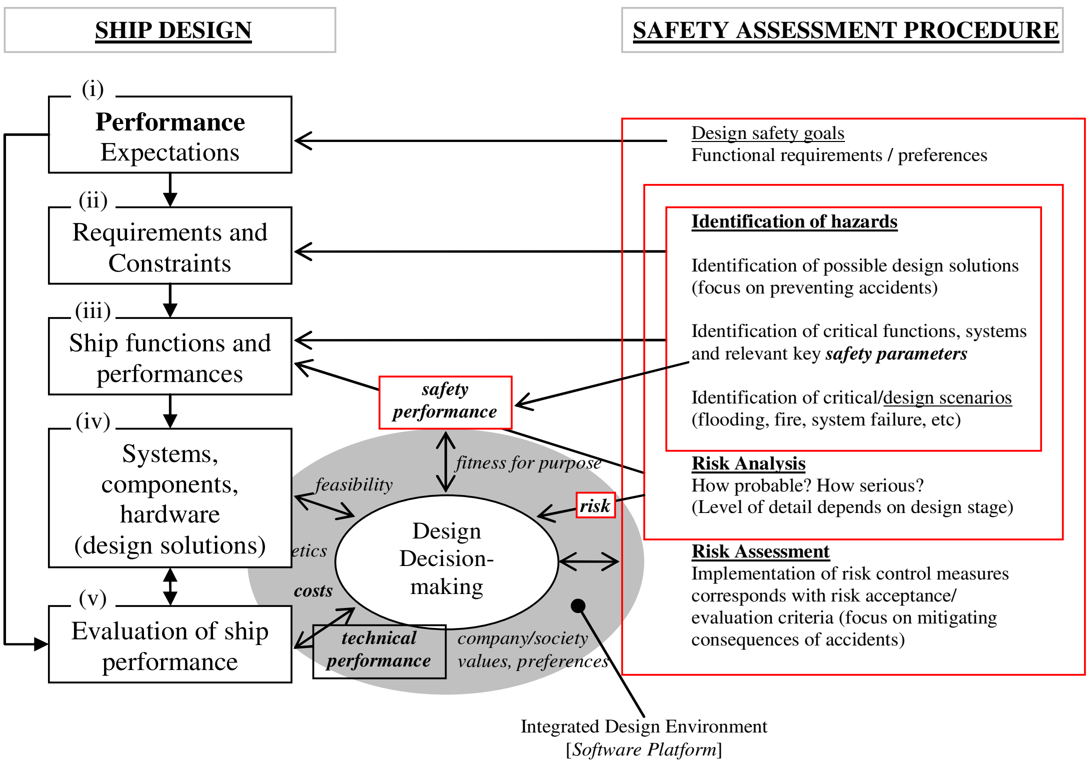

Figure 3-7: High level framework for risk-based design implementation [Vassalos et al., 2006]

These design scenarios are related to the accidents with major hazard potential and thus hazard identifications techniques can be used to recognize them. After the hazards are prioritised based on qualitative risk ranking and the related design scenarios are identified, the specific functional requirements and evaluation criteria are originated. These functional requirements, considered as additional safety performance requirements, constitute beside other design input requirements the driver for the design process. For the design decision-making purpose, safety performance evaluation criteria and risk acceptance criteria should be defined. The performance criteria can be used in the design process along or instead of explicit risk acceptance criteria because these latter ones could be related to the performance evaluation criteria. Therefore, safety in ship design can be achieved as the quantified safety performance level is corresponding to acceptable and quantified risk levels (provided these levels exist and are well defined and approved by regulatory boards) [Vassalos et al., 2006]. Risk acceptance criteria can be related to three categories; safety, economy and environment:

- Safety risk acceptance criteria are generally divided into individual risk (criteria for individual risk of fatality, injury risk, or ill health) and societal risk (criteria for Frequency of Number of fatalities, FN curves, or Potential Loss of Lives, PLL).

- Economy criteria which deal with economic losses related to accidents, business interruption, repair costs, etc.

- Environment criteria cover different kinds of emissions and spills, etc.

However, for this study the risk acceptance criteria of interest are the ones related to safety as economy and environment issues are not considered, hence no additional details about the last two criteria are given here. The two parts of safety risk acceptance criteria are individual and societal criteria. Individual risk criteria are mostly used when identified individuals or a group of individuals are exposed to additional risk, e.g. occupational risk due to work–related hazards [DNV, 2005]. The purpose of individual risk acceptance criteria is to limit the risks to people at work or being transported, etc. A common risk assessment practice is to use an individual risk criterion that defines the intolerable and the negligible risks (broadly acceptable) where intolerable risks should be reduced disregard the costs needed. Between the intolerable and negligible criteria lays the area where the cost effectiveness assessment may be applied. This area is referred to as the As Low As Reasonably Practicable (ALARP) area (See Figure 3-8).In this region the risk should be reduced as long as the costs involved are still proportionate to the risk reduction. Some standard measures of practicability should be defined in order to use this concept. Two alternative criteria often used in maritime safety regulation to determine limits of what is reasonably practicable in combination with the ALARP concept are the Gross Cost of Averting a Fatality (GCAF) and the Net Cost of Averting a Fatality (NCAF) [IMO, 2002a]. Guidelines on the tolerability limits were presented in Table 3.3 as extracted from HSE [2001; 2002].

Table 3.3: Tolerability limits for individual risk criteria [HSE, 2001; HSE and DNV, 2002]

Maximum tolerable risk for workers (e.g. crew members)	10^{-3} per person-year
Maximum tolerable risk for the public (e.g. passengers)	10^{-4} per person-year
Broadly accepted risk	10^{-6} per person-year

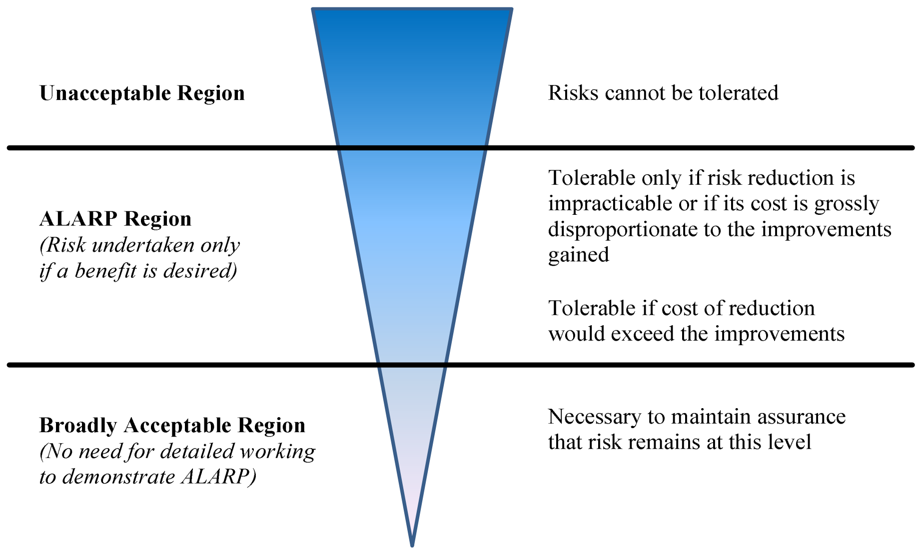

Figure 3-8: The ALARP concept; [HSE, 1992]

The purpose of the second part of safety criteria, societal risk acceptance criteria, is to limit the risks from an activity to a society as a whole. Societal risk acceptance criteria are used to limit the risks of catastrophes affecting many people at once as the whole society is normally concerned about such disastrous events. The criteria define the term “acceptable level of risk” in terms of the overall societal risks of fatalities. It can be argued that societal risk acceptance criteria are based on risk aversion against large and catastrophic accidents rather than explicit rationality. However, these societal criteria are used by large and increasing number of regulators. Developing and justifying societal risk criteria are not as straight forward as individual risk criteria as both the severity of the consequence and the frequency of occurrence of incidents are considered. Two of the most commonly methods used to describe the societal risk criteria are risk matrices and FN curves. Potential Loss of Lives (PLL) method is also used to measure societal risk for a defined activity. FN curves are plotted on diagrams presenting the number of fatalities (N) versus the probability of accidents with N or more fatalities per year (F). Anchors with coordinates as (N,F) were proposed as acceptance criteria and lines drawn through such anchor points are used to extend the acceptance criteria to incidents with other consequences [DNV, 2005]. Figure 3-9 illustrates an FN diagram representing the relation between the Frequency and Number of fatalities for ro-ro/passenger vessels along with the acceptance criteria lines.

Both divisions of the safety risk acceptance criteria are used at the same time for some cases. For instance, onboard a passenger ship, the risk of major accidents to a large number of people onboard can be expressed in terms of societal risk criteria, while some members of the crew exposed to additional hazards are described in terms of the individual risk criteria [DNV, 2005].

For instances where the acceptance criteria are unavailable or not well established, the risk based approach can utilise the comparative analysis to evaluate the studied design. In the comparative analysis technique, a comparative assessment between a design complying with the prescriptive rules of SOLAS and a novel alternative design is conducted. The alternative design has to be proven at least equivalent to the prescriptive rules compliant design. This approach is commonly used for shipboard fire safety due to the introduction of regulation 17 in chapter II-2 of SOLAS on alternative design and arrangements and the supporting guidelines [IMO, 2001; SOLAS, 2004]. Also, for the evaluation process, see Figure 3-1 in Section 3.2 above.

Risk-based design approaches and their concepts are adopted for design and operation, notably, the principle of safety equivalency. The alternative design and arrangements for fire safety in regulation 17 SOLAS II-2 is accepted and implemented by many designers. Other safety aspects of the ship can follow the same procedure as fire safety.

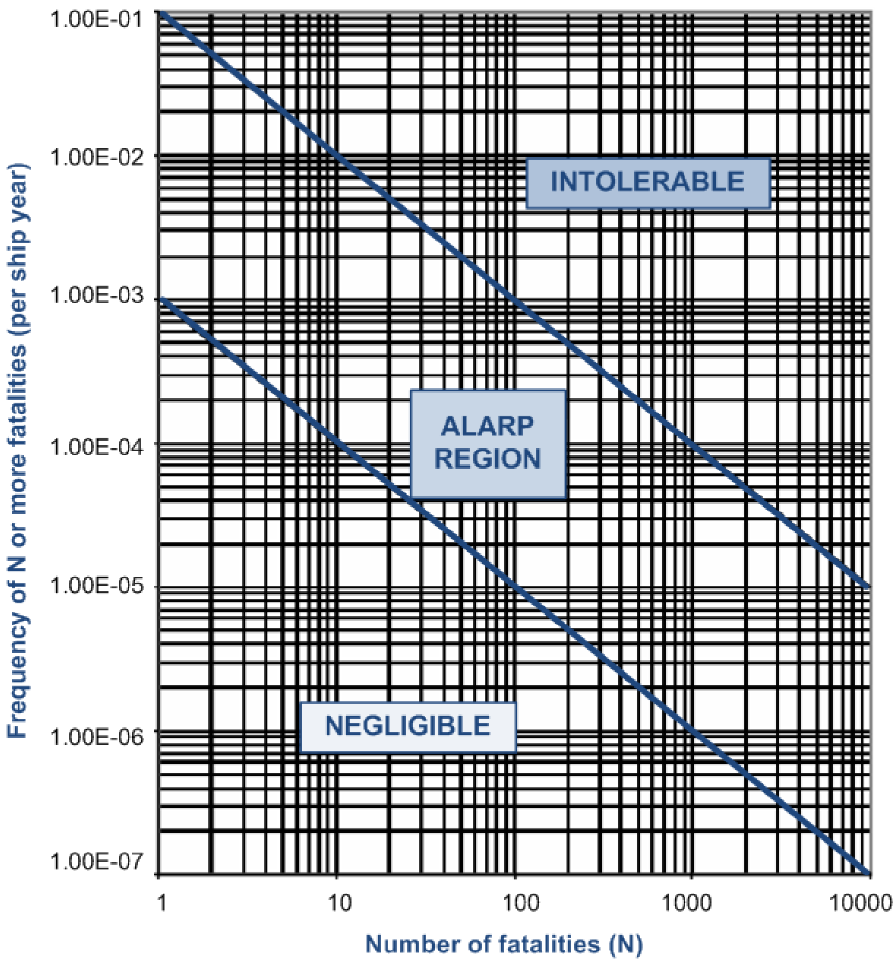

Figure 3-9: Suggested FN curve criteria for ro-ro/passenger ferries; [DNV, 2005]

3.4 Fire Safety Engineering

3.4.1 Fire Components

Fire is the chemical reaction of fuel and oxidizer (typically oxygen in air) releasing energy in form of heat (exothermic oxidization) and evolving light in most cases depending on the fuel and rate of reaction [Quintiere, 1998] [Cowley, 2006]. Usually fuels are hydrocarbon based containing hydrogen and carbon atoms in their molecules. Fuels are present in solid form like wood, fluid like gasoline and gas like methane. Fire is best explained through the fire triangle or fire tetrahedron as referred to in recent publications. The traditional three components of fire are oxygen, fuel (burning material) and heat enough to reach the fire-point temperature of the fuel. The feedback of heat to the solid or liquid fuel maintains vaporisation and produces the gaseous fuel required for combustion. A fourth component called chemical chain reaction was aided to better explain the combustion mechanism (see Figure 3-10) [Quintiere, 1998] [NFPA-webpage, 2008]. It became known that during the combustion of hydrocarbons, chemically active radicals are present. Those species diffuse into the unburned gases and transmit reactivity ahead of the flame by chain reactions [Cowley, 2006].

The four fire components are very inter-related and in case one of these components breaks fire will not survive. Thus, the four common ways to put fire out can be listed as [Cowley, 2006]:

- Removing the heat: Cooling down the burning material by the suitable medium (normally water) increases the fuel heat dissipation rate which should be greater than the generation rate in order to put the fire off.

- Removing the oxidizer: If there is no sufficient oxygen supply for combustion the fire will be extinguished. Oxygen exclusion can be done in many ways including the use of sand or blanket for small fires, layer of foam or dry powder for medium fires or even the carbon dioxide flooding systems that displace air in machinery spaces.

- Removing the fuel: The likely situations where fuel can be removed are those of fuel leakage. In accommodation spaces combustible materials can be removed from the fire vicinity.

- Breaking the chemical reaction: The fire can be extinguished if the chemical reactions between the transient chemical species produced on ignition are broken. This can be ideally done with halons or dry powders. The removal of fourth component of the tetrahedron (chemical reaction) means that the other three components are still present. Hence the removal of another component (typically heat) is required to prevent re-ignition.

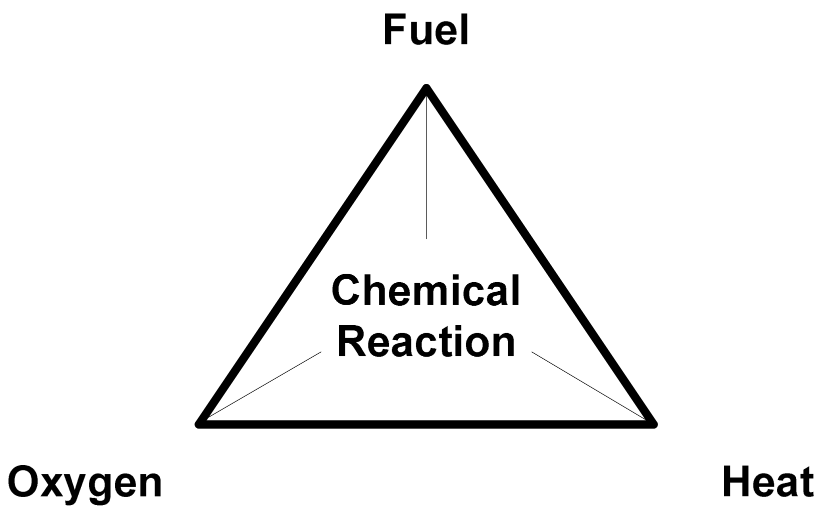

Figure 3-10: The four components of the fire tetrahedron

3.4.2 Types of Fire

Fires differ and can be categorized in four different types as diffusion flames, premixed flames, smouldering and spontaneous combustion [Quintiere, 1998].

Diffusion flames are the most common fires in enclosures. The fuel and oxygen approach each other due to concentration differences and react in the reaction zone. Example of diffusion flames among many others are a burning oil pool where heat feed back to the pool maintain the evaporation of liquid to combustible vapour, or a piece of furniture burning. In the latter the combustible solids go through an irreversible chemical decomposition process called *"pyrolysis"*, where the large complex molecules are broken down by heat to form flammable vapour which diffuse and burn with the oxygen available [Cowley, 2006].

Premixed flames are those fires where fuel and oxygen are mixed before the ignition and propagation occur. In a confined place this process can cause a sudden increase in pressure and can be called explosion [Quintiere, 1998]. Pressure builds up behind the propagating flame where the subsonic propagation is called *"deflagration"* and the supersonic one is called *"detonation"*. A common example of premixed flame is in the machinery space where fuel oil is sprayed onto hot surface to vaporise and mixes with air until the mixture comes in contact with source of ignition then it either burns or explodes if well confined [Cowley, 2006].

Smouldering is generally a slow combustion that occurs between air (or oxygen) and the surface of a solid fuel [Quintiere, 1998]. Smouldering propagates through material in three zones. The innermost one is the pyrolysis zone where the temperature rises sharply and the material under smouldering produces airborne products. This is followed by the second zone where the maximum temperature is located and glowing occurs. Finally the outermost zone that contains very porous residual char and/or ash which temperature falls gradually.

Transition from smouldering to flaming occurs when the release of volatiles exceeds certain critical value and is ignited spontaneously or by pilot flame. The substantial information available about smouldering of material is considered very limited. However, it is clear that many factors affect smouldering where just some of these factors will be stated here; material physical and chemical properties, moisture content, material orientation and smouldering propagation direction [Drysdale, 1988]. The incomplete combustion process leads to production of the toxic carbon monoxide instead of carbon dioxide. Upholstered furniture, mattresses and garbage initiated by discarded cigarette represent very common smouldering situations [Quintiere, 1998].

Spontaneous combustion is the combustion process that can start with slow oxidization of fuel exposed to air [Quintiere, 1998]. The spontaneous ignition temperature of auto-ignition temperature is the lowest temperature at which a fuel will ignite spontaneously in presence of air and absence of ignition source. A common example is lubricating oil sprayed on a hot surface in machinery space; the oil will burn in presence of air when it reaches its auto-ignition temperature. A dangerous type of spontaneous combustion is the self-heating one. In this case the heat is generated in the fuel itself. Fuels like coal, cotton seed and oily rags among many others generate heat upon reacting with air. If the heat dissipation rate is less than the generation rate, the fuel temperature will rise and smouldering occurs until the auto-ignition temperature is reached and spontaneous ignition occurs [Cowley, 2006].

3.4.3 Fire Heat Release Rates

Heat Release Rate or as also called Energy Release Rate is the most important time-varying property quantitatively describing a design fire. It controls the major fire characteristics such like plume flow, gases temperature and smoke layer height. Heat release rate is the power of fire measured in (kW) plotted against time. It represents the size of fire and its potential for damage. The heat release rate of combustion, HRR in (kW), can be considered as the product of the fuel mass loss rate, MLR in (kg/s), and the effective heat of combustion for the burning fuel, Δh_c in (kJ/kg); $HRR = MLR \cdot \Delta h_c$ [Quintiere and Rhodes, 1994]. These values can be measured with different types of calorimeters of which further details can be found in [SFPE, 2002].

It has been found that the rate of fire growth is proportional to time squared. Therefore, $HRR(kW)$ is commonly presented as a function of squared time (s^2); $HRR = \alpha \cdot t^2$ where $\alpha(kW/s^2)$ is the fire growth coefficient. This expression has been fitted to experimental data and explained by the fact that the flame spread velocity is constant overtime [Quintiere, 1998]. Fuels or combustible materials are usually categorised into four types of growth rates; slow, medium, fast and ultra-fast (see Figure 3-11). Heat release rates of slow fires reach 1055 kW in 600 seconds, medium fires in 300 seconds, fast fires in 150 seconds and ultra-fast in 75 seconds.

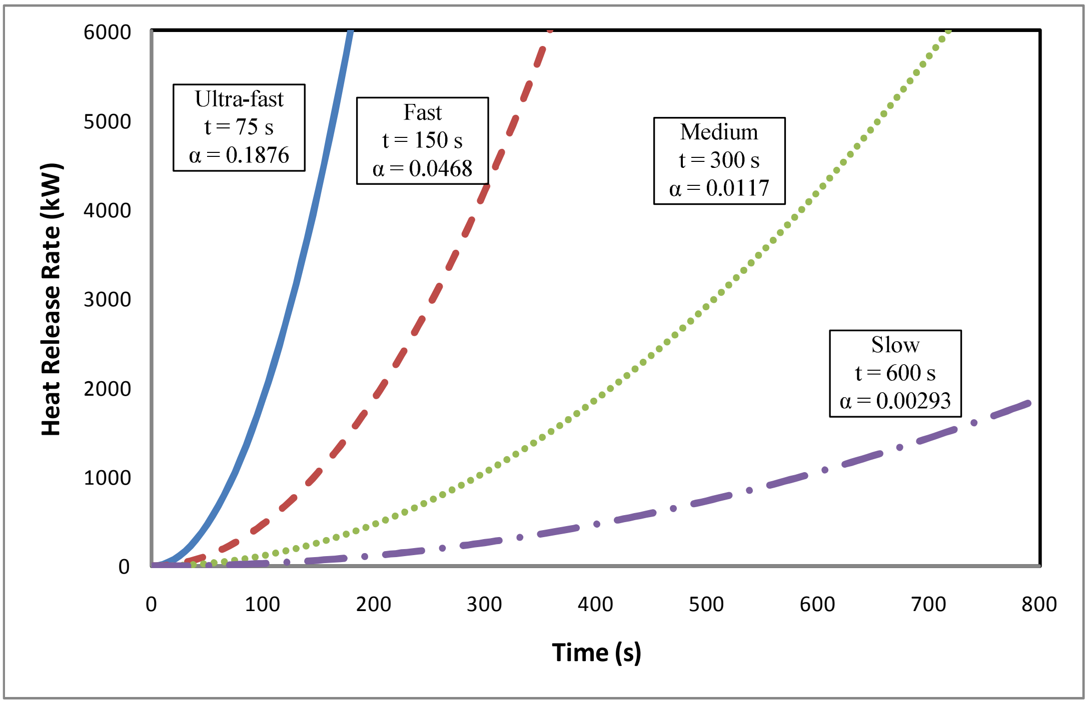

Figure 3-11: Heat Release Rates of t^2 fire categories.

3.4.4 Fire Development in Enclosures

Fire develops in a compartment through different stages ranging from *ignition*, *growth*, *flashover*, *fully developed fire* to the *decay* stage [Karlsson and Quintiere, 2000]. These stages are best presented in a graph of temperature rise versus time as seen in Figure 3-12. **Ignition** can be described as the starting point of the exothermic process evolving heat release and rise of temperature. This can be a piloted (by flame etc...) or spontaneous ignition as described in section 3.4.2 above. Normally at this stage in the very beginning, fire is not affected by the enclosure but depending on the fuel where the combustion can be flaming or smouldering. After ignition, the fuel is on fire and hot gases are produced. The hotter and less dense gases rise due to buoyancy forming along with the flames what is called fire plume. The rising hot gases also entrain fresh air on their way up. The hot plume entrains fresh air from the sides and impinges on the ceiling of the compartment then spread across it and is called ceiling jet. The gases reach the wall of the enclosure and start to descend forming an upper layer of hot gases under the ceiling while the colder gases form the lower layer above the floor. Due to air entrainment on plume level the upper layer grows in volume and descends more toward the floor until it reaches an opening to flow out of the compartment (See Figure 4-3). The hot layer growth is accompanied with increase of temperature in the compartment and particularly in the fire plume and hot layer. Heat is transferred from the upper layer to the adjacent walls and ceiling by convection and radiation. The lower parts of the walls and the floor including the fuel bed are mainly heated by radiation from the plume and hot layer. Fuel heating increases the process of burning rate, thus resulting in further increase in the temperature; noting that different types of material undergo different burning mechanisms [Quintiere, 2000]. This process manifests the **growth** stage of the fire and where oxygen supply through openings is sufficient for combustion the fire is called *fuel-controlled*. As the fire grows the temperature in the compartment increases, thus, heating up the existing fuels [Karlsson and Quintiere, 2000]. At the point where the enclosure temperature reaches an upper limit of 600°C or the radiation to the floor reaches 20 kW/m^2, **flashover** occurs in the compartment [Hadjisophocleous and Benichou, 1999]. The flashover occurrence criteria can differ and depend on the properties, orientation and position of fuel in addition to the enclosure geometry and conditions. Flashover is the transition period from the growing fire to the fully developed fire where all the fuels existing in the compartment are involved in the fire. Flashover is formally defined by the International Standards Organization as "the rapid transition to a state of total surface involvement in a fire of combustible material within an enclosure" [ISO, 1999]. At this stage the fire is at **fully developed** stage and the fuel release rate is at its highest level and very often controlled by the oxygen supply. Hence, the process is called *ventilation-controlled* burning. The average temperature of the compartment at this stage is known to range between 700°C to 1200°C in most cases. As the available fuel in the compartment is consumed by fire the burning process switches from ventilation-controlled to fuel-controlled. At this point the burning rate (energy release rate) start to decrease and the compartment temperature fall down, hence the stage is called **decay** [Karlsson and Quintiere, 2000].

In a totally different scenario of fire development, the fire undergoing its growing process the smoke upper layer descends toward the floor. In the case where no openings are available in the enclosure, the upper layer keeps filling the compartment until reaching the fire flame. Therefore, the air entrained into the plume is vitiated and does not supply the fire with sufficient oxygen to sustain combustion. Eventually the fire dies out due to **oxygen starvation** as show by the dotted curve in Figure 3-12. The unburned fuel is accumulated in the compartment and fuel pyrolysis may continue as well due to the high temperature. In the unwanted case where an opening (door or window etc…) become available, fresh air flows in and mixes with the accumulated fuel. In the presence of any ignition source the mixture burns very rapidly (pre-mixed flame in Section 3.4.2) and might cause an explosion. This phenomenon represents a very hazardous situation and is called **backdraft**. At this point the temperature-time dotted curve would increase rapidly to reach the high temperature of fully developed fires until decay stage Figure 3-12 [Karlsson and Quintiere, 2000] [Drysdale, 1988]

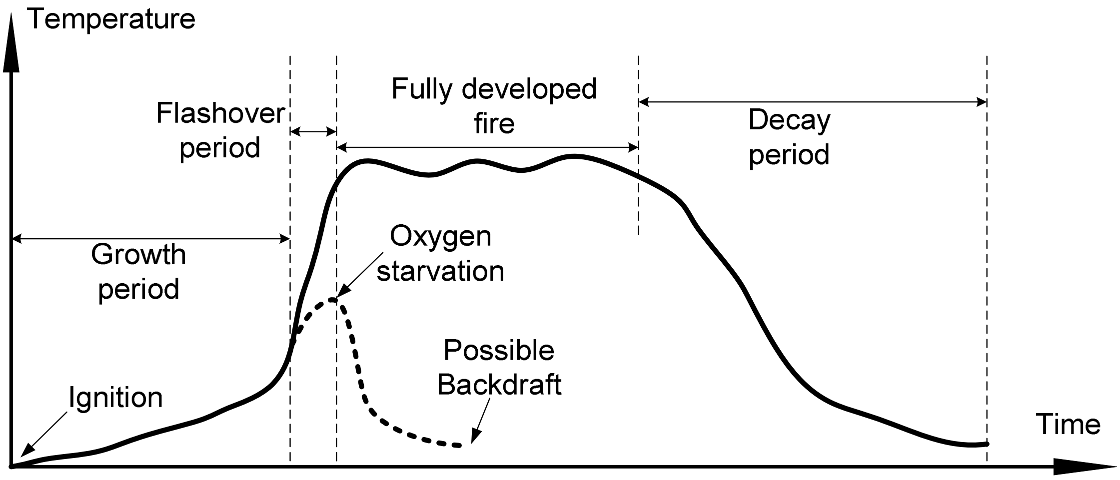

Figure 3-12: Fire development stages; the solid curve represent a well-ventilated fire journey, the dotted curve is a fire under effect of oxygen depletion. [Karlsson and Quintiere, 2000] [Drysdale, 1988]

The described fire scenarios are normally obstructed with fire protection systems which act as barrier for fire consequences escalation. Yung [2003] structured fire scenarios by five steps where each can be obstructed by the corresponding barriers:

- Firstly, fire ignition that can be reduced by awareness.

- Secondly, the fire growth which can be contained by fire protection systems like sprinklers, compartmentation and self-closing doors.

- Thirdly, smoke spread which accompanies every fire event and can be controlled by systems as extraction vents, pressurized zones and self-closed doors.

- Fourthly, the occupants are trapped if the egress routes are filled with smoke. The protection systems for this step are fire alarms, voice communication, protected escape routes and a successful escape route etc…

- Fifthly, the rescue attempts which can be enhanced with a well trained staff onboard ships.

It is therefore essential to conduct time dependent calculations for fire growth, smoke spread and occupants' evacuation in order to quantify the consequences of a fire incident. Models used for such calculations are described in Chapter 4. When the barriers for every step are overcome, it can be considered that the fire is to cause harm to the occupants, and casualties are expected. If any of the steps are not obstructed by the mentioned barriers the risk of having casualties as result of the fire is increased.

3.5 Fire Safety Research Review

3.5.1 Computer Models

Computer models can either follow the probabilistic or deterministic approach. The probabilistic method assesses the fire risk in a compartment by associating various probabilities with the fire-related parameters such as distribution of fuel, ignition, ventilation, passenger / crew interaction, etc. There is usually little or no physics involved in this approach. Thus it proves useful for the likelihood of fire ignition and escalation. However, details such as temperature and gas concentrations cannot be predicted. On the other hand, deterministic models are totally based on a set of governing equations maintaining laws of physics and chemistry in the flow domain. By computing this set of equations for each case, these models predict the required space and time dependent parameters in the field. Deterministic models range from simple hand calculation to complex numerical models requiring immense computational efforts. The main types of computer-simulated deterministic models are network, zone and field models. Field model is a synonymous expression for Computational Fluid Dynamics model in the fire engineering community. Besides there are the egress simulation models also called pedestrian dynamics or crowd flow simulators. These models simulate the human behaviour in an evacuation process. The above mentioned model types were subject to numerous surveys where the most significant ones are referred and described here.

a) Friedman [1992] conducted an international survey on computer models for fire and smoke. The survey covered 31 zone models, 10 field models for compartment fires, 12 models to calculate the thermal response of structural elements, 6 evacuation models, 5 models to calculate the actuation delay of detectors and sprinklers, 3 models for interaction of sprinkler and fire, and finally eight additional models of different categories. Friedman also discussed the difficulties in modelling fires in compartments and assessing the accuracy of a simulation model. Furthermore, he recommended the use of zone models, where geometry is restricted to simple boxes, and field models for irregular geometries including sloped or concave ceilings, long corridors and open stairwells. According to this review, fire can be prescribed as a constant Heat Release Rate (HRR), time-varying HRR with or without oxygen supply control. Also, fire spread is majorly affected by the radiation feedback emitted by the flame, hot smoke layer, ceiling and upper walls. For a more sophisticated representation of fire, bench scale fire experiments can be used to develop empirical or even analytical models, but detailed data of the experiments is needed for achieving accurate fire modelling. Other important uncertainties, always according to Friedman, include incomplete combustion products, plume entrainment, layers mixing, heat losses, and ignitability of fuel-rich smoke encountering fresh air.

b) In the EC funded research project SAFETY FIRST, Ramsdale et al. [2003] [2000] carried out a survey on existing fire models and investigated their validation status and suitability for fire applications onboard large passenger ships. The six zone models reviewed in this project were HAZARD I (FAST), CCFM.VENT, CFAST, Harvard CFC V and VI, and FIREWIND. A fair amount of detail was provided for each model covering the main aspects such as fire, plume, layers, heat transfer, vents, wind effects and chemical substances. Sensitivity analyses deemed the heat release rate (as a function of time) of the design fire as a crucial input that dominates the overall uncertainty in zone model predictions. Other important parameters include the calorific value and composition of fuel in addition to the products yields which define the toxic gas concentrations according to the ventilation conditions within the fire domain. It has been seen that no model has all the desirable features. However, CFAST, which is widely used and its validation literature is largely published, was recommended over other models provided that care is taken regarding its applicability and its sensitivity to the input information.

The study also covered 7 field models investigating the meshing, fire modelling and physics of each model. The investigated models were CFX, FLUENT and STAR-CD as general purpose CFD software and JASMINE, KAMELEON FIRE 3D, SMARTFIRE and SOFIE as fire specialised computational models. All the models reviewed were capable of simulating consumption of oxygen and constraining fire due to lack of oxygen supply. With the suitable input from the user, the models were found able to simulate fire spread and post-flashover behaviour. The published validation literature of each code depends on the time the code has been available. The study did not recommend a single model over the others as all models were able to predict relevant parameters like depth and geometry of smoke, temperature at different positions and heights, heat output, flame temperature and geometry, vent flows, compartment pressure, and size and geometry of fire source. In general, zone models have the advantage of running faster and being easier to use than field models, but their applicability is limited to a small number of cases. On the other hand, field models were more flexible, able to handle complex situations and to predict parameters which zone models were unable to calculate such as flame temperature, size and geometry of fire source.

c) Olenick and Carpenter [2003] carried out an international survey on computer models for fire and smoke, which can serve as an update to the abovementioned international survey previously conducted by Friedman [1992]. In total, 168 computer-simulated programs for fire and smoke were identified and categorised, where the developers were contacted and allowed to provide information about their codes. The different code categories included zone models, field models, detector response, fire endurance, egress and miscellaneous programs. The survey data included classification and description of the model, in addition to its cost, user's guide, technical and validation references, and the developer contact details. The survey even included outdated models which are no longer generally used by the fire society community for completeness. The survey collected a fair amount of detail to allow the user to choose which fire model was suitable for the application of interest. Egress models included a wide variety of sophisticated models including features such as the physiological effects of fire on occupants due to the effect of smoke toxicity and decreasing visibility. The models would also feature methods to visualise the movement of people in a building during simulation. It was noticed that the number of models identified increased drastically since the survey conducted by Friedman [1992], especially in the area of the field models. This was mainly attributed to the increase of available computer power, research and practical knowledge.

All the collected information in the study was made available and updated on the internet at http://www.firemodelsurvey.com/. The work achieved its goal by making the database publically available on the internet to allow fire engineers, designers and other interested parties to reach the necessary reference data of fire and smoke programs in order to decide whether a certain program can achieve the intended objectives. An update of the database was carried out in 2007, which resulted in revised information for some already listed models and addition of new ones. This survey can be referred as one of the most complete and accessible currently available in the public domain.

d) A survey was conducted by Salem (2006), based on information collected from the existing literature and other previous surveys, 56 models of the zone type and 25 models of the field type were identified. Salem investigated limited information of the models such as country of origin, the possibility of running the model on a PC and other general comments. 13 of the zone models can handle multi-compartment fire scenarios, whilst the rest were designed for a single compartment fire. For the field models, various general comments were associated to them, like classification of the software as fire-specialised or general purpose model, single- or multi-compartment model and different physical aspects. Additionally, in the course of this research work a review of the explosion and evacuation models was conducted. maritimeEXODUS (http://fseg.gre.ac.uk/EXODUS/index.html) was identified as a suitable egress model for maritime applications as it can simulate the impact of heel and the effect of fire effluent on passengers' movement. Salem study concluded after a comparison between different zone models (CFAST, BRANZFIRE and Raeume) with a field model (FDS), which was used as benchmark, that there is no single zone model uniformly applicable to all fire effluents parameters in all applications. However, a well-written zone code can be useful for comparative study onboard ships due to its speed in simulating smoke movement in multi-compartment geometries.

e) In a recent paper on numerical fire modelling for passenger ships, Nikolaou and Spyrou [2009] briefly reviewed some of the fire models suitable for fire applications onboard passenger ships. They identified the network model Fire and Smoke SIMulator (FSSIM). Network model is the simplest of fire models treating each compartment as single node. FSSIM was developed to simulate fire growth and smoke spread on naval vessels. The zone model CFAST was recommended over other existing models mainly for the same reasons stated in previous surveys and also the ability to integrate this model with risk analysis. Nikolaou and Spyrou in their review looked at field models, which can be used for fire applications onboard passenger ships. They mentioned, CFX by ANSYS as a general purpose CFD code able of handling fire cases and the fire dedicated codes JASMINE by the Building Research Establishment (BRE, UK), SMARTFIRE by University of Greenwich and FDS by the National Institute of Standards and Technology. Brief comparison between CFAST and FDS were conducted in this work showing agreement in the early stages of fire and disagreement in the later stages. It was also concluded that CFAST is able to handle smoke movement cases with prescribed design fires noting the limitation of keeping the scenarios simple and the number of compartments below 30. FDS was found able to simulate more complex cases, like two-deck scenario, and to produce the relevant parameters. Moreover, the need to reduce uncertainty in terms of knowledge (physical and numerical) and randomness of the process was also noted. Among the drawbacks of FDS, the paper shed light to the lack of material properties needed to model solid combustion and the complexity of representing non-rectilinear shapes in FDS.

The brief review of previous fire and smoke model surveys presented in this section can be consulted for further information about existing models in the literature. Among the many identified models, several ones are found suitable for passenger ships applications under the condition to identify the range of applicability for the scenario of interest. More elaboration on the models basics, their selection and application is in Chapters 4 and 6.

3.5.2 Fire Safety Research with Focus on the Marine Field

The performance based design depends strongly on the numerical modelling of fire and evacuation procedures. Normally the combination of these two models is able to provide a complete simulation of a fire scenario and quantify the consequences in certain measures depending on the sophistication of the simulation models. This type of fire scenario consequence quantification methods was adopted in civil building and transportation fields. Passenger ship geometry is to some extent similar to civil buildings but with additional complexity due to space restrictions, hence the focus on research conducted for buildings and passenger ships.

Some previous studies which conducted fire safety research onboard passenger ships made use of novel simulation tools to predict the performance of designs. However, the investigations were not extensive and the final criteria assessed were limited which reflects the novelty of the application of this approach especially in the marine sector. Andersson [2002] conducted a risk analysis study of smoke systems in accommodation spaces on passenger ships. The analysis was carried out using the zone model CFAST [Jones and et al., 2005]. A single criterion, which is the smoke layer height, was considered in this study to measure the fire risk. Smoke layer height cannot be considered sufficient to measure risk as on one hand radiation flux on an exposed passenger can cause impairment even if the smoke later did not reach the height of the passenger’s head. On the other head, smoke layer reaching the evacuee’s head in a mild fire incident does not necessarily mean the situation is very hazardous as the only impairment to the passenger can be visibility reduction which does not pose danger on human life. Fire fighting effects were omitted due to the difficulty of considering this aspect with zone models. The use of zone models in structures like long corridors, large halls and high atrium was not investigated as the zone models simulations in such areas were always under question. However, it should be mentioned that many useful conclusions can be drawn from this study especially regarding active smoke control systems. In a second study, [Salem, 2006] carried a comparison work for three zone models (Raeume [Shigunov, 2005], CFAST [Jones and et al., 2005] and BRANZFIRE [WADE, 2004]) against the field model Fire Dynamics Simulator [McGrattan, 2008b] used as a benchmark. The comparison showed also that the tested models predicted somewhat different conditions in the different geometries considered. Some models were better in some places while others were more accurate in other places. The shipboard geometries where the scenarios were assumed to take place were varied to cover a wide range of the shipboard area occupied by passengers. Among the others Raeume was found to predict reasonable results in most of the cases considered according to Salem [2006]. The heat release rate considered was reasonable and the burning materials and their combustion productions were considered of wood combustion in all simulation. The intensities of the considered HRRs are acceptable comparing to the range of experimental data of heat release rates for various burning items of [Sardqvist, 1993] which is a summary of a large number of full scale tests on different burning items. Salem also, neglected the fire suppression effects in the calculation of fire consequences. Salem assumed that the hazard occurs in a given design when one of the physical parameters reaches a certain value (for instance when the temperature reaches a value of 100°C). Using such hazard criteria for a design do not account for the evacuees reaction, their response and behaviour. Therefore, the available safe egress time (ASET), or the available time before a given space reaches untenable conditions, was produced in both studies while the required safe egress time (RSET), or the time required by passengers to evacuate a given space, was not estimated in order to compare both lines and assess the hazard associated with the given design. In addition, none of these studies attempted to quantify the effects of the resulted fire conditions predicted by models on the health of the passengers evacuating the fire scenario domain.

In response to the IMO [2002b] release of benchmark evacuation scenarios to be simulated as part of the ship certification process, the Fire Safety Engineering Group in the University of Greenwich simulated fire evacuation at sea by coupling the results of their field based fire model SMARTFIRE to the evacuation model maritimeEXODUS [Galea et al., 2004]. IMO scenarios only address the mustering phase of evacuation and do not account explicitly for sea status like heel and roll neither for fire impact in case of fire. Instead, these are accounted for through a safety factor added to the predicted muster time. In Galea's calculations the output from the SMARTFIRE simulator are fed into the ship evacuation model maritimeEXODUS, hence the impact of fire on people is explicitly accounted for, as well as the sea status effects which are considered explicitly in the evacuation model. In a demonstrative work, four evacuation scenarios were performed on a 3 fire zone passenger ship with two occupied decks (250 passengers) above the assembly deck and two below (400 passengers). In a first scenario without any heel or fire the passengers started evacuation between 7 and 13 minutes, and were all on the assembly deck within 15 minutes 32 seconds. In a second scenario with a heel angle of 20° the evacuation process was slowed to 16 minutes. In the third scenario, a fire was located in a cabin on the lowest occupied deck and the effluents were allowed to spread on the deck above as well. This slowed the evacuation process which required 28 minutes 17 seconds in this case. As regarding consequences, Galea reported that over different runs 26 to 27 fatalities were observed near the cabin fire. Scenario 4 similar to the previous one but with water mist fire suppression in the corridor in front of the fire cabin. An improvement was seen by reducing the number of fatalities to 2-3, however the time to muster was increased to 31 minutes 5 seconds.

It should be stressed that the work just considered hazard from heat and accounted for reduced visibility due to smoke. However, the toxic effects of fire products were not included in the calculations which may have looked very different if toxicity was considered. Additionally, passengers were allowed to cross in front of the fire room which might be an unrealistic case and will definitely result in an elevated number of casualties due to heat.

Jia [2004] also used the CFD-based fire simulator SMARTFIRE to predict fire development on a Swissair Flight 111 but this time to assist the investigation of Transportation Safety Board of Canada [TSB] on the in-flight fire which caused the plane to crash killing everybody onboard. The main advantage of SMARTFIRE was its ability to handle the complex curved geometry of an aircraft fuselage, and the maze of cabling, ducting and other utilities in the above-ceiling voids. Separate drawing and meshing software were used to assist the simulation settings. Additionally, data from experiments was used to provide information on heat release rates and properties of materials, rate of fire spread and behaviour of materials. Different fire scenarios were simulated and the fire initiation sites were chosen based on the information of possible fire causes provided by the investigation team of TSB. Mainly the two types of scenarios were the simulation of ventilation air flow conditions prior to fire start and then fire flow modelling with using ventilation flow as initial conditions. These simulations greatly helped the investigations and developed a better understanding of the possible effects, or lack thereof, of numerous variables relating to the in-flight fire. According to Jia, SMARTFIRE then became the first fire model to be used in an air crash investigation which reveals the novelty in using computational fire engineering tools in accurately modelling air fire accidents.

In the VTT Technical Research Centre of Finland, an assessment tool was developed to quantify fire safety performance in buildings. An evacuation simulation method was embedded into the field based model Fire Dynamics Simulator which allows the modelling of crowd flow and interaction between evacuation and fire simulations. This means, that the effects of fire can affect people and their evacuation process and also at the same time evacuees' actions can affect the fire and smoke development. The fire model FDS is used to calculate the development of fire and smoke and its post-processor is used for visualisation. The combined fire and evacuation tool is called FDS+Evac and can be seen as a sub-programme of FDS source code [Hostikka et al., 2007a]. The programme has three main functionalities; simulation of large and dense crowds, simultaneous interaction between fire and evacuees, and decision making actions depending on the socio-psychological aspects like familiar people and spaces. FDS+Evac put great efforts on modelling the complex human behaviour. Hostikka also concluded from after several researchers that casualties in fires are caused by incomplete information or inappropriate use of the facility rather than panic which is assumed to be non-rational behaviour. This justifies the modelling of decision making from the rational basis of taking the path estimated to be the fastest towards the exit. Also the programme accounts for effects of familiar places and people (like parents and children) and decision making under stress or affected by the group influence. This model accounts for human movement and congestions by solving an equation of motion for each human and considering the forces including body forces and friction from other humans and walls. FDS solver is used to solve the human movement equations. VTT group used to account for fire effects on evacuees a correlation derived from Frantzich and Nilsson [2003] experimental data on walking speed trough smoke. Besides, the Fractional Effective Dose (FED) by Purser [2002] is used to compute heat and toxicity effects.

The development of the fire safety assessment tool FDS+Evac was conducted as a project which summary was published in 2007 [Hostikka et al.]. As part of the project, evacuation experiments were conducted to obtain information human behaviour, flow rates and decision making. The first type of experiments was the usual drills carried out as part of safety training in buildings. The second type was actual evacuations where the decision making might be similar to a real fire evacuation case [Hostikka et al., 2007b]. The results of the project focused more on the validation of human movement against experiments and other software rather than coupling of fire effects and human behaviour. FDS+Evac can be considered in advance in evacuation models especially regarding human behaviour considerations. However, the fact of that the model is a sub-program of the fire model FDS restrict its use along with other fire models.

In a recent publication on fire modelling for fire ships, Spyrou and Nikolaou [2009] investigated the application of zone and field fire models onboard passenger ships. Mainly CFAST and FDS were looked at by simulating a simple case of cabin and corridors and other cases containing the complexity of geometry onboard a ferry ship. Zone model simulations tested fire scenarios in a range of cabins separated by a corridor, comparing a cabin fire with an open and closed door where oxygen starvation was observed. The study pointed out the insensitivity of zone model to the position of an opening between two compartments. On the other hand, the field model showed more detail of the flow like ceiling jet and formation of upper layer where precision and accuracy were subject to the density of the numerical grid. In different fire scenarios onboard ferry, the precision of field model FDS in the transient period of fire was pointed out as compared to zone model simulations. Sensitivity studies about the effects of initiation fire and sprinkler were conducted. An initiating fire kept only for 40s showed a delayed HRR pattern as comparing to a continuous initiating fire and the sprinkler effects were successful on fire where the heat release rate was critically reduced. In a two decks scenario, the incapability of zone model to compute certain features predicted by FDS was indicated; features such as mixing of upper and lower layer and multiple fire interaction. However the prediction of these features in field based fire models come on the expenses of enormous computation efforts required. It was made clear from this study that the application of fire simulation tools onboard ships would need some considerations and vigilance especially regarding the zone models.

3.6 Concluding Remarks

After reviewing the different parts of literature relevant to this study, some of the required knowledge to be used in this research is acquired and some other existing gaps in the field are identified.

The review highlighted the developments over time of the regulation governing fire safety onboard ships where one of these latest developments was to introduce the equivalency approach in fire safety. Then, the conventional ship design was reviewed and the need for a new design concept was illustrated. The review introduced the design for safety concept based on risk assessment.

The review covered a reasonable part of the fire safety engineering field, especially the parts that were found to be directly related to the current research and surveys of the relevant simulation models.

Finally, research studies, which partially adopted the same approach of the research undertaken in this thesis, were reviewed in this chapter. The knowledge acquired from those studies will be used in this research and additional development will be conducted in order to further close the identified gaps and take the shipboard fire safety a step forward.

4 Approach Adopted

4.1 Introductory Remarks

It became clear from the previous chapters that safety management in ship design is changing from complying with regulations to quantification and evaluation of safety performance. Thus, safety in design is no longer just a straight forward application of rules but safety aspects in recent designs are based on the performance of the design itself and measured in form of risk which is the unit of safety performance. The achievement of this performance assessment initiates the full use of the state-of-the-art tools. Fire and smoke development prediction and evacuation models, consist the core of the tools used to assess the performance of a novel design deviating from rules. This chapter outlines the approach adopted in this thesis to use the state-of-the-art tools in developing an integrated suite of tools that can serve as an assessment model for fire safety performance onboard. This chapter also serves as an introduction to the thesis approach and basic concepts and functionalities of simulation tools. This helps in identifying the applicability and limitations of different types of models and provides a deeper understanding in order to select the suitable models to be used in this study. In addition, this chapter sets the relevant methods to quantify the effects of fire effluents on human life safety.

4.2 Concept of the Assessment Procedure

The ship design shift from regulation to risk based necessitates the quantification of design safety performance. As in all safety aspects onboard fire risks need to be measured. This thesis deals more with the consequences of hazards more than their causes and frequency of occurrence. The consequences of a fire scenario, from human life safety perspective, can best be assessed by comparing the time available before the conditions become untenable to the time required to escape the hazardous conditions. A design fire scenario consists of the design fire which is the fire characteristics, and all the conditions driving the fire development. These conditions include the geometry where the scenario is taking place along with other specifics like openings, bounding materials and fire detection and suppression etc… In each considered scenario, time histories of smoke interface height, temperatures, toxic gases concentrations and radiant heat flux are obtained using the appropriate fire programs. These time histories provide the **A**vailable **S**afe **E**gress **T**ime (ASET) that is the time available to complete evacuation before the considered space reaches untenable conditions. This time line is compared to the **R**equired **S**afe **E**gress **T**ime (RSET) which is the time required to complete the evacuation of occupants from a given space and can be obtained using pedestrian dynamics simulation tools (or evacuation models) [SFPE, 2002]. The Required Safe Egress Time in turn consists of the time for fire detection and alarm activation followed the time taken by the occupants to recognize the situation before they response and move toward the mustering point. Those time lines are illustrated in Figure 4-1. When the RSET is greater than the ASET, it is considered that the occupants in the fire domain are exposed to untenable conditions and hence incapacitated. On the other hand, when RSET is less than ASET, it is assumed that the occupants have the sufficient required time to evacuate the domain before the conditions become untenable. This approach of time lines comparison provides the concept of an assessment tool of a design regarding fire safety performance by calculating the final consequences of a fire scenario in terms of life loss.

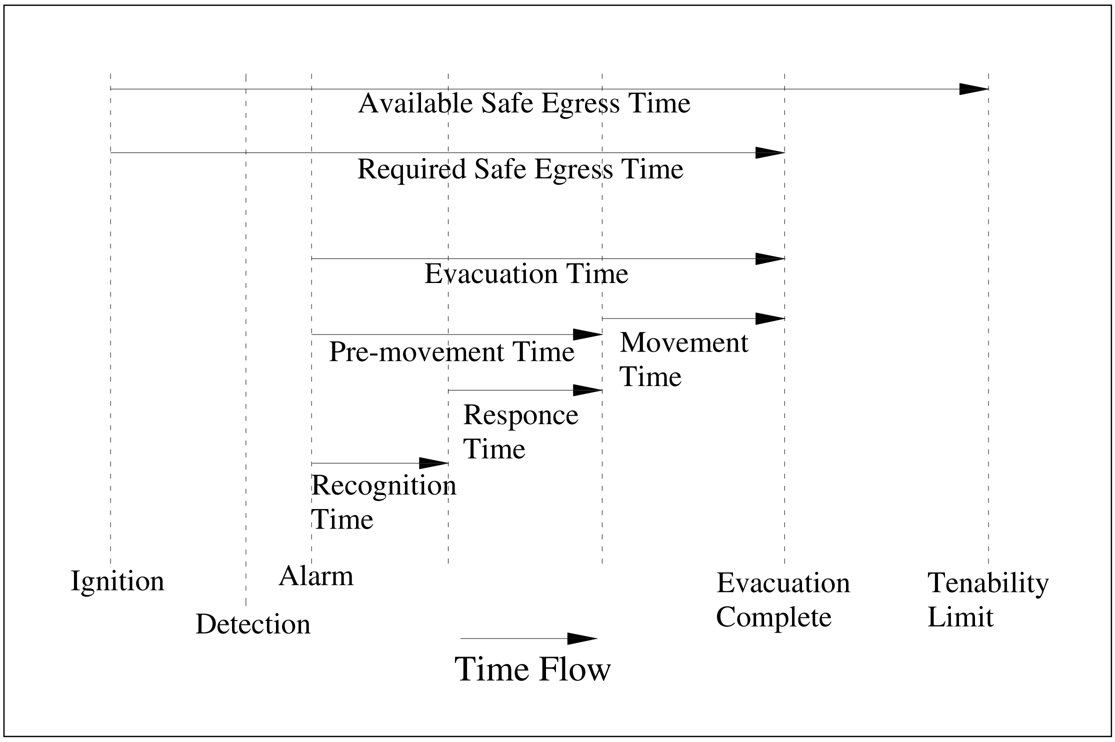

Figure 4-1: Time lines sequence in fire incidents

4.3 Description of the Assessment Procedure

The time lines illustrated in the previous Figure 4-1 can be calculated explicitly by the corresponding programs and then assessing whether an evacuee is incapacitated or not by comparing the RSET and ASET lines. Nevertheless, a detailed analysis of a fire scenario would not be possible or at least very difficult to be achieved by explicit calculation and comparison of the lines. Computer simulated tools give the possibility to conduct such analysis for spaces occupied by hundreds of evacuees. The main advantage of simulation tools is their capability to predict the safety level of a design in its early stages and even the possibility to assist fire fighting or evacuation procedures aboard due to the rapidity in predicting fire effluents and their impact on humans. Fire and smoke development prediction and evacuation models, consist the core of the tools used to assess fire hazards. The integration of fire and evacuation programs, fire effect quantification methods provides a suite to calculate the consequences of a fire scenario in terms of human life loss for all the occupants present in the considered fire domain.

The integration algorithm of the fire and evacuation models forming the assessment tool is depicted in Figure 4-2. To start, the inputs of the fire model are all defined and can be referred to as design fire scenario. These fire scenarios are defined based on the collection and analysis shipboard fire data in Chapter 5. A fire scenario consists of the design fire, which defines the fire characteristics, and all the conditions driving the fire and smoke development. The design fire is known to be the most important component of the scenario and defines the fire characteristics which include fire size and location, heat and mass release rate time histories, and fuel properties. The other driving conditions of the fire scenario include the bounding material properties, geometrical arrangement covering all vents and obstacles in the domain in addition to all forms of fire containment and fighting activities. All design fire scenario conditions are subject to uncertainty and hundreds of scenarios can be generated based on different input combinations. However, no attempt in this thesis was made to quantify this uncertainty and just simple demonstrative scenarios normally assuming the worst possible cases are adopted here.

The design fire scenario inputs are simulated in the fire model to predict the resulting conditions in a domain. The application and functionality of fire models specifically for this study are elaborated in Chapter 6. Benchmarking exercise of fire models against experimental data and study of specific fire input demand of each model are the driving factor of selecting the suitable models for this study. Considerable effort is spent on using the selected codes on specific fire applications onboard passenger ships.

Fire resultant conditions, which have direct impact on humans, are calculated in terms of temperature, radiative heat flux, gases concentrations and smoke obscuration. Fire conditions predicted by the fire model and the geometric arrangement, along with the planned escape route and occupant’s properties (distribution, speed and response time) constitute the inputs of the evacuation model.

Similar to the fire model inputs, the design occupancy and escape routes involve uncertainties which are not quantified in this thesis, though again the worst cases are used such as full berthing in cabins and late response to fire alarms. In the evacuation model two kinds of simulations are performed. Firstly, the evacuation procedure is predicted by solving the pedestrians' dynamics. Secondly, the quantification methods integrated to the model calculate the effects of evacuee's exposure to fire effluents. These quantification methods are well elaborated in Section 4.6. The final outputs of the assessment suite are presented as the final consequences of a fire scenario in the form of well defined criteria in terms of fatalities and injuries. This is illustrated in Chapter 7, where also the applicability and sensitivity of the assessment suite are investigated. Finally, a design case study in Chapter 8 illustrates well the usability of the fire safety assessment approach.

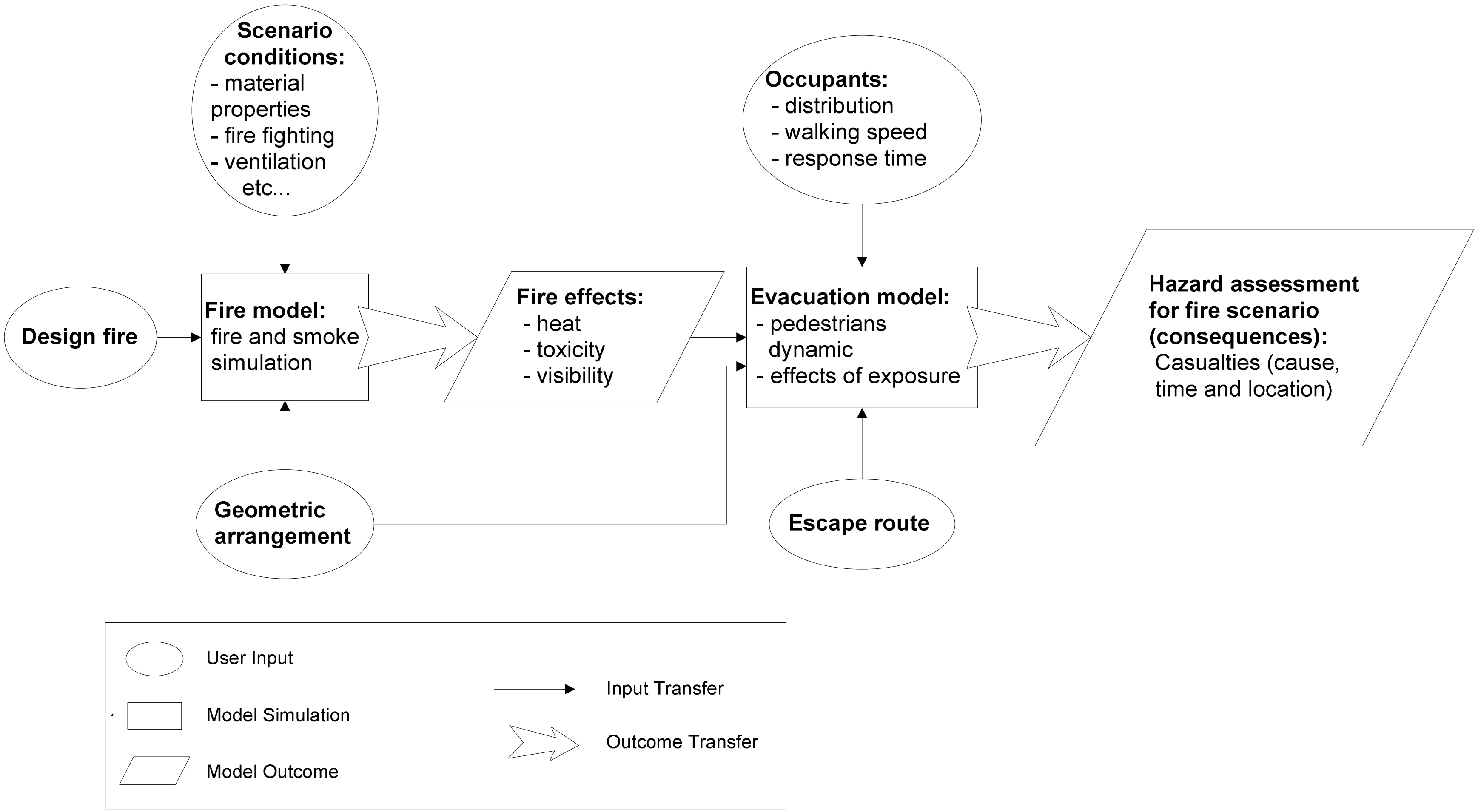

Figure 4-2: Structure of the assessment suite.

4.4 Fire Simulation Models

This section provides an introduction to the basic concepts of each type of the fire simulations models – zone and field based – and describes the sub-models and functionalities of these programmes. This helps in identifying the applicability and limitations of different types of models and provides a deeper understanding in order to select the suitable models to be used in this study.

4.4.1 Zone Models

4.4.1.1 Basic Concept

Zone models are widely used to calculate fire effluents because of their ability to produce reasonable results at low computational costs comparing to field models. Zone models divide the computed domain into a very limited number of zones. The most common ones are those which divide each compartment generally into two zones except the fire room where a fire plume is present and is added to the upper layer control volume. This idea came from the observation of fire experiments where hot gases collect below the ceiling forming an upper layer in the top and the cold gases remains low above the floor and form the cold lower layer (see Figure 4-3). Each zone is assumed to have uniform mass, volume, internal energy, density and temperature. Applying the conservation of mass, energy and species to these zones (layers), a set of Ordinary Differential Equations is obtained. Solving these equations beside the equation of state (ideal gas law) and the definition of density and internal energy, time histories of required layers properties can be obtained. Gases concentrations time histories follow from the species conservation equations while the mass and energy conservation equations produce the upper and lower layer temperatures, layer height and the compartment pressure, and the densities are derived from the equation of state (ideal gas law) [Jones and et al., 2005] [Shigunov, 2005]. The general conservation equation of mass, species and energy are presented below in this section [Karlsson and Quintiere, 2000].

The conservation of mass for a control volume means that the rate of mass change with time in this volume plus the sum of all the net mass flow out rates of the volume is zero. The equation of mass conservation can be written as:

$$\frac{dm}{dt} + \sum_{j=1}^{n} \dot{m}_j = 0 \qquad \textbf{Eq 4-1}$$

where dm/dt is rate of mass change term and $\sum_{j=1}^{n} \dot{m}_j$ for the room illustrated in Figure 4-3 below assuming that the control volume is formed by the upper layer and the upper plume can be written as:

$$\sum_{j=1}^{3} \dot{m}_j = \dot{m}_{out} - \dot{m}_{ent} - \dot{m}_{sou} \qquad \textbf{Eq 4-2}$$

where $\dot{m}_{out}$ the mass flow rate out of the room vent, $\dot{m}_{ent}$ the mass flow rate entrained into the fire plume and $\dot{m}_{sou}$ the mass flow rate produced by the fire source.

The conservation of species implies the same principle of mass conservation for species i to a control volume. Thus the equation of conservation of species i for which the mass fraction is given as Y_i can be written as:

$$m\frac{dY_i}{dt} + \sum_{j=1}^{n} \dot{m}_j \left(Y_{ij} - Y_i\right) = \dot{S}_i \qquad \textbf{Eq 4-3}$$

where m is the mass of the layer, Y_{ij} is the mass fraction of species i leaving the control volume through a flow stream j (see Eq 4-2), and $\dot{S}_i$ is the generation rate of species i from fire source.

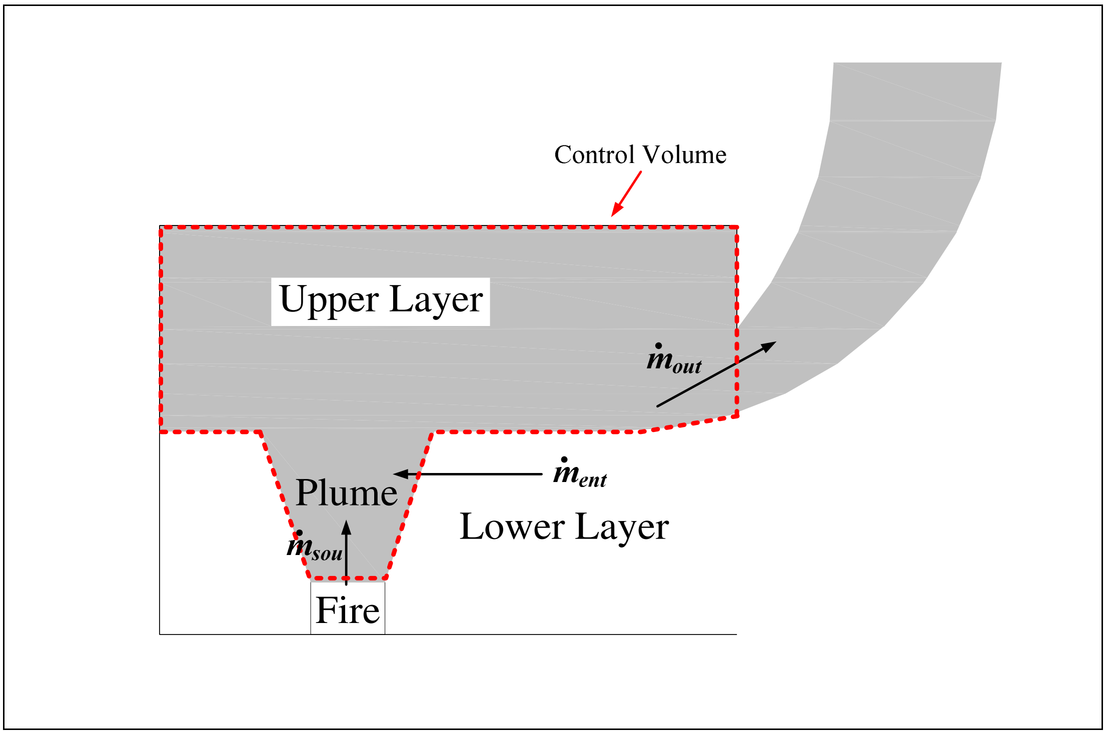

Figure 4-3: The two layers (upper and lower) and the fire plume observed in enclosure's fire.

The conservation of energy for a control volume is applied with the equation of mass conservation and the equation of state $P = \rho RT$ and can be written as

$$V c_p \frac{dT}{dt} - V \frac{dP}{dt} + c_p \sum_{j=1}^{n} \dot{m}_j \left(T_j - T\right) = \dot{m}_{reac} \Delta h_c - \dot{Q}_{loss} \qquad \textbf{Eq 4-4}$$

where V is the volume of the control volume, P is the global pressure in the room, T is the temperature of the gases in the control volume, T_j is the temperature of the gases crossing the boundaries of control volume through a flow stream j (see Eq 4-2), $\dot{m}_{reac}$ is the mass rate of the reaction of gas fuel supplied, Δh_c is the effective heat of combustion, and $\dot{Q}_{loss}$ is the net rate of heat lost at the boundaries.

4.4.1.2 Sub-models

The conservation equations which constitute the core of zone models contain source terms (like fire) and transport terms (heat and mass transport). Some of these terms are considered essential to the basis of zone models and others can be neglected in some cases. The extents to which these terms are considered and inter-related reveal the sophistication of the model. The relationships and representations of these sources and transport terms are referred to as sub-models and are discussed below.

Fire

In zone models, a fire is prescribed as a Heat Release Rate in a certain location in the fire domain. The predefined Heat Release Rate specifies the rate at which fuel mass is released. The fuel mass loss rate (MLR), burning rate or pyrolysis rate is related to the HRR as $\dot{m}_f = HRR/\Delta h_c$, where Δh_c is a prescribed heat of combustion of a specified fuel (See Section 3.4.3). A fire is constrained if the supply of oxygen available for the combustion is less than the needed supply; otherwise the fire is called unconstrained. The needed oxygen supply can be calculated as $\dot{m}_o = HRR/q_o$ following the fact that the amount of heat released when 1 kg of oxygen is consumed is considered constant for all fuels and has a value of q_o= 1.32 10^7 J/kg. Above each burning object, a plume is formed and pumps mass and energy from the lower layer to the upper layer. In an unconstrained fire, all the burning takes place in the fire plume. On the other hand, in a constrained fire the burning in principle occurs where the oxygen is sufficient. Thus if the oxygen entrained into the fire plume is insufficient, the unburned fuel will eventually flow and burn in a place like the upper layer of the fire room or will reach the plume in between the two compartments on doorway or even the upper layer of the next compartment and so going on until it burns all or escape the domain through an out-vent. Usually most of the zone models can handle more than one fire in various locations but no direct interaction between the plumes of these fire objects is considered even if they exist in the same compartment [Shigunov, 2005].

Heat Transfer

Three types of heat transfer are known and can be encountered in fire problems; conduction, convection and radiation. The first form of heat transfer (conduction) is not considered to occur between gas layers as the last two forms (convection and radiation) will be dominating the heat transfer between layers. However in some zone models like Raeume and CFAST, a one-dimensional form of conduction is applied for the heat transfer through walls, ceilings and floors of the domain [Jones and et al., 2005] [Shigunov, 2005].

Vent Flows

Flow through vents is a dominant component of any fire model because it is sensitive to small changes in pressure. Apart from the fire plume, these flows transfer the greatest amount of enthalpy on an instantaneous basis of all the source terms. Vent flow sensitivity to environmental changes arises through its dependence on the pressure difference between compartments which can change rapidly.

Two types of vent flows are usually modelled in zone models; horizontal flow through vertical vents (doors, windows, etc.) and vertical flow through horizontal vents (hatches, ceiling holes, etc.). The later type of vent flows is usually most likely to be encountered in ship applications or in roof venting for fire fighting purpose.

Bernoulli's law is usually used to compute the flow through vents using the pressure difference across the vent. Atmospheric pressure is around 100 000 Pa. Fires produce pressure changes from 1 Pa to 1 000 Pa while mechanical ventilation systems produce pressure differences in the range 1 Pa to 100 Pa [Jones and et al., 2005].

In principle when a hot upper layer is formed in a fire room, this layer is enriched with mass and enthalpy pumped by the fire plume. Accordingly the upper layer expands and pushes the lower layer down; hence air from the lower layer flows from the fire compartment to the next one. At the moment the upper layer reaches the door's soffit of the fire room a door plume is formed between the fire compartment and the adjacent one where a new upper layer is formed and also enriched with mass and enthalpy pumped from the upper layer of the fire compartment by a plume. The upper layer in the next compartment expanding in volume pushes the lower layer down allowing an air flow from the lower layer back to the fire compartment. Therefore it can be said that through a vent two opposing flows are taking place and those flows are driven by pressure and density differences resulting from temperature difference.

Fire Suppression

In zone models, sprinkler effects on fire are taken into account just by the means of reducing the heat release rate and neglecting all effects of interaction between the water spray and the combustion gases. Zone models always reduce the heat release rate and are unable to predict an overwhelming fire or an under designed sprinkler [Jones and et al., 2005] [SFPE, 2002]. Sprinkler effects are not considered in all zone models. However, when these effects are considered, they reduce the heat release rate of the fire. This is done by modifying the heat release rate in applying the suppression correlation to the existing heat release rate [SFPE, 2002]:

$$\dot{Q}(t - t_{act}) = \dot{Q}(t_{act}) exp\left[\frac{-(t - t_{act})}{3.0(W'')^{-1.85}}\right] \qquad \textbf{Eq 4-5}$$

Where $\dot{Q}$ the heat release rate in (kW), t_{act} is the activation time of the sprinkler in seconds, t is any after the activation time and W'' is the spray density in (mm/s). The latter quantity of spray density can be obtained by dividing the water volumetric flow rate the protected area.

Figure 4-4 below illustrates the effects of sprinkler on the heat release rate where the spray density of this sprinkler is assumed to be 0.0833 mm/s (or 5 litre/m^2/min). The sprinkler is assumed to be activated at 140 seconds after fire ignition and immediately starts smothering the fire until total extinction. However, as mentioned above, this correlation cannot account for an overwhelming fire and thus always reduce the heat release rate.

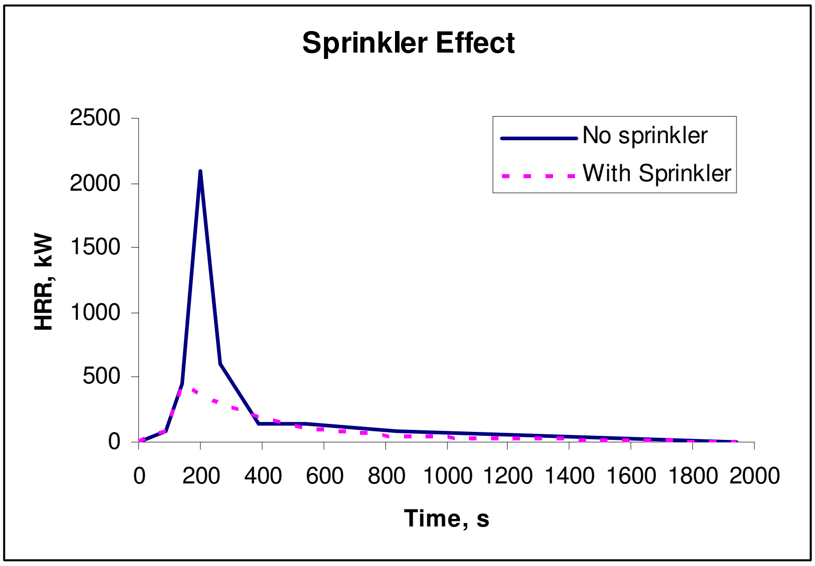

Figure 4-4: Sprinkler effects on the heat release rate.

4.4.1.3 Limitations and Assumptions

The assumptions made in zone models introduce some limitations and drawbacks which require extra caution when using these models. Some of these limitations can be stated as follows [Jones and et al., 2005]:

- The gas is treated as an ideal gas with constant molecular weight and specific heats.

- Zone model's concept implies a sharp boundary between the upper and lower layer. However, the transition can be over about 10% of the room height depending on the strength of stratification in the room.

- Pyrolysis rate is usually prescribed in zone models hence so is the heat release rate. Therefore, no account is being taken for the increase in pyrolysis rate due to the radiative feedback from the flame or department unless considered initially by the user prescribed pyrolysis rate.

- Also because the heat release rate is a prescribed user input in zone models; no flame spread is accounted for.

- Mass flow into the fire plume is due to turbulent entrainment which is a result of buoyancy effects. Entrainment coefficients values are empirically determined in zone models. Thus a small error in these values will have a small effect on the fire plume and on the door plume between the fire compartment and the adjacent compartment. However, in a multi-compartment case this small error is multiplicative and can result in a significant error in the furthest compartment.

- In real fire situations, smoke is introduced into the lower layer in two ways; firstly due to mixing at vent level and which is accounted for in the empirically derived mixing coefficients. Secondly from the downward flow along the walls where the buoyancy of gases is reduced by their contact with the walls. This is not accounted for in zone models and can result in slight underestimation of lower layer temperatures and species concentrations.

- The volume fire is assumed to radiate in all directions uniformly from a single point. The radiations emitted are assumed to be diffuse and gray. Thus the radiant fluxes emitted are independent of direction and wavelength. In addition to that each layer or wall segment is assumed to be at a uniform temperature and in quasi-steady state.

- The contents of the compartments are totally ignored and all the heat dissipation through conduction is assumed to happen on the ceiling, walls and floor.

- A plume is assumed to impinge instantaneously on the ceiling of the compartment. Thus the time for the gases to reach the ceiling is not accounted for in a zone model.

- Upon the impingement of the plume on the ceiling, an instantaneous spread of gases is assumed to happen over the whole area of the compartment's ceiling. This assumption can be so real for a compartment with length-to-width ratio that is not very large neither very small. However, in cases with high aspect ratios, the results should be examined closely to avoid overestimation of the smoke propagation speed.

With all the above being said it is clear that when zone models are applied, this cannot be done blindly and the specific case of application should be considered separately and examined closely. This is particularly important onboard passenger ships where compartments with high aspect ratios are frequently encountered in the corridors and paths, the fact that requires cautious application of zone models.

4.4.1.4 Models Adopted in the Study

The two zone models used in this study are: Raeume [Shigunov, 2005] which was developed in the Ship Stability Research Centre at Strathclyde University and CFAST [Jones and et al., 2005] from the National Institute of Standards and Technology and which is one of the most used zone models in the fire protection society. The two zone models adopt the common concept of two zone per compartment explained in Section 4.4.1.1 above. However the differences between the models reside in the sub-models where parameters such as air entrainment, heat radiation and conduction can be calculated differently through various methods. It is worth to mention that CFAST has the capability of changing a door status from close to open or other way round during simulations. Conversely Raeume do not possess this capability mainly due to the numerical stabilities that might arise due to the sudden change of boundary conditions. The different settings and inputs for both models are specified in Sections 6.2 and 6.3 below.

4.4.2 Field Models

4.4.2.1 Basic Concept

Field models also known as *Computational Fluid Dynamics models* divide the studied domain into several smaller units or control volumes in order to compute the flow (See Figure 4-5). The conservation laws of mass (Continuity), momentum

(Newton's second law), energy (First law of thermodynamics) and species concentrations are applied to each of these control volumes forming the set of time-dependent, non-linear partial differential equations. Solving these equations beside the equation of state provide a prediction of the properties of a fluid flow with a level of accuracy depending on the size and number of the control volumes considered.

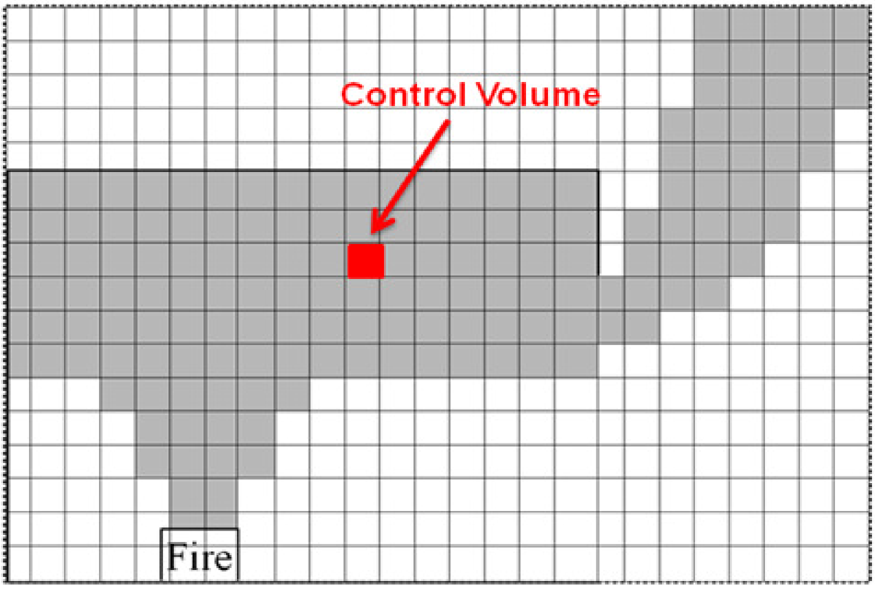

Figure 4-5: The two layers and plumes in a room fire as divided by field models into small control volume.

The derivation of governing equations is not in the aim of this study. However, for consistency, these equations are listed here in suffix notation [Versteeg and Malalasekera, 2007]:

The continuity equation can be written as follows:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial t}(\rho u_i) = 0 \qquad \textbf{Eq 4-6}$$

where u_i is the velocity vector and ρ is the variable density noting that the density in a combusting flow is dependent on pressure, temperature and species concentration.

The momentum equations can be written as follows:

$$\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_i}(\rho u_i u_j) = -\frac{\partial P}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_i} + F_i \qquad \textbf{Eq 4-7}$$

where p is the pressure, F_i represents the body forces including gravity and τ_{ij} is the viscous stress tensor:

$$\tau_{ij} = \mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3}\delta_{ij}\frac{\partial u_k}{\partial x_k}\right) \qquad \textbf{Eq 4-8}$$

The transport equations for species k can be written as follows:

$$\frac{\partial}{\partial t}(\rho Y_k) + \frac{\partial}{\partial x_i}(\rho u_i Y_k) = \frac{\partial}{\partial x_i}\left(\rho D_k \frac{\partial Y_k}{\partial x_i}\right) + \dot{\omega}_k \qquad \textbf{Eq 4-9}$$

where Y_k is the mass fraction of a species k, D_k is the species diffusion coefficient in (m^2/s) which is usually considered a single value for all the involved species and $\dot{\omega}_k$ is the source (or sink) term representing the generation (or destruction) of a species due to chemical reactions.

The energy equation in its simplified form can be written as follows:

$$\frac{\partial}{\partial t}(\rho h) + \frac{\partial}{\partial x_i}(\rho u_i h) = \frac{\partial}{\partial x_i}\left[\frac{\mu}{\sigma_h}\frac{\partial h}{x_i}\right] + \frac{\partial p}{\partial t} + S_{rad} \qquad \textbf{Eq 4-10}$$

where h is the enthalpy, S_{rad} is the radiation loss or gain, σ_h is the mixture Prandtl number and μ is the dynamic viscosity.

4.4.2.2 Sub-models

A range of sub-models is used to help solving the governing equations. These sub-models are derived from physical reasoning and most importantly include combustion, turbulence and radiation models. These sub-models are presented and described below [Versteeg and Malalasekera, 2007] [Ferziger and Peric, 2002]:

Combustion Models

The combustion phenomenon is a very complex one involving physical and chemical processes in the micro and macroscopic levels. Usually combustions encountered in enclosure's fire sector are of the non-premixed or diffusion flames type; exceptions like backdrafts and explosions etc… are of the premixed or partially premixed combustion types. Thus, just the non-premixed type of combustion will be further discussed in this section. Among several concepts used for non-premixed combustion modelling, the most common approaches are presented below:

In the **Simple Chemical Reacting System** also known as flame-sheet model, it is assumed that the concern is about the global nature of the combustion and the final major species concentration while detailed kinetics is not of interest. Thus, the combustion is considered as a single infinitely fast chemical reaction with stoichiometric oxidant and fuel proportions. A non-dimensional variable called the mixture fraction is derived from the mass fraction of fuel and oxidant. Algebraic relations are established between the mass fractions of fuel, oxidant, inert and products and between temperature and enthalpy. Then, a transport equation for the scalar mixture fraction is solved along with the enthalpy equation. It should be noted also, that in cases where the radiation and other heat losses are insignificant the source term in the enthalpy transport (energy) equation is neglected thus the resulted equation is similar to the mixture fraction one. Enthalpy then is considered a conserved scalar and just one transport equation is needed to be solved to compute both scalars.

In turbulent cases, the application of Simple Chemical Reacting System is not as straight forward as the laminar cases. The algebraic relationships are between the mass fractions and the instantaneous mixture fraction, and between the temperature and instantaneous enthalpy. On the other hand, the mixture fraction and enthalpy computed by the transport equations are density-weighted averaged. Therefore, to calculate the mean values of temperature and mass fractions it is necessary to know the statistics of the instantaneous variables of temperature, mass fractions and density in function of instantaneous mixture fraction. A statistical approach using Probability Density Function method is used to calculate the fluctuating scalars [Versteeg and Malalasekera, 2007].

In **Eddy Break-Up model**, the rate of consumption of fuel is controlled by the flow properties. The reaction rate is mixing controlled and expressed in terms of turbulence time scale k / ε, where k is turbulent kinetic energy and ε is its dissipation rate. Therefore, the combustion predictions by this model are highly dependent on the turbulence model predictions. If the turbulence features are poorly predicted, then the combustion predictions are also very limited. If the reaction rate is controlled by kinetics rather than mixing, fuel consumption may be expressed by the more sophisticated Arhennius kinetic rate expression.

Eddy Dissipation Concept is a modified version of eddy break-up model that attempts to incorporate the significance of fine structures in a turbulent flow where the combustion chemistry is important.

In some kinetically controlled applications the combustion chemistry and prediction of intermediate and minor species are of great interest. Therefore, finite rate kinetics effects are modelled based on **laminar flamelet** concept. In this approach, the diffusion flame is considered as a statistical ensemble of thin laminar flames called flamelet and the major heat release is assumed to occur in narrow regions in the vicinity of stoichiometric contour. The basic idea of the model is that the chemical time scales are much smaller than the turbulence scales. Thus, the fuel and oxidant react in thin one-dimensional structures normal to the stoichiometric contour. Turbulence effects are incorporated to the laminar flamelets by including appropriate parameters to stretch and strain the flamelets. The properties of the flamelets like temperature, density and species mass fractions in function of mixture fraction are evaluated to yield the laminar flamelet library. For further details on this model the reader is referred to [Versteeg and Malalasekera, 2007].

Away from the physical and chemical complications of the combustion process, fire can be modelled as a **volumetric heat source**. This approach is commonly used where the combustion process details are not required to be known. Instead the volumetric heat source accounts for the resulting effects of the combustion – production of heat and smoke. The shape, size, heat and mass production of the volume should be prescribed in advance and not obtained as results of the simulations. These inputs can be obtained from previous experimental data or well established correlations [Gobeau et al., 2002].

Turbulence Modelling

At certain Reynolds numbers most of fluid flows become irregular and hence called turbulent. Then the flow is no longer steady and vortices (eddies) of different scales appear in the flow. Quintiere [1998] reported that a flame higher than approximately one foot (~30cm) will naturally possess random fluid mechanical unsteadiness, illustrated by visible eddies in the smoke and flame. This random behaviour of the flow is called turbulence and should be resolved; hence solution methods can be classified into three main categories:

1. Direct Numerical Simulation (DNS):

   All the turbulence features are resolved numerically by solving the set of Navier Stokes equations. However this approach requires a very high grid resolution and eventually huge computing efforts. Therefore this method is scarcely used in engineering problems.

2. Large Eddy Simulation (LES):

   The basic idea of this approach is to filter (volume average) the flow in order to resolve the large grid scales (large eddies) which are supposed to contain must of the energy. While the remaining sub-grid turbulent scales (small eddies) which cannot be resolved by the grid are modelled usually using Smagorinsky model. This approach is less grid resolution demanding than DNS and is increasingly used in engineering applications. This method is found attractive for fire applications as the dominant large eddies in fire plume can be resolved in a moderate grid depending on the fire size and the sub-grid scales are modelled by empirical correlations.

3. Reynolds Averaged Navier Stokes (RANS):

In this approach the flow is time averaged such that only the main steady flow is resolved while all the turbulent fluctuations are modelled. Many methods have been adopted to model the Reynolds stresses term containing the turbulence effects. A broadly used method is the two equation model k-ε, where (k) is the turbulent kinetic energy and (ε) is its dissipation. Modifications to this model have been done to account for the buoyancy related effects on the Reynolds stresses. Another two-equation model is the k-ω model where (k) is again the turbulent kinetic energy and (ω) is specific dissipation rate. A combination between k-ε and k-ω models is the Shear Stress Transport (SST) where k-ω is applied in the near wall region and k-ε in the rest of the flow. A more sophisticated approach is to derive a transport equation for the Reynolds stresses, thus the method is called Reynolds Stress Model. However this last method is less used than the previous ones.

Radiation

Radiation is a very important mean of heat transfer in fire cases especially in the vicinity of fire source where the highest temperatures are located. The equation of radiant heat transfer is an integro-differential one which solution is very difficult even for the simple cases of two dimensional planar medium. Noting as well, that radiant heat transfer happens in a non-isothermal and non-homogeneous medium and those variations should be accounted for in the calculations. Therefore, the introduction of simplifying assumptions becomes necessary and a balance between accuracy and computational efforts should be done.

A number of different approaches are available; those that are usually encountered in fire problems are presented below [Gobeau et al., 2002], [Novozhilov, 2001], [Modest, 1993] and [Versteeg and Malalasekera, 2007]:

1. Fractional heat loss:

This approach accounts for radiation by simply ignoring in the simulations the percentage of the heat release radiated from fire. This percentage depends mainly on the fuel type and a value of 30% is common in fire cases. Therefore the output heat of the fire is the remaining convective percentage. The radiated heat is completely ignored in some simulations. However in others it is accounted for by distributing the percentage of radiated heat to the air in the cells next to the walls opposite to the fire. In the latter method the radiant heat transfer is not obtained but set by the user in form of pre-defined heat distribution across a prescribed wall area.

2. Zonal method:

In this method the computational domain is divided into a finite number of isothermal volumes and surface area zones. Then, the direct exchange areas between volumes and surfaces are evaluated and an energy balance is performed for the radiative exchange between any two zones. This will result in a set of simultaneous equations for the unknown temperature or heat fluxes. The method is not widely used for complicated geometries since a great amount of memory is required to store the numerous exchange factors between the zones [Modest, 1993].

3. Flux method:

This method assumes that radiant intensity is uniform on a given intervals of the solid angle. This is capable to reduce the integro-differential equation to an approximate set of partial differential equations in terms of average radiation intensities. Most commonly used is the six-flux method which assumes that radiant flux across each of the six faces of a structured grid cell is uniform. This method transforms the integro-differential equations into transport equations for radiation intensity which solution is similar to fluid flow equations. It is also possible to use non-uniform solid angle divisions which form the basis of the discrete ordinates method described below.

4. Discrete Ordinates method:

In DO method the entire solid angle of $4.\pi$ is discretised into a certain number of different directions where the intervals are replaced by numerical quadratures. The angular approximation transforms original integro-differential equation into a set of coupled differential equations. This set of equations can be solved by applying the finite volume approximation. Starting from a boundary where the intensity is known, the unknown intensities along each ordinate can be found. Then the radiative source terms for the enthalpy equations can be calculated. The standard DO method can be directly applied to Cartesian and axi-symmetric geometries but not to non-orthogonal and unstructured grids. However, a modified method suitable for complex geometries was developed [Versteeg and Malalasekera, 2007].

5. Finite Volume method:

This method shares several features with the Discrete Ordinates method. Equations for intensity are solved for a set of discrete directions, which spans the entire solid angle of $4.\pi$. In addition to control volume integration the Finite Volume method uses control angle integration as well. Interpolation techniques for non-orthogonal mesh are available for radiative heat transfer calculations in complex geometries. However, there is difficulty in the evaluation of cell intensities and handling of control angle overhanging because of the misalignment of cell surfaces with discretised control angles [Versteeg and Malalasekera, 2007].

6. Monte Carlo method:

This is a statistical method where a number of rays are emitted in random directions from random locations on a certain element. These rays are then traced until they either hit an obstacle or go out of the computational domain.

Eventually the accuracy of the radiative heat transfer calculation in this method is strongly dependent on the number of rays. The high accuracy of this method comes in the expense of immense computational efforts needed for the calculations. Therefore it is unlikely to encounter this method in problems of fires and smoke movement in large complex geometries.

7. Discrete Transfer method:

Discrete Transfer method forms a good combination between the computational economy and the required precision for radiative heat transfer in fire modelling. It can be considered a hybrid method of the Zonal, Discrete Ordinate and Monte Carlo methods described above. This method is based on ray tracing and assumes that the radiation flux leaving the surface elements in a certain range of solid angles can be approximated by a single ray. The number of rays and their directions should be specified in priori. An appropriate equation for the radiation intensity is solved along each ray. A computational grid for radiation calculation is formed in the domain; this might be different from the fluid dynamic grid. In gray medium case the ray is assumed to cross a computational cell with uniform radiative properties (temperature, absorption and scattering coefficients). However, this method may be extended to non-gray problems by dividing the spectrum into different bands. The discrete transfer method is still considered computationally expensive especially where a large number of rays are solved.

The radiative properties (absorption and scattering, where the sum of these two is called extinction) of a fire medium are a function of wavelength, temperature, pressure, composition and path length. The fire medium consists mainly of combustion gases (like H_2O, CO_2, and CO etc…) and soot which radiative properties depend on the wavelength. Therefore, to account for the variations related to the electro-magnetic spectrum, the entire wavelength is divided into several bands where it is assumed that the absorption and emission characteristics of each species remain either uniform or change smoothly over these bands. Thus the accuracy of the predictions is expected to increase as the bands' width become narrower. Several approaches were used to solve this problem like statistical narrow band models and exponential wide band model. In the first type of models, statistical narrow band, the spectrum of thermal radiation is divided into small intervals for each radiating species. For each interval, the spectral lines are assumed to follow an exponential probability distribution. The large amount of data for each contributing interval and for most important species over ranges of temperature and pressure make the method impractical in engineering applications. The second type of models, exponential wide band, make use of the fact that infrared radiation from each species is concentrated into up to six wide-band spectral regions, associated with principle vibrational transitions. The individual spectral lines within these vibrational transitions are associated with different rotational transitions. The positions of the rotational lines within each band are approximated by simple exponential expressions. In a different perspective, a simple method to calculate the local absorption coefficient is to assume that the smoke layer is a gray, isothermal gas of a prescribed absorption coefficient. This approach can be considered relatively accurate in small to medium size fires. However, in large fires the error can be considerable. A less simple method is to express the local properties for each control volume in function of temperature in addition to gas and soot concentrations [Gobeau et al., 2002], [Novozhilov, 2001], [Karlsson and Quintiere, 2000].

4.4.2.3 Boundary Conditions

The boundary conditions control all kind of events that limit and bound the computational domain. These boundaries can be a flow entering or leaving the domain (doors, windows, etc...), transferring mass, momentum and heat, only heat transfer through walls or finally a source/sink of mass, momentum or heat due to an external event (fire, suppressant, etc.). Boundary condition types differ but in general it can be said that these conditions will be one or a mixture of the following types:

- First type is Dirichlet boundary conditions which are prescribed variable values like to assign a velocity or temperature for a flow entering the domain.
- Second type is Neumann boundary conditions that prescribe the gradients of the variables, for instance assigning the gradients of all variables on a plane of symmetry to zero.

- Third type of boundary conditions is the sources or sinks of heat, mass and momentum like defining a fire via the volumetric heat source approach.

Two CFD models were selected to be used in this study. The first software is Fluent [Fluent, 2003], a general multipurpose CFD-package which can be used to simulate a fire induced flow and predicts its consequences. Fluent is a widely validated and used programme in the majority of CFD fields. The second model is called Fire Dynamics Simulator [McGrattan, 2008a] from the National Institute of Standard Technology. This model is developed for the purpose of fire dynamics simulation and effluents predictions. FDS is very widely used in fire protection societies and all fire applications. The different sub-models chosen for the corresponding computations are presented later in different chapters of this thesis.

4.5 Evacuation Models

Evacuation models also known as crowd-flow models or pedestrian's dynamics models are very common in urban planning and design. A number of different methods and theories were developed in the civic field which can be directly applied to the marine sector. However, evacuation models in the marine field have additional considerations like the motion and tilt of the ship in addition to a complicated mustering procedure according to the assembly point and nature of the emergency onboard. Usually ship motions, if considered during the evacuation procedure, can be accounted for by using safety factors or by reducing the walking speed; noting that certain evacuation models like maritimeEXODUS takes into consideration the impact of heel and list on passenger movement capabilities based on evacuation tests data according to [Galea et al., 2004].

Crowd flow models are fundamentally different from fluid dynamics models. Fluid flows can be described by continuum formulations governing the whole flow. Hence macroscopic models are appropriate. In contrast, crowd flows contains collections of people that exhibit individual and diverse behaviour which have to be taken into consideration. Thus, macroscopic models are inappropriate for crowd flow modelling. Microscopic simulations, in contrast, allow more reasonable pedestrian dynamics simulation as they capture the complex behaviour of individual members.

4.5.1 Model Adopted

Helios (an acronym for Human Environment Local Interactions Onboard Ships) is the name of the evacuation model used for this study and it was developed in the Ship Stability Research Centre at Strathclyde University. *Helios* is a general software for modelling and analysing shipboard operations. In addition to pedestrian dynamics, it contains many other features like hydrostatics calculations and loading of vehicles into a ship, however those features are not of interest for the present study. Therefore, no details of the additional features are provided here but further information can be found in [Majumder et al., 2005a, b; 2007] and [Guarin et al., 2004].

Helios is a microscopic evacuation model and thus there are no general equations that govern the crowd flow as it is the case in macroscopic fluid flow models. People in this model are mostly driven by individual free choice rather than by conservation equations. This individual modelling is essential to capture complex behaviour of an evacuating crowd hence most of the available models differ in their microscopic rules and algorithms. *Helios* is different than other evacuation models which treat evacuees as particles and model the crowd flow through equations of motion for each person as described in section 3.5.2 for FDS+Evac model.

The core of the model is a spatial database generated from the general arrangement (GA) drawings and hull geometry. Spatial database is a data structure that represents the layout of the shipboard and supports the computation of different queries like annotations and simulations. Numerical models are built around the spatial database and contain the abovementioned features like evacuation simulations, hydrostatics calculations etc… As far as this study is concerned, the human evacuation procedure simulated in Helios is illustrated in Figure 4-6 and described below.

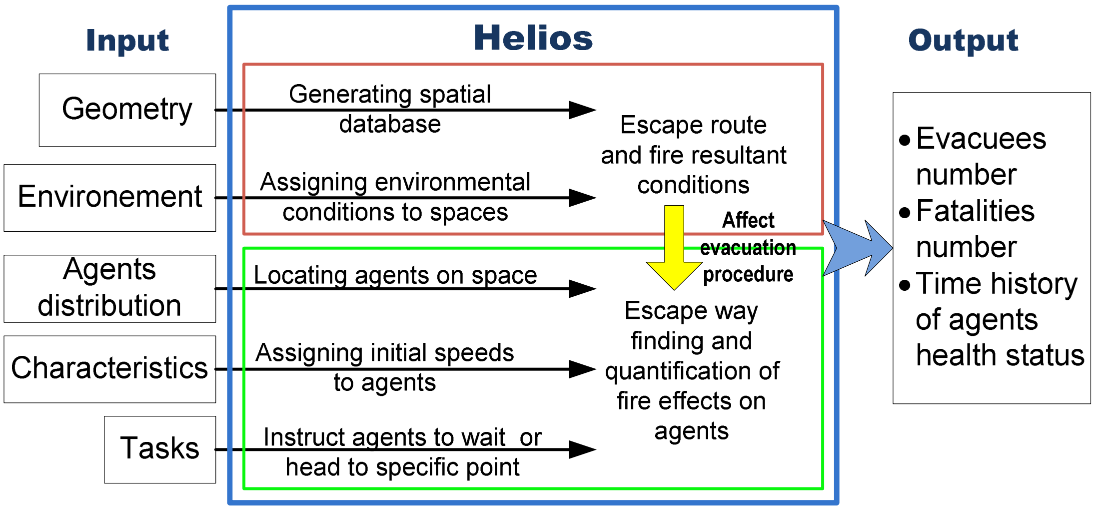

Figure 4-6: Work procedure of the evacuation model Helios.

The initial inputs of the model consist of the geometrical arrangements, fire conditions, and agents' distributions, their characteristics and the tasks expected to perform. In the initial stage, Helios converts the geometrical arrangements into spatial database usable by the model as described in details in Section 4.5.1.1. Fire effluents in form of heat and gases concentrations data are stored at frequent and evenly spread locations on shipboard spaces. Evacuees are assumed to be exposed to the conditions stored in the nearest location to them. At this stage also, the positions of evacuees are allocated on the spatial database and their initial speeds are assigned. The agents are instructed to perform different tasks which are mainly to wait in place or escape to a specified location. As time process starts, the agents perform their instructed tasks. In the escape process, the evacuees move from their location to the assigned assembly point by finding their way as described in Section 4.5.1.2. The way finding procedure is updated each time step with respect to the new obstacles visible by the agents from their new location. The fire conditions are also updated with time marching. Fire conditions affect agents through visibility by slowing the evacuation speed and through heat and toxicity by deteriorating the evacuee's health status. This is described in details in Section 4.6. As the individual health status of agents is assessed throughout the evacuation procedure, the model provides as output the number of safe evacuees or number of injuries and fatalities with the location, time and cause of casualty.

4.5.1.1 The Spatial Database

The spatial database is a data structure representing the shipboard layout, supporting computation queries and composed of triangular faces. The generation of the spatial data base out of the common ship general arrangement drawings is described in this section [Majumder et al., 2005b]. Figure 4-7 provides an overview of the procedure adopted to convert GA drawings into spatial database.

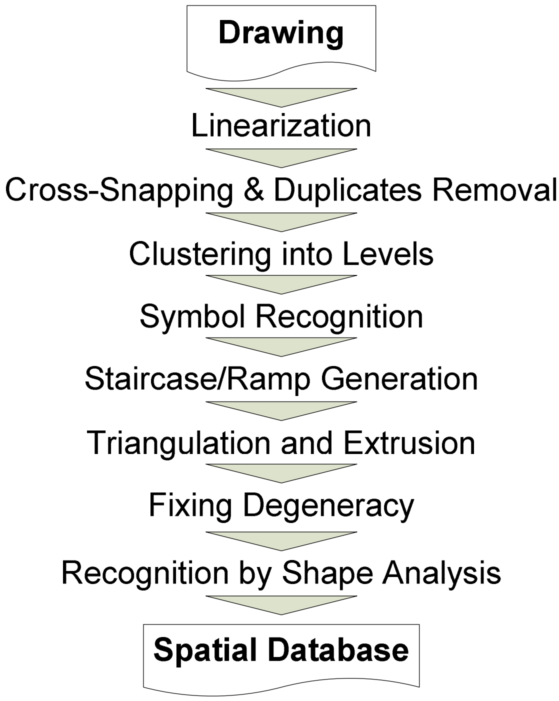

Figure 4-7: General arrangement drawings to special database reproduced from [Majumder et al., 2005b].

GA drawings are two-dimensional vector graphics consisting of line segments and algebraic curves like arcs, circles and splines. In the first stage, the curves are replaced by piecewise linear approximates. The next stage is for cross snapping (merging close endpoints) and removal of coincident line segments. At this stage the data is still as set of linear segments laid out in 2D form. The sets of lines belonging to a single deck should be clustered together in ascendant order to from the connection between ship decks. In the next stage, the symbols added to the GA drawings to provide information about the layout are extracted, processed and appended to the database. Then, the geometries of staircases and ramps connecting decks are reconstructed. As the exact shapes of these staircases and ramps are not readily available, the least steep connection is generated by optimization. Now the data represents a ship of multiple levels consisting of line segments standing walls and obstacles. The floor spaces are partitioned and represented as connected triangular faces. The partitioning of space into triangular pieces is called constrained triangulation and enables solutions for route planning; point location and visibility implementation (see Figure 4-8). Then, in the extrusion stage, height values are assigned to each of the walls.

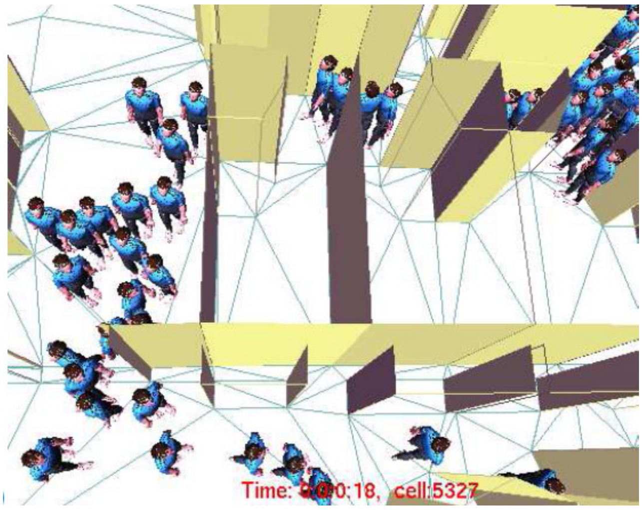

Figure 4-8: Triangle mesh of floor space in cabins area.

As the triangulation approach can lead to degenerate triangles, there is a stage to exclude this degeneracy for sake of robustness and correctness of subsequent computations. At the end of the spatial database generation, final operations are supported for recognizing shapes of regions. This is done by statistical clustering in the feature space of shape/size signature in order to identify different shipboard spaces like cabins and corridors etc… The complete spatial database is then used by Helios to human evacuation simulations and other computations.

4.5.1.2 Human Occupants Modelling

Rather than trying to address complexities of human physiology and psychology, occupants are treated as objects specific characteristics and capability of being instructed and programmed execute various tasks. The evacuation model converts the complex human behaviour to a set of crucial characteristics such as distribution and walking speed of evacuees, and their response to an emergency. These characteristics are normally instructed and programmed explicitly to different groups of evacuees according to their age, gender and exposure situation. In addition, each evacuee can be assigned different tasks such as waiting in place or moving to one or a series of designated locations. For human navigation or way finding is among the most important procedural implementation of evacuee behaviour. The computation of navigation involves two procedures; topological planning and geometric plan-following. The first procedure creates a path consisting of a sequence of triangular cells of the triangulation that needs to be passed through to reach a destination. This is normally a zigzag path that is unrealistic to be followed in an evacuation procedure. In the second procedure, the actual path to be followed by the evacuee is created. This path goes through triangular cells avoiding the zigzag and aiming at the furthest way point accessible without intersecting any wall. Therefore, each evacuee, instead of moving from a node to an adjacent one and so on to get to his destination, heads toward the furthest visible node in a straight line in order to get at the end to the assigned assembly point (see Figure 4-9).

Another procedure is performed to make sure that evacuees following their designated paths do not path through the body of other evacuees. This procedure is called dynamic avoidance and ensures that the evacuation path is deviated from the extents of other evacuees normally represented as squares.

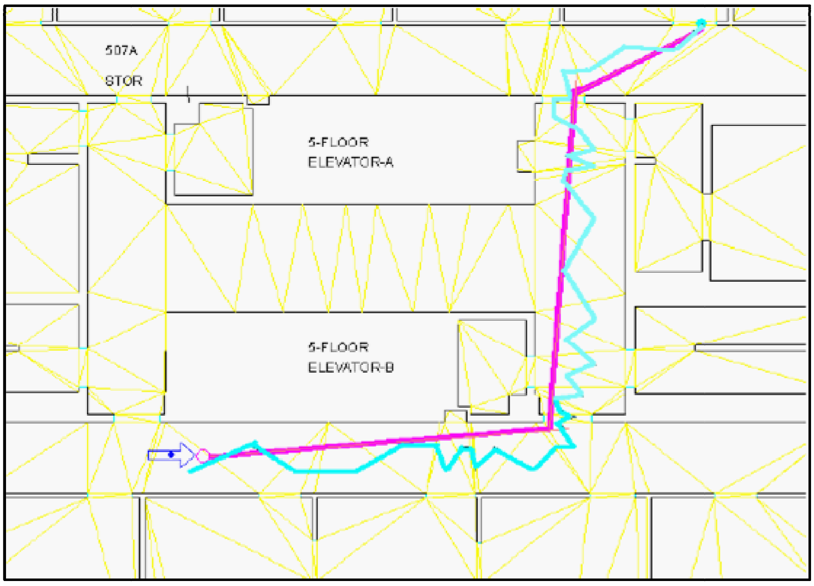

Figure 4-9: Evacuee's path as based on furthest visible way point comparing to adjacent way point [Majumder et al., 2005b].

4.5.2 Application of Evacuation Model

The inputs required for the evacuation model are the ship general arrangement (GA) of the area where the evacuation process is taking place and the occupant's properties and distribution in that area. Also, all different required tasks should be assigned to the evacuees in advance. The geometric arrangements locate the obstacles that hinder the evacuation process and settle the escape route of the evacuees. The walking speed of several persons in a queue is restrained by the speed of the leading evacuee. Congestion is considered by constraining the number of people going through an opening (door or corridor etc…) by the wideness of this opening.

There are no records of any model calibration against experimental results and the only calibration exercises performed were the validation / verification tests provided by IMO regulations [IMO, 2002b]. The use of this evacuation model in this study is considered very reasonable as the main focus of the study is mostly the effects of fire resultant conditions on the evacuation process in general and human health status in specific. For this, considerable efforts were made in order to ensure that the effects of fire effluents on evacuees are quantified within a reasonable accuracy.

The passenger's exposure to fire effluent effects accompanying the evacuation procedure obviously affects the evacuees' characteristics. Thus, the effects of fire effluent on human life safety are incorporated to the evacuation model in order to evaluate the resulting impairment to the evacuees. Threats to human life in fire cases can be divided in three types, inhalation of asphyxiant gases, exposure to radiant and convective heat, and visual obscuration. The fractional effective doses and concentrations of these three types are considered in safety evaluation. The quantification equations utilised to assess the impairment level associated with each evacuee are presented and integrated to the evacuation model Helios. All the details, equations and developments of human exposure to fire effects are presented in the section below.

4.6 Fire Effects on Human Life Safety

All fires produce heat in addition to smoke which is the dispersion of fine solid and liquid particulates in hot gaseous medium. Exposure of humans to these fire products along with vision impairment due to smoke obscuration presents hazardous conditions. Heat and smoke can deteriorate movement, impair visibility, block escape routes and even totally incapacitate occupants. Effects of fire and smoke on human life safety can be divided in three major parts:

- Firstly, toxicity due to inhalation of asphyxiants stimulated by presence of other toxicants, in addition to respiratory and pulmonary irritation;
- Secondly, heat exposure due to convective and radiant heat;
- Finally visibility impairment due to smoke obstruction and sensory irritation.

Each part of the effects is explained and the equations to quantify these effects on human life are presented below.

4.6.1 Toxicity

Fire products composition and amount vary following different material combustion or pyrolysis. However, the toxic gases present in fire products and that have direct effects on human life safety are generally known and include Carbon Monoxide (CO), Carbon Dioxide (CO_2), Hydrogen Cyanide (HCN), Halogen Acids or inorganic irritants (HCl, HBr and HF), Nitrogen Oxides (NO_x) and organic irritants (like aldehydes, etc…).

Carbon Monoxide, Carbon Dioxide and Hydrogen Cyanide are classified as asphyxiants or narcosis-producing whilst Halogen Acids, Nitrogen Oxides and organic irritants are all considered as irritants for sensory, upper respiratory and pulmonary systems. Narcosis refers to the effect of toxicant capable of resulting in the central nervous system depression, with loss of consciousness and ultimately death. Carbon Dioxide is also known as a stimulator that increases respiration rate when it is present in low concentration; however when it is more than 5 percent per volume of air, CO_2 becomes an asphyxiant itself. The standard for quantifying the toxic potency for different gases is known as the LC_{50} for 30 minutes exposure of animals, which is the concentration of toxic gas statistically calculated from data relating gases concentrations to animal's response and considered to cause death to 50 percent of test animals within a specified exposure and post-exposure time. The extensive data of studies collected from experiments for different gases and materials allowed the development of a strategy to calculate killing doses of different gases. This strategy is known as the Fractional Effective Dose methodology. The FED is the ratio of the exposure dose or the Ct product (gas concentration times the exposure time) to the exposure dose or Ct product of the toxicant that has been determined from experiments to produce lethality in 50 percent of test animals within a specified exposure or post-exposure time [Hartzell, 2003] and [Purser, 2002]:

$$FED = \frac{dose\ received\ at\ time\ t, Ct}{effective\ Ct\ dose\ to\ cause\ incapacitation} \quad \textbf{Eq 4-11}$$

This FED is useful when it is added for different toxic components and integrated over specified period of exposure time [Hartzell, 2003]:

$$FED = \sum_{i=1}^{n} \sum_{t_1}^{t_2} \frac{C_i}{(Ct)_i} \Delta t \qquad \textbf{Eq 4-12}$$

where C_i is concentration of toxic component i

$(Ct)_i$ is the specific dose (gas concentration x exposure time) required to produce lethality

t is time increment (minutes)

Assessment of the threat to human life due to toxic gases is calculated by the accumulation of exposure time of an evacuee's at each increment of exposed time. When the accumulated FED reaches unity it is expected that the mixture of toxicants is lethal to 50 percent of exposed animals (LC_{50}), i.e., the exposed person is expected to be incapacitated. The major toxic gases are discussed separately in the following section below.

4.6.1.1 Asphyxiant Gases

Carbon Monoxide (CO) is produced in both smouldering and flaming combustion and is largely dependent on oxygen supply where ventilation controlled fires favour the formation of CO. The toxic effects of carbon monoxide are those of anemic hypoxia. Hypoxia refers to the condition in which there is an inadequate supply of oxygen to body tissue, with anemic hypoxia being characterized by a lowered oxygen-carrying capacity of blood even when the arterial pressure of oxygen and the rate of blood flow are normal. This is due to competition between O_2 and CO for the heme-binding sites of hemoglobin. Conversion of haemoglobin to carboxyhemoglobin (COHb) rather than oxyhemoglobin (HbO_2) result in toxicity. Death has been observed with COHb saturations ranging from 1 to 99 percent; that is the percent of blood hemoglobin converted to COHb. However, most fatalities were recorded in the range of 50 to 70 percent [Hartzell, 2003] [Quintiere et al., 1982].

The carboxyhemoglobin (COHb) concentration in blood for an exposed person can be calculated from the following equation [Purser, 2002]:

$$\%COHb = (3.317 \times 10^{-5})(ppm\ CO)^{1.036}(RMV)(t) \quad \textbf{Eq 4-13}$$

where $ppm\ CO$ is CO concentration particles per million (10^6 x volume fraction)

RMV is the volume of air breathed or respiration rate (Litre/minute)

t is exposure time (minutes)

Therefore the fraction of effective (or incapacitation) dose can be calculated as

$$FED_{CO} = \frac{\%COHb}{(\%COHb)_{Inc}} = \sum_{t_1}^{t_2} \frac{(3.317 \times 10^{-5})(ppm\ CO)^{1.036}(RMV)(\Delta t)}{(\%COHb)_{Inc}} \quad \textbf{Eq 4-14}$$

where $(\%COHb)_{Inc}$ is the COHb concentration in blood required for incapacitation.

The values for RMV and $(\%COHb)_{Inc}$ are given for a 70 kg human at different level of activities. Occupants at rest are assumed to breath at a rate of *8.5 L/min* and need *40%* as COHb dose for incapacitation. For persons performing light activities like walking at a speed of 6.5 km/h, the respiration rate is *25 L/min* and incapacitation dose of COHb is *30%*. If a person is assumed to run at 8.5 km/h or walk at 5.6 km/h up a 17 percent gradient the breathing rate and incapacitation dose are assumed to be *50 L/min* and *20%*, respectively. These values of various respiration rates and incapacitation doses of Carboxyhemoglobin concentration in blood are presented in the table below.

Table 4.1: Respiration rates and incapacitation doses of COHb concentrations for persons performing different levels of activities; reproduced from [Purser, 2002]

Level of activity	Rest (sitting)	Light work (walking 6.5km/h)	Heavy work (run 8.5 km/h or walk 5.6km/h up a 17 percent gradient)
$RMV\ (L/min)$	8.5	25	50
$(\%COHb)_{Inc}$	40%	30%	20%

Therefore, to reveal human behaviour according to the aforementioned equations and figures, an adult at rest exposed to CO at 5000 ppm will experience incapacitation in 21 minutes. However, for a person at light work level the incapacitation for the same CO concentration of 5000 ppm is expected after around 5.3 minutes. For the hazard assessment conducted in this study all the evacuees are considered to be engaged in light work which is a reasonable assumption for the evacuation process. Thus, the values of *25 L/min* and *30%* are used for respiration rate and incapacitation dose of COHb, respectively.

Hydrogen Cyanide (HCN) is only found in the combustion of hydrogen containing materials and its generation depends on both the burning material and the temperature. This gas is much more toxic than carbon monoxide and acts rapidly. The action of HCN is due to the cyanide ion, which is formed by hydrolysis in the blood. Unlike CO which stays in the blood, HCN goes through body water and make contact with the cells of tissues and organs. Thus, where CO limits the oxygen supplied by blood, HCN prevents its utilisation by the cells. Data relating human behaviour in response to different HCN concentrations are limited. It is generally agreed that CO and HCN toxicants are additive in their effects [Hartzell, 2003].

Although HCN is considered as the next most important toxic gas after CO causing incapacitation by asphyxia, it has minor effects below a threshold of 80 ppm up to one hour of exposure time. For concentration range from 80 to 180 ppm, the time for incapacitation is between 2 and 30 minutes while above 180 ppm incapacitation will occur within 2 minutes.

The following equation is applied for HCN concentration above 80 ppm to calculate the fractional effective dose by HCN [Purser, 2002]:

$$FED_{HCN} = \sum_{t_1}^{t_2} \frac{(\Delta t)}{exp(5.396 - 0.023 \times ppm\ HCN)} \qquad \textbf{Eq 4-15}$$

where $ppm\ HCN$ is HCN concentration particles per million (10^6 x volume fraction)

t is exposure time (minutes)

Carbon Dioxide (CO_2) is generally present in fire products and its formation depends on ventilation conditions rather than the burning material or fuel type. Carbon dioxide by itself is low in its toxicology potency and insignificant for concentrations lower than 5% by volume of air. However, it stimulates breathing where the respiration rate is approximately doubled for CO_2 concentrations of 3 percent and tripled for 5 percent per volume. This hyperventilation increase the intake of asphyxiant gases like CO and HCN, hence reduce the time to incapacitation and death. At a concentration of 6 percent the effects become intolerable within 20 minutes. Symptoms of dizziness, headache and fatigue start to occur above 7 percent with danger of unconsciousness occurring within few minutes increasing from 7 to 10 percent. Loss of consciousness is likely within 2 minutes at 10 percent CO_2 [Purser, 2002].

As CO_2 effects increase the respiration rate which will increase the inhalation of asphyxiants, it is necessary to calculate the factor accounting for breathing rate increase [Purser, 2002]:

$$VCO_2 = \frac{exp(0.1903 \times \%CO_2 + 2.0004)}{7.1} \qquad \textbf{Eq 4-16}$$

where $\%CO_2$ is CO_2 concentration in percentage by volume.

On the other hand as CO_2 itself becomes an asphyxiant at concentrations above 5% an equation for its fractional effective dose can be written as follows [Purser, 2002]:

$$FED_{CO_2} = \sum_{t_1}^{t_2} \frac{(\Delta t)}{exp(6.1623 - 0.5189 \times \%CO_2)} \qquad \textbf{Eq 4-17}$$

where $\%CO_2$ is CO_2 concentration in percentage by volume.

Oxygen depletion (O_2) is also a result of fire and it is capable of causing human hypoxia and hence incapacitation. The effects of low oxygen are dependent on both the concentration and the exposure time. For oxygen concentrations between 20.9 and 14.4 percent per volume, no significant effects are observed apart from slight loss of exercise tolerance. Slight effects on memory and mental task performance, and reduced exercise tolerance are expected at concentration in the range of 14.4 to 11.8 percent of O_2 in air. At 11.8 to 9.6 percent, severe incapacitation and loss of consciousness can occur while between 9.6 and 7.8 percent also loss of consciousness and death are expected. The fractional effective dose of oxygen is calculated as follows:

$$FED_{O_2} = \sum_{t_1}^{t_2} \frac{(\Delta t)}{exp\big(8.13 - 0.54(20.9 - \%O_2)\big)} \qquad \textbf{Eq 4-18}$$

where $(20.9 - \%O_2)$ is the percentage of oxygen vitiation.

t is time increment (minutes)

The Interactive Effects of Asphyxiants

The above asphyxiants interact and contribute independently to the incapacitation of a human. Carbon monoxide (CO) and hydrogen cyanide (HCN) are considered directly additive. Carbon dioxide (CO_2) increases the uptake of CO and HCN in proportion to its effects on the respiration rate RMV. The effect of low oxygen hypoxia is additive to the combined effects of CO and HCN. The asphyxiant effect of CO_2 is considered to act independently of the effects of CO, HCN and O_2. The above observations can be formulated as follows to calculate the total fractional effective dose due to toxicity:

$$FED_{tox} = \left[(FED_{CO} + FED_{HCN} + FLD_{irr}) \times VCO_2 + FED_{O_2}\right] \; or \; FED_{CO_2} \quad \textbf{Eq 4-19}$$

FLD_{irr} is the fraction of lethal dose of the irritants contributing to hypoxia. This term represents a correction for the effects of irritants on lungs functioning. The effects of this term are just observed after several hours post-exposure time and mainly at extremely high concentrations of the irritants as described in section 4.6.1.2 below. The different types of irritants are presented in the following section for consistency. However, the term accounting for irritants is omitted in the model used in this study and its effects are neglected. Only the effects of asphyxiant gases, where sufficient data is available, are under consideration.

4.6.1.2 Irritant Products

Polymers containing halogen like (chlorine, fluorine or bromine) result in the formation of **Halogen Acids** like Hydrogen Chloride (HCl), Hydrogen Fluoride (HF) or Hydrogen bromide (HBr) etc… The production of these acids is largely material dependent. The most important gas is hydrogen chloride (HCl) being a sensory and pulmonary potential irritant. Concentrations as low as 75 to 100 ppm were found to be extremely irritant to the eyes and upper respiratory tract. No studies showed physical incapacitation even with high concentration as 17000 ppm and 5000 ppm for 5 and 15 minutes respectively. However, it is questionable whether the data from studies relating halogen acids with rodents can be directly applied to humans [Hartzell, 2003].

Nitrogen Oxides (NO_x) is a mixture having as its major components the nitrogen dioxide (NO_2) and nitric oxide (NO) where the later is known to be only one fifth as potent as the former. Nitrogen oxides were shown in studies on rats to have lethal toxic potency comparable to that of hydrogen cyanide due to its property as pulmonary irritant [Hartzell, 2003]. The effects of the mixture of gases can be considered by correcting the equation of HCN, however this is neglected in the current study due to the limited information provided [Purser, 2002].

Organic Irritants are numerous in fires with acrolein being the most significant. Acrolein with concentration of few particles per million can produce high irritation to the eyes. Studies on baboons (monkeys) with concentrations up to 2780 ppm for 5 minutes showed no physical incapacitation during the exposure period. However, death within hours after exposure was resulted by pulmonary complications. Here also, there is no sufficient information available to establish clear criteria for the killing dose of those irritants [Hartzell, 2003].

Hazards to sensory and upper respiratory systems due to irritants are assessed by a similar procedure to FED called Fractional Effective Concentration. Unlike the FED where the exposure *dose* is the main criterion, in FEC the *concentration* is the important parameter that judges the hazard on the exposed occupant. Accumulation with time exposure is not required in FEC, but just the concentration at a specific time of exposure. Then, FEC can be formulated as the ratio of (immediate concentration of the irritant at a specific time) to (threshold concentration of irritant required to cause incapacitation). The total FEC is the sum of the FECs of all the irritants present in the domain, where a total FEC equal to unity means incapacitation. This FEC can be written as follows:

$$FEC_{irr} = \frac{[HCl]}{F_{HCl}} + \frac{[HBr]}{F_{HBr}} + \frac{[HF]}{F_{HF}} + \frac{[SO_2]}{F_{SO_2}} + \frac{[NO_2]}{F_{NO_2}} + \frac{[acrolein]}{F_{acrolein}} + \frac{[formaldehyde]}{F_{formaldehyde}} + \frac{[other\ irritants]}{F_{other\ irritants}} \qquad \textbf{Eq 4-20}$$

where $[HCl]$, $[HBr]$, $[HF]$, $[SO_2]$, $[NO_2]$, $[acrolein]$, $[formaldehyde]$ and $[other\ irritants]$ are the irritants concentrations in particles per million (ppm).

F_{HCl}, F_{HBr}, F_{HF}, F_{SO_2}, F_{NO_2}, $F_{acrolein}$, $F_{formaldehyde}$ and $F_{other\ irritants}$ are the threshold concentrations when incapacitation due to additive irritants is expected.

However, threshold criteria for specific irritants are still vague and most information has been only anecdotal. Some of the values suggested by experts are listed here for consistency. The threshold concentration for incapacitation in particles per million (ppm) are listed in the table below from two different references [Hartzell, 2003] and [Purser, 2002].

Table 4.2: Incapacitation concentrations (ppm) for irritant effects; [Purser, 2002] and [Hartzell, 2003]

Irritant	HCl	HBr	HF	SO_2	NO_2	acrolein	formaldehyde
Hartzell	1000	1000	500	150	250	30	250
Purser	900	900	900	120	350	20	30

Another important effect of irritants is that the particulates of small size may penetrate deep into the lung and cause inflammation some hours after exposure. The lethal effects of those irritants can be accounted for during the calculation of the FED_{tox} by including the fractional lethal dose term (FLD_{irr}). This term is calculated by summing the fractions for lethal doses of different irritants until the total fractional lethal dose reaches unity when incapacitation is expected.

$$FLD_{irr} = \frac{[HCl]}{LD_{HCl}} + \frac{[HBr]}{LD_{HBr}} + \frac{[HF]}{LD_{HF}} + \frac{[SO_2]}{LD_{SO_2}} + \frac{[NO_2]}{LD_{NO_2}} + \frac{[acrolein]}{LD_{acrolein}} + \frac{[formaldehyde]}{LD_{formaldehyde}} + \frac{[other\ irritants]}{LD_{other\ irritants}} \quad \textbf{Eq 4-21}$$

where $[HCl]$, $[HBr]$, $[HF]$, $[SO_2]$, $[NO_2]$, $[acrolein]$, $[formaldehyde]$ and $[other\ irritants]$ are the irritants concentrations in particles per million (ppm). LD_{HCl}, LD_{HBr}, LD_{HF}, LD_{SO_2}, LD_{NO_2}, $LD_{acrolein}$, $LD_{formaldehyde}$ and $LD_{other\ irritants}$ are the threshold concentrations (or lethal doses) when incapacitation due to additive irritants is expected. The critical concentrations for the irritants are shown in the table below [Purser, 2002].

Table 4.3: Critical lethal doses for incapacitation caused by irritants; [Purser, 2002]

Irritant	HCl	HBr	HF	SO_2	NO_2	acrolein	formaldehyde
$LD_i(ppm)$	114,000	114,000	87,000	12,000	1,900	4,500	22,500

4.6.2 Heat

In most of fire events, heat is released during combustion as the burning of most materials is considered an exothermic process. The heat is released majorly in forms of convection and radiation where the former is measured by its temperature (°C or K) and the latter by its flux (kW/m^2). Heat poses threat on human life in three basic ways: hyperthermia (or heat stroke), burns to body surface and respiratory tract burns. Human body dissipates heat by evaporative cooling (perspiration) and blood circulation. A human body exposed to heat of higher rate than its dissipation capability, will experience a series of reactions ranging from minor effects to serious injuries or death. One can reasonably tolerate excess heat to a certain critical level after which the ability of heat tolerance decreases rapidly with fast body reaction. For convection heat, an exposure criterion of 120 °C is suggested, where above this value considerable pain is quickly incurred and burns to skin in few minutes. However, exposure to convective heat below 120 °C can still result in hyperthermia. Hyperthermia or heat stroke occurs when the body is exposed to heat level higher than it can dissipate. Thus, the entire body temperature is elevated leading to damage in the central nervous system and possibly death. Respiratory tract burns do not occur in the absence of skin burns upon inhaling air containing less than 10 percent by volume of water vapour. Hence, in this case, the tenability limits for skin burns are lower than those respiratory tract burns [Hartzell, 2003]. It is not unusual to find moisture in the fire environment due to humidity, the combustion or application of water based suppression. Humid air, steam or smoke with a high thermal capacity or latent heat may be dangerous at a temperature of 100 °C causing respiratory tract burns [Purser, 2002].

For an occupant exposed to air containing less than 10 percent water vapour by volume the time to incapacitation (t_{conv} in minutes) at a certain temperature (T in °C) can be calculated from the following equations:

For fully unprotected skin or lightly clothed occupants (this equation is used to account for convective heat effects on evacuees onboard) [Purser, 2002]:

$$t_{conv} = 5 \times 10^{7} T^{-3.4} \quad \textbf{Eq 4-22}$$

For fully clothed occupants [Hartzell, 2003]:

$$t_{conv} = 4.1 \times 10^{8} T^{-3.61} \quad \textbf{Eq 4-23}$$

For radiant heat, the tolerance threshold is 2.5 kW/m^2. Below this level the heat can be tolerated 30 minutes or longer however when this threshold is reached the tolerance is reduced, burns are produced and consequently time to incapacitation will rapidly decrease. Thus above the threshold of 2.5 kW/m^2, the time to incapacitation (t_{rad} in minutes) for an occupant exposed to a radiant heat flux (q in kW/m^2) is calculated by the following equation [Purser, 2002]:

$$t_{rad} = \frac{4}{3} q^{(-4/3)} = \frac{1.333}{q^{1.333}} \quad \textbf{Eq 4-24}$$

An occupant can be incapacitated by short exposure to high radiant heat or temperature as well due to long exposure to low radiated or convective heat. Thus, the same dose concept of toxicity can be applied here to calculate the fraction dose of heat acquired during exposure time.

$$FED_{heat} = \sum_{t_1}^{t_2} \left(\frac{1}{t_{conv}} + \frac{1}{t_{rad}} \right) \Delta t \quad \textbf{Eq 4-25}$$

The fractions of convective and radiated heat are summed at each time step for the whole exposure time.

4.6.3 Visibility

In addition to the gaseous part of smoke there is the other visible part. This visible part is constituted of the fine liquid and/or solid particulates dispersed in the air and known as aerosols. Since aerosol and visible lights have approximately similar wavelengths, light is scattered and vision is obscured through smoke. Therefore, smoke can block visibility of the escape routes and effectively deteriorate the evacuation procedure of occupants. The development of smoke that can hinder evacuation is known to be very rapid. Smoke obscuration is usually known as the first hazard to occur after a fire incident; it is observed in an early stage before heat or toxicity attains untenable conditions. The fast development of visible smoke can give a quick warning of fire; however, it impairs evacuation either partially or totally and poses threat on human lives. Smoke effects on the movement speed and way-finding ability of evacuees depend on the concentration of smoke and its irritancy to eyes and respiratory tract. The ability of smoke to obscure visibility is governed by the smoke light extinction coefficient (K_{ext}) or optical density (OD). Those two parameters have the same units of ($1/m$) and are related by the equation [Drysdale, 1988]:

$$OD = K_{ext}/\ln 10 = K_{ext}/2.3 \qquad \textbf{Eq 4-26}$$

where the factor of 10 is introduced to be consistent with the measurement of the attenuation of sound and electrical signals (decibels).

The intensity of monochromatic light passing a distance L through the smoke is attenuated according to Lambert-Beer-Bouguer law as [Drysdale, 1988]:

$$\frac{I}{I_0} = exp(-K_{ext}L) = exp(-K_m M_s L) \qquad \textbf{Eq 4-27}$$

where I_0 is the intensity of the incident light, I is the intensity of light through smoke, L is the path length (m), M_s is the mass concentration or density of smoke particulate (kg/m^3) and K_m is the mass specific extinction coefficient (m^2/kg). Thus the light extinction coefficient and mass specific extinction coefficient are related as $K_{ext} = K_m M_s$. The density of smoke particulate is obtained from the product of mass concentration (or density, kg/m^3) in a specified volume domain and mass fraction of smoke particulate (mainly soot) in this volume as $M_s = \rho Y_s$. The volume domain can differ with the prediction models; it can be in layer for a zone model or a cell in a field model. The value of the mass specific extinction coefficient K_m is derived from experimental studies and a mean value of $8700\ m^2/kg$ with an expanded uncertainty (95% confidence interval) of $1100\ m^2/kg$ was proposed by [Mulholland and et al., 2000].

One of the first fundamental studies on this subject was conducted by Jin in Japan [Jin, 2002]. The studies included investigation of the walking speed of evacuees in irritant and non-irritant smoke filled corridor. A range of low mass concentrations of smoke was used, where the maximum light extinction coefficient did not exceed a value of 1.15 (1/m). In addition to the relation between walking speed and light extinction coefficient, Jin developed useful linear relations between visibility of signs and light extinction coefficient in non-irritant smoke [Jin, 2002].

$$Visibility(m) = \frac{(5\sim10)}{K_{ext}}\ for\ light\ emitting\ signs \qquad \textbf{Eq 4-28}$$

$$Visibility(m) = \frac{(2\sim4)}{K_{ext}}\ for\ reflecting\ sign \qquad \textbf{Eq 4-29}$$

Purser, based on Jin's and other experimental studies, suggested for the assessment of visual obscuration hazard a model depending on the effective concentration. The model is called the smoke Fractional Effective Concentration FEC_{smoke} and Pruser suggested different impairment criteria for small and large enclosures [Purser, 2002]:

$$FEC_{smoke} = OD/0.2 \;\; for\ small\ enclosures \\ or\ \ OD/0.08 \;\; for\ large\ enclosures \qquad \textbf{Eq 4-30}$$

Purser stated that when FEC_{smoke} reaches unity, then it is predicted that the level of visual obscuration would be sufficient to seriously affect escape attempts.

In addition to its effect on walking speed, smoke also affects the decision making ability of the occupants. The behaviour of people in fire and smoke was studied experimentally and statistically. Bryan, in his study of US and UK populations' behaviour in fire environment reported a similar value for both populations of approximately 60 percent of people who will continue moving through smoke logged areas [Bryan, 2002]. The decision of moving or turning back as well as the walking speed also depends on the lighting and way guidance provision [Webber and et al.]. Recent experimental studies were performed by [Frantzich and Nilsson, 2003] to investigate walking speed and behaviour in a smoke filled tunnel. In a 37 meters long and 5 meters wide tunnel six cars were placed as obstacles for the evacuees. The tunnel was illuminated with five light fittings with fluorescent tubes. In addition flashing lights were installed to draw the evacuees' attention to the exits. Acetic acid was boiled and mixed with the smoke to achieve the irritant effects to eyes and nose. The light extinction coefficient in the experiments varied between 2 and 7 (1/m). The walking speed of each evacuee was calculated by dividing the total distance walked (traced by cameras) by the total time in the tunnel. Thus, the obstructions, decision time and stops were included in the total time but not considered individually. The walking speed that decreased with the light extinction coefficient varied between 0.8 and 0.2 (m/s). Noting that during the experiments, walking speed was observed to increase when evacuees walk alongside the walls. The results of the University of Lund experiments were obtained from the authors in form of spread sheets with permission of use [Frantzich and Nilsson, 2003].

The results of Jin (non-irritant smoke) along with Frantzich (only data with lighted tunnel are used) are presented on the same graph below (Figure 4-10).

As the range of light extinction coefficient used in each experiment is different, no direct comparison between the two sets of data is feasible. However, the two ranges of extinction coefficients are found continuous where Jin's experiments do not exceed an extinction coefficient value of (1.15/m) and Frantzich considers smoke concentrations with K_{ext} between (2/m) and (7/m).

A linear regression analysis using SPSS 16.0 for each data set provided a linear relation between the walking speed (m/s) and the light extinction coefficient, K_{ext} (1/m).

$$Walking\ speed = \beta \cdot K_{ext} + \alpha \qquad \textbf{Eq 4-31}$$

In the table below, the values of the regression coefficients and their standard errors are given:

Table 4.4: Regression coefficients and standard errors for the walking speed correlations; [Frantzich and Nilsson] and [Jin]

	$\beta(m^2/s)$	$\alpha(m/s)$	Std. error $\beta(m^2/s)$	Std. error $\alpha(m/s)$
Frantzich	- 0.057	0.706	0.015	0.069
Jin	- 0.314	0.965	0.198	0.152

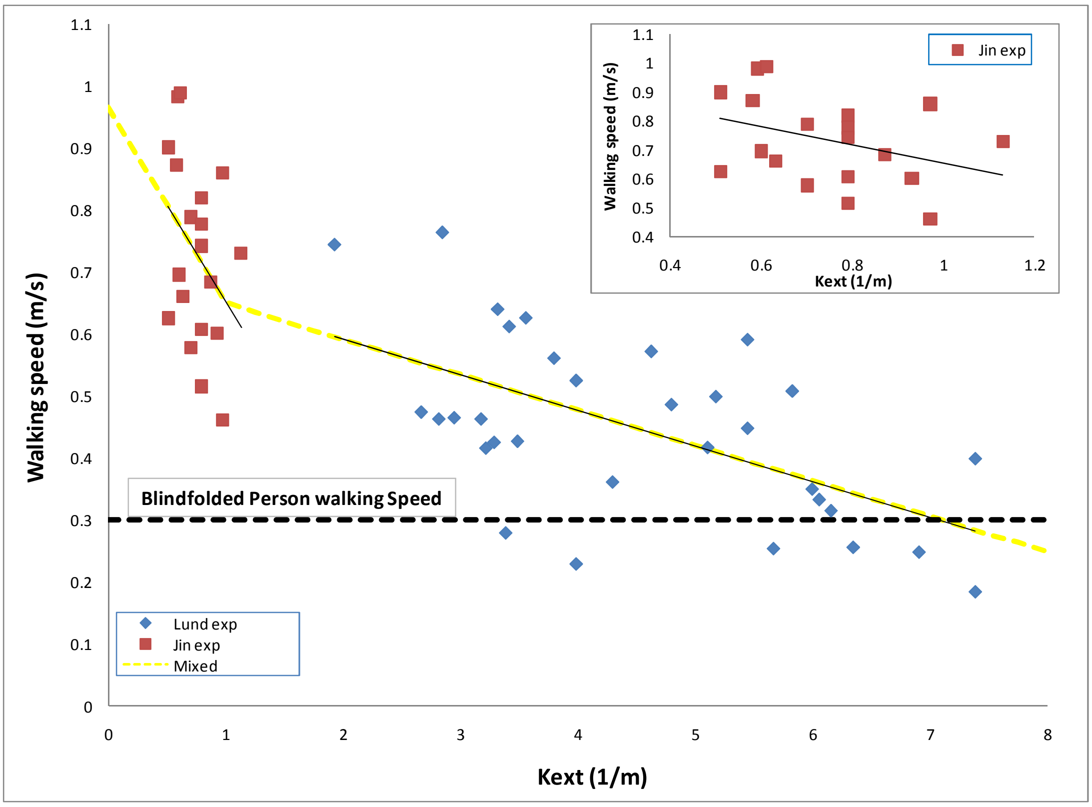

Figure 4-10: Set of experiments of Jin (non-irritant) and Frantzich with regression lines.

A very important observation in the experiments conducted in Lund University was that evacuees continue walking despite the low visibility due to high smoke concentrations and perception of touch becomes more important than vision for way finding in this situation [Frantzich and Nilsson, 2003, 2004]. Therefore, the minimum average walking speed of a person was taken as the speed of a blindfolded person or people walking in total darkness using their hands to find their way; this speed was set as 0.3m/s [Bukowski, 2003]. Thus, the model in the current study implements a combination of Jin and Frantzich relations. The two lines in the graph intersect at the point $(K_{ext}, Walking\ speed) \cong (1, 0.65)$. The relation derived from Jin's data is used for $K_{ext} \leq 1/m$ while Frantzich relation is used for the range $K_{ext} > 1/m$ until the evacuee reaches a minimum speed of 0.3 m/s where the walking speed in not decreased anymore.

4.7 Application of the Assessment Procedure

The assessment suite is applied to defined design fire scenarios where also parametrical studies are conducted to achieve the best utilisation of the model. Thereafter, a design case study is performed to illustrate the utilisation of the fire safety assessment approach in the context of the new “design for safety” concept based on risk quantification. These implementations are presented in Chapters 7 and 8.

The safety performance level of an alternative design deviating from the prescriptive rules is compared to the safety level of a prescriptive design in order to prove that the novel design performs at least equally safe. This equivalency approach was introduced by SOLAS Chapter II-2 to prove that a novel design can provide at least the same level of safety as a design complying with the prescriptive regulations. From a different perspective, in case of the existence of a well established set of risk acceptance criteria, the proposed design can be assessed against those safety parameters.

The performance based design approach has been widely applied in the shore-based sectors like civil buildings and in other transportation fields specially aviation. However, this approach was not extensively applied in the marine sector particularly on passenger ships. Passenger ships are considered of sound importance regarding the application of performance based designs because this is a particular field in the marine sector where unusual and luxury designs deviating from rules are required in order to attract the highest number passengers. The importance of this approach is that safety requirements are no longer applied as limitations and constrains but are considered among the main targets of the design. In addition, the performance based design approach provides more flexibility to the designers as prescriptive regulations inhibit the development of innovative, equally safe and more cost effective designs.

4.8 Concluding Remarks

After formulating the problems faced in shipboard fire safety and specifying earlier in this thesis the set of objectives to be accomplished for solving these problems, the proposed approach of the research study was outlined along the chapter. This chapter presented a high level introduction of the approach adopted in the study to address the aforementioned problems in shipboard fire safety and serves in providing a basis for elaborating further the proposed approach in the following chapters. The subsequent chapters explicitly explain the different list of actions presented in the proposed approach to accomplish the aim and objectives of the study. The chapters elaborating the main ideas proposed in the approach were also referenced during this chapter to enhance the thesis cohesion.

This chapter also introduced the basic concepts of fire models and described the different possible sub-models and functionalities. The models that will be used in this study were specified; namely the zone models are Raeume and CFAST whilst the field models are Fluent and FDS. In addition, Helios is the model to be used for evacuation simulation and the integration of fire conditions effects on human life safety. Each of these models adopts the main concepts associated with each model category presented in this chapter. The different sub-models and corresponding settings used for the models are specified for each individual simulation case in different chapters later in this thesis.

In addition, the equations to quantify fire effluent effects such as toxicity, heat and visibility are presented. Toxicity was considered in form of fractional effective dose which account for the asphyxiants commonly encountered in fire case. In addition, heat was considered in both its convective and radiative forms, in the fractional effective dose concept as well. Finally, linear relations between the evacuee's walking speed and smoke concentrations were developed from experimental data in order to account for smoke effects on visibility and evacuation procedure.

5 Shipboard Fire Incidents

5.1 Introductory Remarks

Fire incidents onboard passenger ships are numerous and usually known by the ship owner or operator. This data if collected can provide a formal statistics of fires onboard passenger ships. However, most of these incidents do not exceed the event of a burning dustbin extinguished by the first aid onboard. On the other hand, when these fire incidents escalate to accidents, these are usually reported in investigation and safety bodies, the data can be collected in order to draw some useful conclusions that gives the right orientation for further investigations. Thus, the aim of this chapter is not to provide a full statistical data about fire incidents onboard ships but to collect the data of remarkable fire accidents reported in safety boards and draw some useful conclusions for the current study. The chapter starts by reviewing studies that classify shipboard fire hazards among other hazards threatening ship safety. Next, fire incidents data is collected, clustered, analysed and interpreted. Finally, the possible fire scenarios are ranked in a manner to screen ship spaces for the most hazardous areas that merit closer attention.

5.2 Identification of Possible Hazards and Associated Scenarios

As fire was always recognized as a serious threat onboard vessel, reports of various shipboard fire accidents with different severity were recorded for passenger ships and other types of vessels. This reveals the importance of fire issue regarding safety of ships. In a recent risk evaluation study by Konovessis and Vassalos to investigate hazards onboard roll-on–roll-off passenger vessels (RoPax) fire was identified as a significant potential hazard [Konovessis and Vassalos, 2007]. Considering RoPax vessels of 4000 GRT and above for the period 1994 – 2004 and neglecting cases related to construction, repair and terrorism, hazards including fire, flooding and others were identified. Among the top-ranked high-consequences hazards, three fire related ones were cited; fire in accommodation while in open sea or navigating in coastal waters, fire on vehicle deck while unloading due to accumulation of fuel spills and fire in machinery spaces while in open sea or navigating in coastal waters. The study conducted a casualty analysis based on data obtained by Lloyds Maritime Information Unit (LMIU) for the same category of vessels and period stated above. Table 5.1 below shows fire as the most probable cause for serious accidents even though other hazards like collision, contact and machinery damage are more frequent. According to LMIU serious incidents are those who involve a single fatality or multiple fatalities, damage to the vessel that has interrupted her service or if the vessel has been lost.

Table 5.1: Number of incidents and frequencies for RoPax of 4000 GRT and above (1994 – 2004); reproduced from [Konovessis and Vassalos, 2007].

	Number of Incidents		Percentage of Incidents (%)		Frequency (per ship year)	
	Total	Serious	Total	Serious	Total	Serious
Collision	141	16	18.4	12.1	1.59×10^{-2}	1.81×10^{-3}
Contact	131	13	17.1	9.8	1.48×10^{-2}	1.47×10^{-3}
Fire/explosion	**99**	**37**	**12.9**	**28.0**	$\mathbf{1.12\times10^{-2}}$	$\mathbf{4.18\times10^{-3}}$
Wrecked/stranded	100	33	13.0	25.0	1.13×10^{-2}	3.73×10^{-3}
Hull damage	30	7	3.9	5.3	3.39×10^{-3}	7.91×10^{-4}
Foundered	2	2	0.3	1.5	2.26×10^{-4}	2.26×10^{-4}
Machinery damage	214	21	27.9	15.9	2.42×10^{-2}	2.37×10^{-3}
Miscellaneous	50	3	6.5	2.3	5.65×10^{-3}	3.39×10^{-4}
Total	767	132	100.0	100.0	8.67×10^{-2}	1.49×10^{-2}

In another study to assess risk for passenger ships, Vanem and Skjong conducted fire statistics studies onboard two types of passenger ships, RoPax and cruise liners. Vanem considered a total of 32 232 ship-years of ro-ro passenger vessels (RoPax) over 5 000 GRT for the period 1990 – 2002 and 3 185 ship-year of cruise liners over 4 000 GRT for the same period of time [Vanem and Skjong, 2004]. The data was mainly collected from Lloyd's Register – Fairplay. By omitting fires on ships undergoing repair as well as fires categorised as non-serious, a total of 59 fire accidents onboard RoPax and 37 accidents onboard cruise liners were collected. Vanem reported the frequency of fires onboard RoPax as 1.9×10^{-3} per ship-years as compared to Konovessis reported fire frequency as 4.18×10^{-3} fires per ship-years; where the difference in values can be mainly referred to that Konovessis review covered a slightly different period of time. The frequency of fire accidents onboard cruise liners was found by Vanem to be 1.2×10^{-3} per ship-years. In either case, the numbers obtained in both studies clearly illustrated the danger associated with shipboard fires. According to Vanem, onboard RoPax vessels, 61.0% of fires started in engine rooms, 8.5% in car decks, 8.5% in accommodation areas, 10.2% in public spaces and 11.9% fire locations reported as unknown. Onboard cruise liners, Vanem reported 67.6% of fire origins in engine rooms, 13.5% in store rooms and laundry, and 8.1% in accommodation areas while the rest (10.8%) is unknown [Vanem and Skjong, 2004].

Fire Accidents Data

Beside the evaluations from previous studies reviewed above, data of fire accidents was collected to identify the spaces onboard passenger ships reported as most vulnerable to fire hazards and the resulting consequences. Many shipboard fire incidents of different severities were recorded for passenger ships. Some incidents were considered minor and no harm was caused while others resulted in high number of casualties and even loss of the whole vessel. Among these incidents, 34 fire cases associated with passenger ships including ferries and cruise vessels were collected for this study. Data was retrieved mainly from accident investigation and transportation safety bodies supplemented by data from other different sources (See

Appendix A). The aim of collecting this data is to identify the possible fire hazards and their associated scenarios onboard passenger ships. The data collected illustrates the probable locations and consequences of fire accidents in order to draw some conclusions. This is not intended to be presented as full statistical data for shipboard fires of passenger vessels. Hence, many fire incidents are not reported in this study, especially small engine room fires which are very frequent and easy to occur. In addition, disastrous fire incidents are fortunately not very frequent which makes the number of cases collected moderate. There is no doubt that the cases collected here cannot be treated as full statistics of fire incidents onboard passenger ships, however, this data is considered sufficient to draw some useful conclusions that can be used as guidelines for this study.

The data of fire incidents collected was used in different ways. Firstly, the fire incidents are well reported by investigation boards, which make it possible to recognise the possible fire scenarios and their possible causes and consequences. Different fire scenarios in different places were identified from the collected fire incidents onboard passenger ships. The data collected was also useful to identify the location of fire scenarios, possible causal factors and the consequences following fire incidents. Possible fire scenarios, identified from the data collected, with their causal factors and consequences are presented in Table 5.2 below. Some causal factors can be similar in different places where for example arson acts and equipments failures can occur in almost any space onboard the vessels. Whereas, for other shipboard spaces, some specific causal factors such as fuel leakage in engine rooms and lint accumulation in laundries were identified. The consequences were observed to be less harmful in protected areas like engine spaces, however in some incidents the fire escalation is uncontrollable and the consequences are disastrous. On the other hand, the consequences of fire scenarios occurring in places with less protection and dense population tend to be severe most of the times. The fire origin locations and consequences are further analysed and interpreted below in the clustered analysis forms.

Table 5.2: **The indentified possible fire scenarios, their possible causal factors and consequences.**

Fire Scenario	Possible causal factors	Consequences following fire incident
Stateroom	Smoking, electrical fault, naked flames, arson, etc…	Smoke spread in the accommodation area. Possibly fire spread to adjacent compartments.
Storage room	Electrical fault, arson, unauthorised storages, etc…	Smoke spread in the accommodation area. Possibly fire spread to adjacent compartments.
Engine room	Fuel leakage, hot work, equipment failure, etc…	Local fire early controlled by crew or suppression system. Severe escalation.
Laundry	Lint accumulation, overheating, etc…	Smoke and possible fire spread trough doors and ventilation ducts.
Service spaces	Electrical fault, arson, smoking, etc…	Smoke spread in public spaces and possible fire spread.
Vehicles deck	Fuel leakage, electrical fault, arson, etc…	Fire / explosion on deck.

In order to understand the sequence of events leading to a fire incident, the fault trees of two of the possible critical scenarios are illustrated in Figure 5-1 and Figure 5-2. These fault trees represent the logic diagrams showing the combination of lower events leading to higher events until the fire incident occurrence. The events are related by logic gates. In the case where two or more lower events should occur all together to lead to a higher event, these lower events are connected through an “AND” logic gate. If any of the lower events will lead to a higher one, then the lower events are connected through an “OR” logic gate.

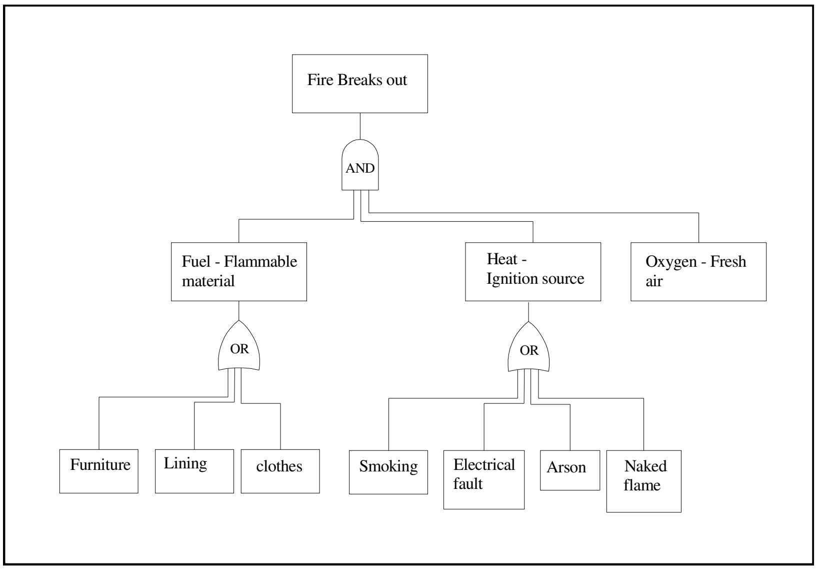

Figure 5-1: **Fault tree leading to fire in a stateroom in the accommodation area.**

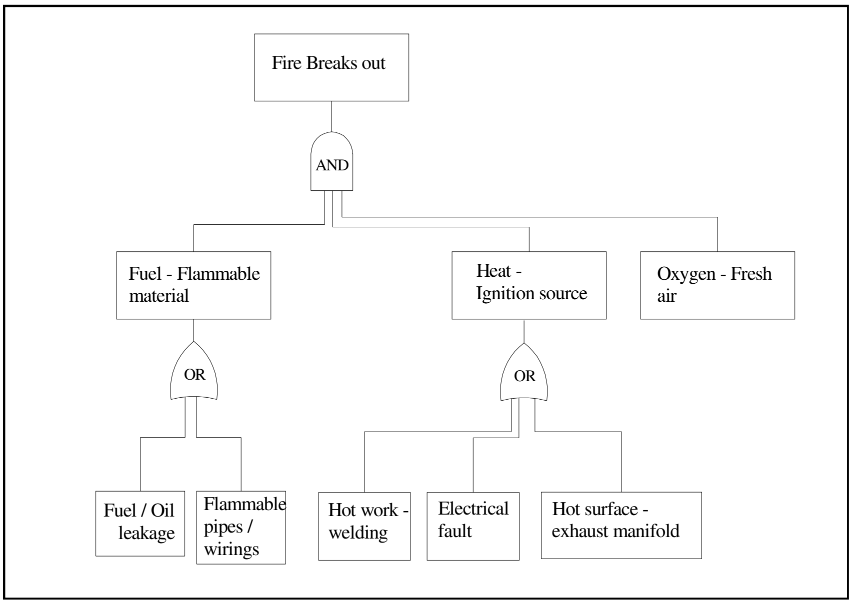

Figure 5-2: **Fault tree leading to fire in the engine room.**

In a different approach to analyse the data collected, these fire incidents were clustered in two different forms deemed to be useful for this study. In the first cluster the distribution of fire origin locations was revealed while the second clustering from was to analyse the percentages of casualties resulted from different fire locations. In Figure 5-3, depicted the first cluster form of fire cases showing the variability of the location of fire origin onboard passenger ships. It is found that 44% of the fire incidents collected were originated in engine spaces, 17% in service spaces, 15% in storage spaces, 12% in accommodation spaces, and 9% on vehicle decks while 3% of the fire origins were unknown. The service spaces include places like shops, laundries and galleys. Storage spaces are meant to be all storage concealed spaces including closets and small store rooms while the accommodation spaces cover the staterooms and corridors. Bearing in mind that not all minor fires reported in engine rooms are collected here, the numbers above are found consistent with those reported by Vanem and Skjong above [2004].

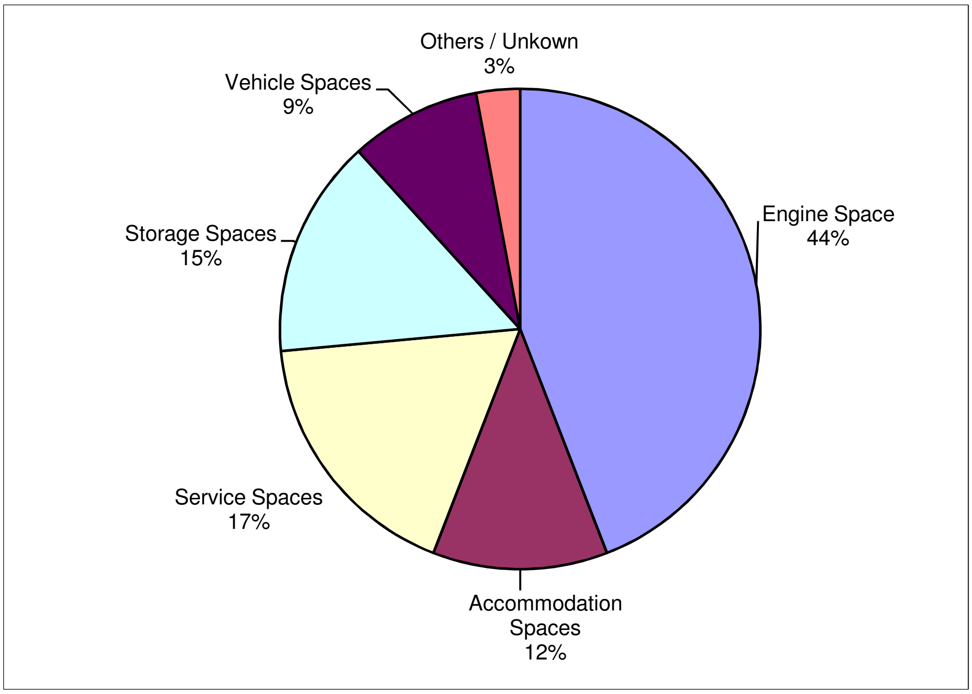

Figure 5-3: **Distribution of the locations of fire origins**

The second cluster form shows the casualties resulted from the various fires originated in different locations onboard. It is found that engine room fires are the most frequent, however most of these fires did not result in any casualty onboard the vessel. Considering the total of 34 cases collected, it is found that the fires generated in the storages spaces resulted in 18% of the fatalities, fires started in engine room caused 52% of the deaths while the rest is distributed as 8% caused by accommodation area fires, 15% from fires originated on vehicle decks and 7% originated from service spaces (see Figure 5-4). However, it was found more meaningful to exclude the case of *Al-Salam Boccaccio* whose fire was originated in the engine room and capsized taking with her all the persons onboard. The reason of ship capsize was not referred directly to the fire incident but to the water accumulation on the vehicle deck due to inadequate fire fighting activities (See Appendix A). The data was analysed again and presented to illustrate the percentage of fatalities with respect to the origin of fire. Figure 5-5 below reveals those percentages. It is clear now that fires originated in engine areas, even though very frequent, contribute just to 2% of the casualties comparing to 17% of fatalities caused by fires in accommodation spaces. The highest number of fatalities (36%) is the result of fires generated in storage spaces whist 31% and 14% of deaths are the result of fires started on vehicle decks and service spaces, respectively. Fires originated in the engine room represent almost half of the incidents, however fires located in other locations with denser occupancy imply a higher potential for life loss. Engine fires are in most cases contained due to the presence of fire detection and suppression systems in those vulnerable areas. In addition, the machinery spaces are bounded by decks and bulkheads of high fire integrity to contain possible fire escalations.

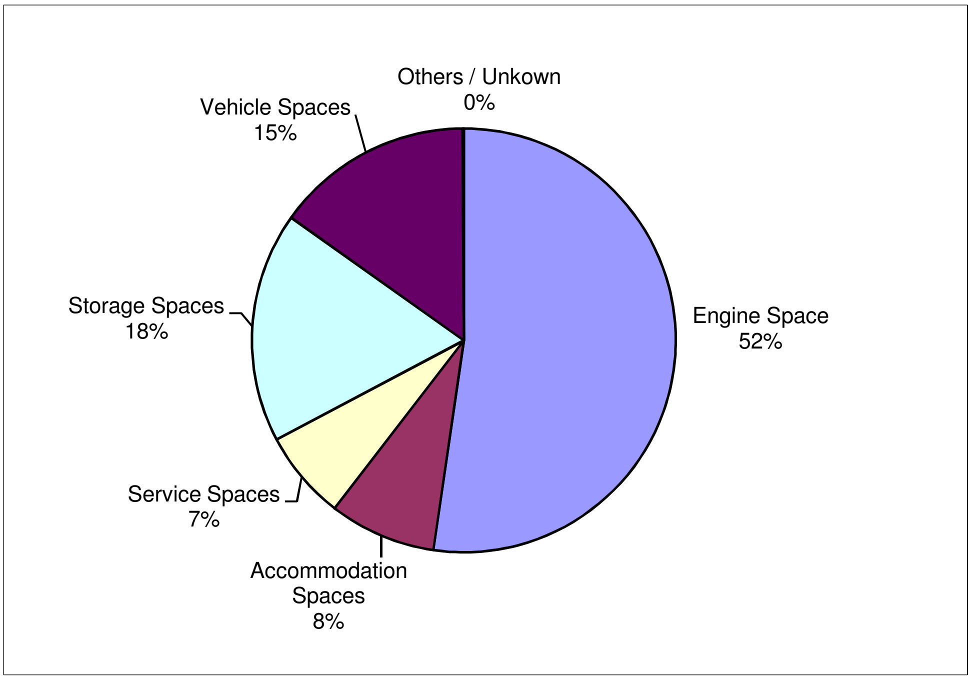

Figure 5-4: Percentage of fatalities distributed according to location of fire origin including *Al-Salam Boccaccio*.

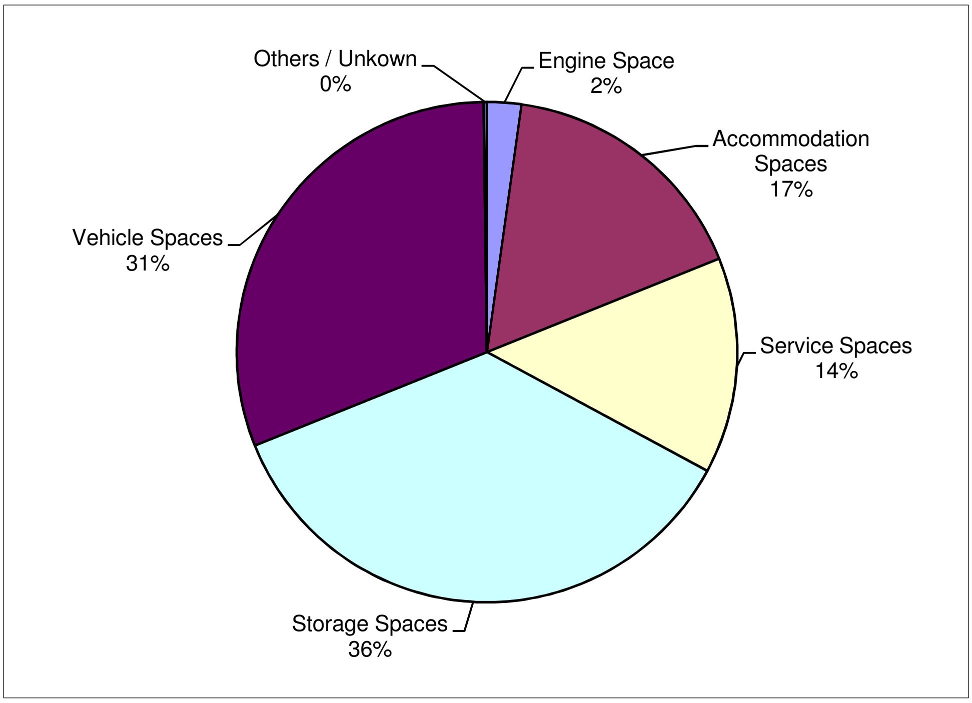

Figure 5-5: Percentage of fatalities distributed according to location of fire origin excluding *Al-Salam Boccaccio*.

It can be deduced that the data analysis showed that disregard the high frequency of fire occurrence in engine spaces comparing to that of storage and service spaces, and accommodation, the resulted casualties in each of the last three is much higher than engine room casualties, considering that fatalities due to the capsize of *Al-Salam Boccaccio* are not included in the analysis. Storage spaces were meant to be all store rooms and unattended closets which are present in the accommodation areas where the highest density of occupancy is expected. The majority of the casualties reported due to fires from service spaces and accommodation areas including storage spaces were resulted from smoke inhalation. Smoke was always identified as the most effective killer in fire events in accommodation spaces. The rapid spread of smoke in absence of appropriate barriers (like self-closing doors or smoke extracting systems etc…) poses serious hazards on life. The combination of vision impairment and toxicity is responsible of delaying, capturing and killing many lives in such fire events.

The above figures can change dramatically depending on including or excluding the statistics of a single case – *Al-Salam Boccaccio 98*. This shows that the values calculated cannot be considered as robust and should not be generalised. However it was found more convenient to exclude the odd case to prevent the dependence of results on a single accident. Still many conclusions can be drawn from this data collection and analysis, and among these lights are shed on two interesting observations here. These are the severe consequences of fire incidents onboard ships and the unpredictability of fire origin location which can be anywhere onboard ship from engine room to accommodation spaces including service and storage rooms and many others as seen in the data collected above. The severity of fire escalation can be clearly illustrated in the accident of *Al-Salam Boccaccio 98* which is the ro-ro ferry who capsized after a fire incident onboard taking with her more than one thousand innocent lives. This accident was considered as being a recent one where the ship is supposed to comply with the latest safety regulations. However, it should be noted that the direct reason of the ship capsize was the fire fighting water accumulated on the vehicle deck of the vessel. On the other hand, the accident that can clearly manifest the unpredictability of fire origin is *Star Princess* which is the passenger cruise ship who suffered a fire started on an external stateroom balcony. This incident is also one of the most recent ones, demonstrating that even the modern ships complying with all the regulations still contain vulnerable areas uncovered by the rules. The first fire case of *Al-Salam Boccaccio 98* presented above is sufficient to tell how a fire ignited in any place onboard can result in a total ship loss taking the lives of all passengers onboard. While the second case of *Star Princess* shows that fire can be originated in unexpected areas where the prescriptive rules apply just minor or no fire restrictions.

5.3 Ranking of Fire Accident Scenarios

The fire scenarios associated to the identified possible hazards are ranked to give priority to the scenarios with higher risk and discard the ones with lower risk. The risk level is represented by the combination of the probability (or frequency) and consequence (or severity) of a fire scenario as illustrated in the equation below [IMO, 2002a].

$$Risk = Probability \times Consequence \qquad \textbf{Eq 5-1}$$

It is recommended by IMO to define the consequences and probability indices on a logarithmic scale. This is to facilitate the risk ranking. Therefore, the risk index (RI) becomes the sum of probability or frequency index (FI) and the consequence or severity index (SI), as shown in the equation below.

$$Log\ (Risk) = Log\ (Probability) + Log\ (Consequence) \qquad \textbf{Eq 5-2}$$

The ranking tables of frequency and severity indices and the risk matrix adopted in this study are reproduced from the guidelines for Formal Safety Assessment [IMO, 2002a] and presented below in Table 5.3, Table 5.4 and Figure 5-6.

Table 5.3: Logarithmic severity (or consequence) index scaled for a maritime safety issue; reproduced from [IMO, 2002a].

SEVERITY INDEX				
SI	**Severity**	**Effects on Human Safety**	**Effects on Ship**	**S (Equivalent fatalities)**
1	Minor	Single or minor injuries	Local equipment damage	0.01
2	Significant	Multiple or severe injuries	Non-severe ship damage	0.1
3	Severe	Single fatality or multiple severe injuries	Severe damage	1
4	Catastrophic	Multiple fatalities	Total loss	10

Table 5.4: Logarithmic frequency (or probability) index scaled; reproduced from [IMO, 2002a].

FREQUENCY INDEX			
FI	**Frequency**	**Definition**	**F (per ship year)**
7	Frequent	Likely to occur once per month on one ship	10
5	Reasonably probable	Likely to occur once per year in a fleet of 10 ships, i.e. likely to occur a few times during the ship's life	0.1
3	Remote	Likely to occur once per year in a fleet of 1000 ships, i.e. likely to occur in the total life of several similar ships	10^{-3}
1	Extremely remote	Likely to occur once in the lifetime (20 years) of a world fleet of 5000 ships	10^{-5}

	SEVERITY INDEX	Minor	Significant	Severe	Catastrophic
FREQUENCY INDEX		**1**	**2**	**3**	**4**
Frequent	**7**	8	9	10	**High Risk** 11
	6	7	8	9	10
Reasonably Probable	**5**	6	7	8	9
	4	5	6	7	8
Remote	**3**	4	5	6	7
	2	3	4	5	6
Extreme Remote	**1**	2 **Low Risk**	3	4	5

Figure 5-6: Risk matrix based on the estimation of frequency and severity indices in Table 5.3 and Table 5.4; the risk index is the sum of frequency and severity indices (RI=FI+SI).

The results of the risk assessment performed as screening of the ship spaces were quasi-quantified. By this, it is meant that frequency indices were quantified from numerical values while the severity indices were derived in a qualitative manner based on analysis and judgements. The frequencies of fire incidents calculated by Vanem were used for both RoPax ships and cruise liners. Frequencies of different spaces onboard both vessel types were calculated as the total frequency of fires onboard each vessel type multiplied by the percentage associated with the different spaces identified as fire origins. On the other hand, the analysis of the collected data of fire incidents onboard passenger vessels was used to judge the severity indices of different scenarios. This is illustrated in Table 5.5 and Table 5.6 below.

The ranking of different fire scenarios on various spaces onboard RoPax ships identified the incidents taking place on accommodation areas and car decks as highest fire risk with risk index RI = 6. Fire scenarios in engine rooms and public spaces were found less risky with risk indices RI = 5. Onboard cruise liners, the fire scenarios of the category store room and laundry were found the most risky with RI = 6 similar to fire scenarios in accommodation areas with the same risk index. Engine room fire scenarios showed a risk index lower than the previous scenarios with RI = 4. The rankings of both vessel types are illustrated in Table 5.5 and Table 5.6 below.

Table 5.5: The frequency and severity indices and the resulting risk indices for different fire scenarios onboard RoPax ships.

RoPax	Frequency	Frequency Index	Severity Index (Human Safety)	Risk Index (FI+SI)
Engine	1.159×10^{-3}	4	1	5
Car Deck	1.615×10^{-4}	2	4	6
Accommodation	1.615×10^{-4}	2	4	6
Public Space	1.938×10^{-4}	2	3	5
Others	2.261×10^{-4}	2	1	3

Table 5.6: The frequency and severity indices and the resulting risk indices for different fire scenarios onboard cruise liners.

Cruise liners	Frequency	Frequency Index	Severity Index (Human Safety)	Risk Index (FI+SI)
Engine	8.112×10^{-4}	3	1	4
Accommodation	9.72×10^{-5}	2	4	6
Store/Laundry	1.62×10^{-4}	2	4	6
Others	1.296×10^{-4}	2	1	3

The ranking of fire accidents scenarios identified high risk in the spaces generally located in the accommodation areas. These spaces include the staterooms, store rooms and laundries. Both RoPax ships and cruise liners showed that fire scenarios in the accommodation spaces are of great risk. RoPax vessels were also found exposed to a high fire risk in accommodation areas which are equally risky to the car decks with a risk index of 6. Engine fires scenarios, even though showed to be very frequent with a frequency index FI = 4 for both RoPax ships and cruise liners, the consequences were minor with severity index SI = 1. It can be deduced that the accommodation areas are equally risky on both types of the passenger ships. As observed in the reviewed fire cases, the presence of the narrow long corridors connecting the rooms in the accommodation areas provide the smoke with fast means of transportation to spread in the whole domain. The long, slow and crowded evacuation from the rooms keep the passengers exposed to smoke effects and hence vulnerable to the risk of incapacitation. Therefore, these spaces onboard merit closer examination and further analysis in later stages of the study. Note that in this study human safety is concerned while damage to property and environment are not taken into account.

5.4 Concluding Remarks

This chapter clustered the collected data in useful forms to provide better understanding of the development of shipboard fire scenarios. By discarding the case where inadequate fire fighting activities resulted in total loss of the ship, it was found that most of the engine room fires were contained without leading to serious consequences. While, fire incidents taking place in the accommodation areas were found to have high potential for life loss. These scenarios were ranked as high risk scenarios among the others. Therefore, it was found that fire scenarios in the accommodations spaces merit closer examination and further studies using deterministic calculations as will be illustrated in the following chapters.

6 Application of Fire Models

6.1 Introductory Remarks

This chapter examines the proper application of fire models to ship spaces. This is done in two major parts. The first part is a benchmarking exercise of the simulation models with experimental data which ensures that the models are employed properly and in the right order. The sensitivity of the models input parameters are analysed to further identify the specific strengths and deficiencies of each model in order to select the suitable ones to continue this study. The critical parameters obtained from the numerical simulations are compared to the same quantities obtained from experiments. The target quantities are drawn on graphs to compare the experimental and computed values. This benchmarking procedure is not intended to serve as a complete validation of the models in use as each of them was extensively validated by the developers, but rather to assure that the right settings are utilised for the designated fire cases and to select the models which are more suitable for the study.

The second part of the chapter involves applying and comparing the selected fire models to specific ship geometry as this implies higher challenges comparing to normal building geometries. Therefore, the application of these models to different shapes of shipboard merit further testing and closer examination. The models selected earlier are applied to specific ship geometries and the outcomes are examined closely. As accommodation areas were identified among the most hazardous onboard, the selected fire applications in this chapter include cabin fire, large space fire and corridor fire.

6.2 Models Benchmarking with Experiments

6.2.1 Case Description

The experimental case used in this study is the Steckler fire room. Steckler fire room was found a suitable comparison case because the main interest of this work is to model fire effects in enclosures mainly started in staterooms or similar compartments. Although other benchmarking work like Grandison [2001] considered several validation cases ranging from simple CFD trials to compartment fire modelling, it is assumed here that the fire room case covers the main critical features like heat transfer through the boundaries and resolution of the buoyant flow induced by fire. Therefore this case is considered sufficient to show the capability of the software in predicting the main characteristics of enclosure fire regarding life safety.

The experiments were conducted by Steckler et al. [1982] in a compartment measuring 2.8 m x 2.8 m in plane and 2.18 m in height with a door connecting the room to the outside. The door is located in the centre of one of the walls and measures 0.74 m wide by 1.83 m high. The walls and ceiling are 0.1 m thick and they are covered with a ceramic fibre insulation board to establish near steady state conditions within 30 minutes. The fire was created using a methane burner of diameter 0.3 m, located in the centre of the room and generating a steady state non-spreading fire of heat release rate equal to 62.9 kW [Steckler et al., 1982] [Quintiere et al., 1981]. The heat of combustion for pure methane is 5 x 10^7 J/kg and the combustion efficiency is considered to be 91%, thus the fuel release rate is 1.38 10^{-3} kg/s. A plan view of the room is illustrated in Figure 6-1.

The initial conditions considered in this case were atmospheric pressure at sea level 100 000 Pa and ambient temperature of 29 ^{o}C.

The results quantities used for comparison are; corner thermocouple stack located in one of the near corners to the doorway, and thermocouple and velocity stack centrally located in the door way. The velocity measured is U-velocity i.e. horizontal velocity perpendicular to the door. Corner stack is located 0.305 m from the front wall and 0.305 m from the side wall, while doorway stack is located in the middle of the doorway, 1.4 m from the side walls (see Figure 6-1).

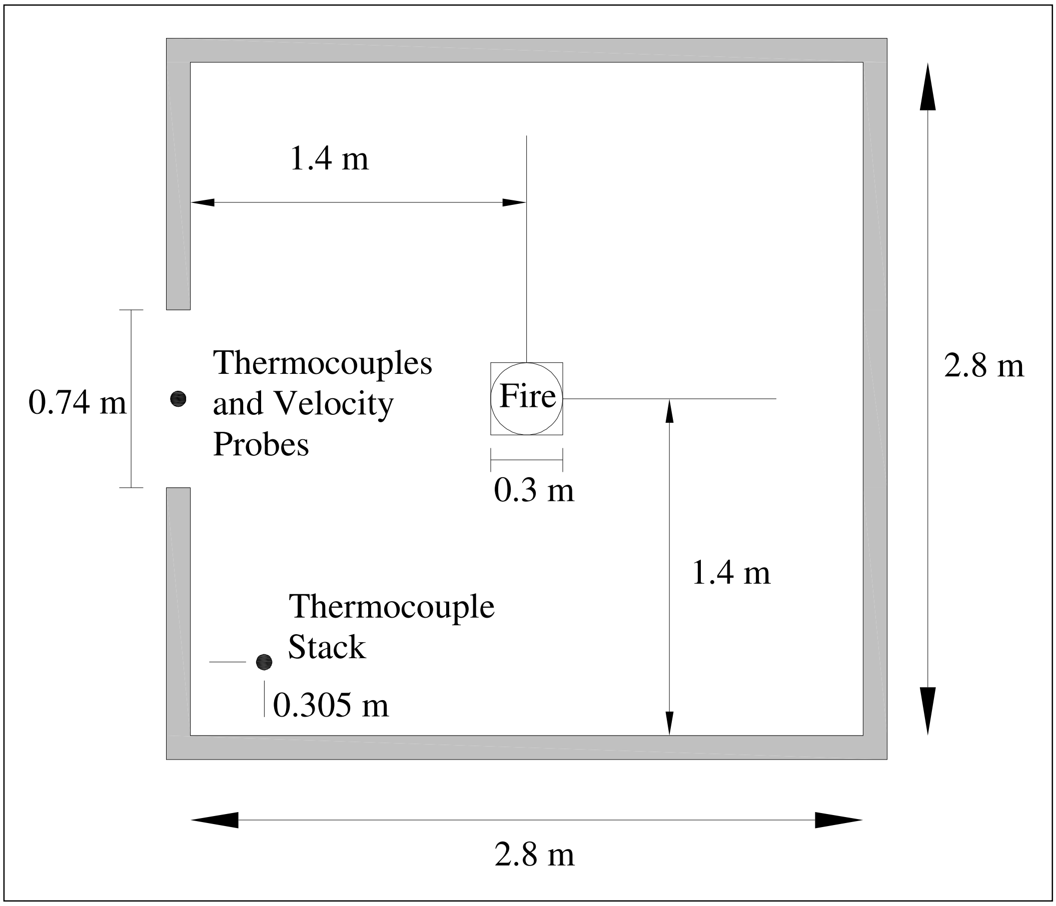

Figure 6-1: Configuration of the Steckler fire room [Steckler et al., 1982].

6.2.2 CFD Model – Fire Dynamic Simulator

6.2.2.1 Program Configuration

Fire Dynamic Simulator (FDS) is a field model that uses the concept of Computational Fluid Dynamics to predict fire effluents flow. No combustion is modelled to represent the fire in FDS; but the Heat Release Rate is prescribed beforehand and assigned per unit area. Thus a convenient way to model the burner is to set a squared vent heat flux source of 0.3 m side dimension located in the centre of the room and generating a total heat rate of 62.9 kW. Note that FDS automatically restrict the input heat release rate according to oxygen availability in the compartment. The radiative heat loss fraction was taken as 15% of the total heat release rate (as the fuel used in the burner is commercial methane). The computational domain has been extended for 2 m outward from the door to allow an accurate resolution of the flow through the doorway. As the room was insulated in the experiments to achieve near steady state conditions, the walls and ceiling are assumed to be made of glass fibre insulation which physical properties were retrieved from CFAST data [Jones and et al., 2005]; the properties are listed in Appendix C. The thickness of walls and ceiling was set to 0.1 m and emissivity to 0.9. The floor can either be set to the same material as the walls or it can be defined as adiabatic where no heat conduction is considered; both settings did not show any significant difference in the final results. For the radiation heat transport in the domain, FDS uses the finite volume method described in Chapter 4. The solution is considered to reach steady state conditions after 200 seconds of simulation time, thereafter data can be retrieved for comparison.

Turbulence in FDS is resolved by Large Eddy Simulation described in Chapter 4. Thus, the large scale eddies which are assumed to dominate the flow are resolved on the numerical grid level whilst the smaller scale eddies are modelled using Smagorinsky technique. The computational domain is divided into small identical cubical control volumes forming the numerical grid (see Figure 6-2). The boundary layer is not resolved in FDS but instead the fluid velocity on the solid boundaries is assumed to be a fraction of the velocity in the adjacent cell. FDS contains several empirically based algorithms that account for sub-grid scale phenomena including heat transfer at boundaries, radiation and combustion. Note that it is not recommended to use symmetrical plane (MIRROR) in FDS simulations in order to cut the computational efforts by half. The reason is that LES technique does not perform a time averaged solution for the Navier-Stokes equations. Thus, in LES the fire plume is not presented as an axially-symmetric flow field as in Reynolds-

Averaged-Navier-Stokes models and hence, putting a symmetric plane along the centre line of the fire plume will change the flow dynamics [McGrattan, 2008b].

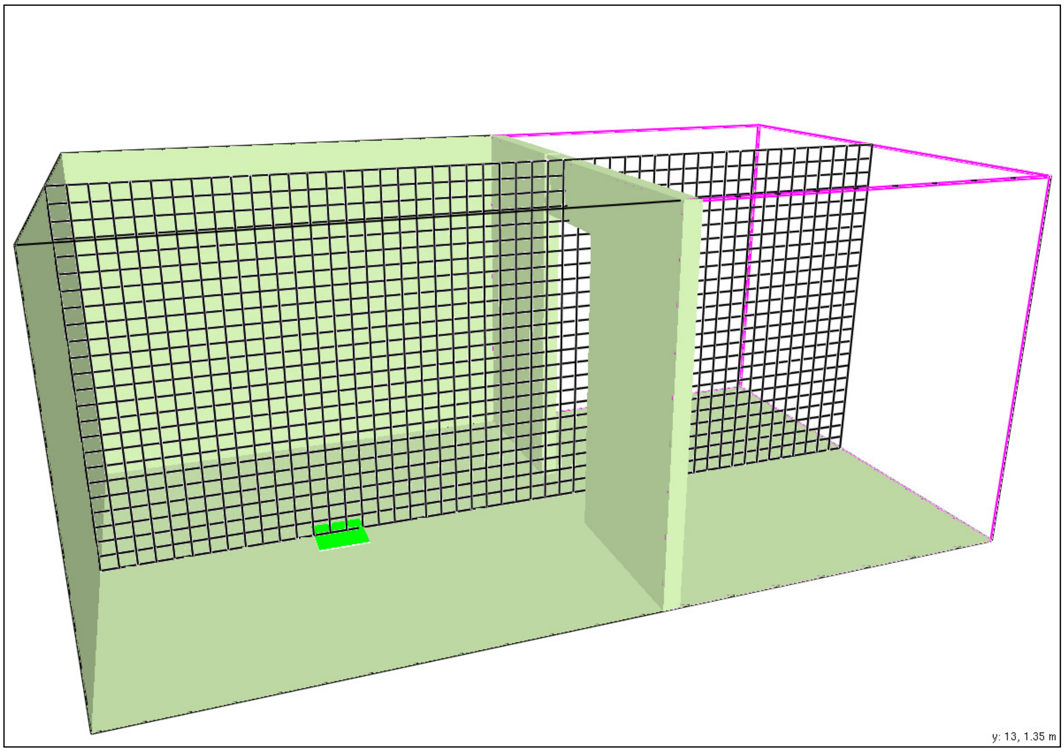

Figure 6-2: Snapshot from Smokeview, the post-processor of FDS showing the geometry and a slice view of the grid.

6.2.2.2 Model Sensitivity and Simulation Results

The accurate predictions of a model are subject to its input parameters. These parameters are numerical like the computational grid and physical like heat release rate and boundary materials etc. For this case, most of the physical inputs are already defined by the experiments and directly implied into FDS. The most important numerical parameter stays the computational grid. It is important for CFD simulations to conduct grid sensitivity study in order to decide which cell size is suitable for the application required. It is recommended in FDS Users Guide [McGrattan, 2008b] to assess the flow field resolution by the non-dimensional expression $D^*/\delta x$, where δx is the cell size and D^* is the characteristic fire diameter which is not necessarily the same as the physical fire diameter. The non-dimensional value of this expression represents the number of mesh cells spanning the characteristic diameter of the fire. Obviously, the greater the ratio $D^*/\delta x$, the more the resolution of fire dynamics is accurate. FDS verification and validation guides report that past experience showed that $D^*/\delta x$ values in the range of 5 to 10 usually produce good results at reasonable computational time [McGrattan, 2007]. First, the characteristic diameter is obtained by the following correlation:

$$D^* = \left(\frac{\dot{Q}}{\rho_\infty c_p T_\infty \sqrt{g}}\right)^{2/5}$$ **Eq 6-1**

where $\dot{Q}$ is the total heat release rate (62.9 kW in this case), ρ_∞, c_p, and T_∞ represent air properties density (kg/m^3), heat capacity (J/Kg.K) and temperature(K), respectively, at ambient conditions. Taking the large recommended ratio for the expression $D^*/\delta x = 10$, the resulting cell size is 30 mm. This resulting cell size will supposedly provide the accurate results according to the characteristic fire diameter rule. Therefore, the grid sensitivity study for this case includes three uniform cubical grids of different cell size; 100 mm, 50 mm and 30 mm to study the changes of result depending on grid size. Considering the experimental inconsistencies and errors, and the numerical errors of the models, the simulation results are found in good agreement with the experiments as depicted in Figure 6-3, Figure 6-4 and Figure 6-5. Figure 6-3 illustrates a comparison between the temperature time histories monitored at an elevation of 1.6 m in the room corner as predicted by the three different meshes, while Figure 6-4 and Figure 6-5 provide a comparison of the constant temperature profile in the room between the three meshes and experimental data. The differences between the three grids and experimental results are in the range of 3 to 6°C. It is clear that the finer meshes are predicting temperature profile shapes that match better the experimental ones and an upper layer temperature slightly closer to the experimental results (See Figure 6-4 Figure 6-5). However, the computational time required for the slight improvement (~ 1-2 %) is quite enormous. Using a PC Pentium D CPU 3.20 GHz, the run with 100 mm cell size required around 1.4 hours of CPU time, the 50 mm mesh took 14.3 hours of CPU time and the finest mesh of 30 mm cell size run for around 4 days and 7 hours.

From another perspective, comparing the predicted flow through the doorway, Figure 6-6 illustrates a comparison between the velocity profiles on the doorway. All three meshes show good agreement with experimental results apart from the slight shift of the neutral plane (where U-velocity is nil) by few centimetres down. This is mainly because the vertical cells in the doorway are not very numerous in the coarse mesh which restricts the exact resolution of velocity profile.

It can be deduced that the level of grid refinement strongly depends on the type of application. The fine mesh predicts the small details and fluctuations of the flow whilst the coarse mesh is capable of calculating the main characteristics of the flow. Therefore, for the purpose of this study the results obtained with cell size 100 mm, 50 mm and 30 mm can be considered as mesh independent. Note that, though it is a steady state case, the results still fluctuate with respect to time. The reason is that turbulent diffusion flames show random fluctuations which are the characteristics of turbulence effects and strongly affect the shape and height of flame and hence the resulted temperatures in the room. These fluctuations have a frequency of the order of 1-3 Hz, i.e., occurring one to three times per second [Karlsson and Quintiere, 2000].

It should be noted that for enclosure fire simulations, small fires require finer mesh than large fires. As the characteristic diameter is in function of the released heat rate, $D^* \propto \dot{Q}$, the greater the heat release rate, the larger the characteristic diameter and hence a large cell size δx can still sustain a high value for the ratio $D^*/\delta x.$ Thus, the current case with heat release rate of 62.9 kW is considered as a small fire requiring a mesh finer than most of other fires encountered in real room fire cases. It can be concluded in this section that FDS used in room fire applications is capable of producing good results with a reasonable mesh of 0.1 m cubical cell side size.

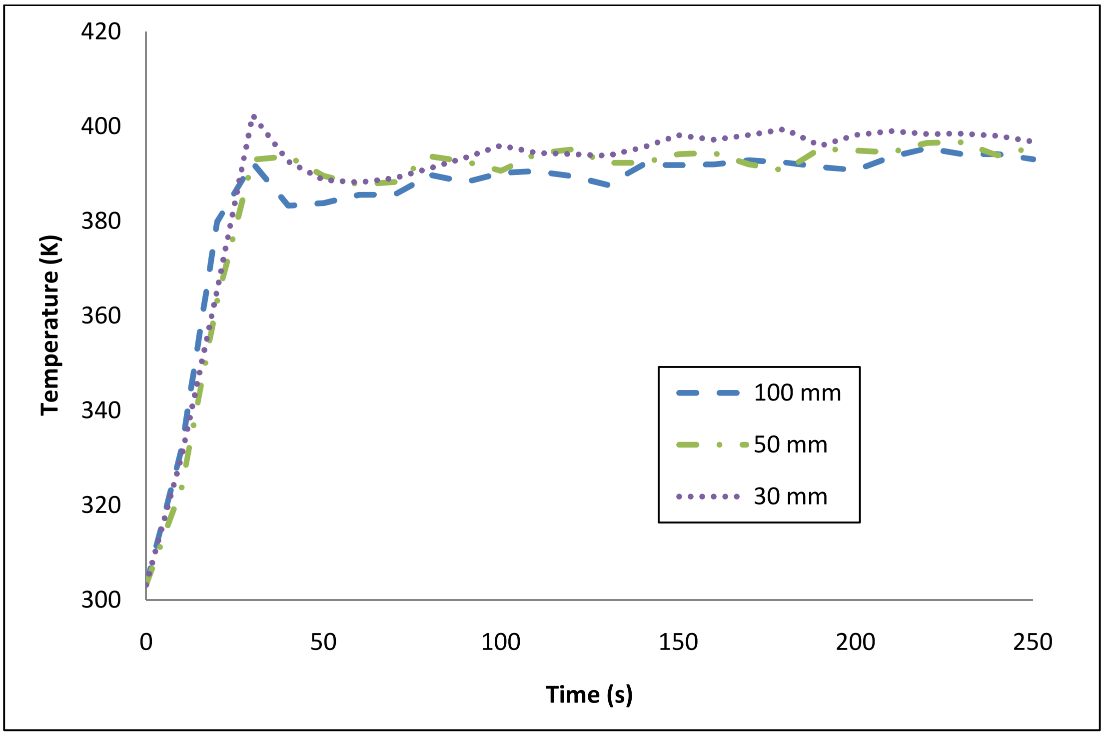

Figure 6-3: Temperature time histories monitored, for the purpose of grid sensitivity study, in the room corner at 1.6 m height of three different cell sizes: 100 mm, 50 mm and 30 mm.

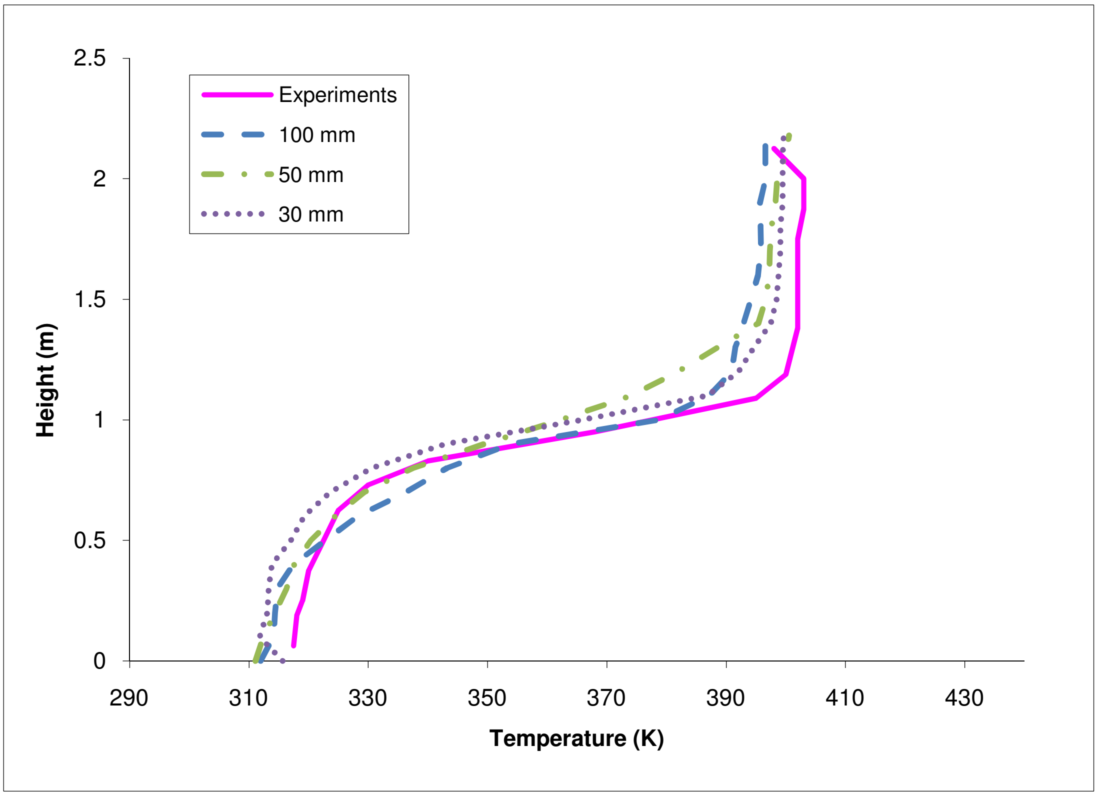

Figure 6-4: Temperature profiles in the corner of the room comparing experimental results to three simulations with different cell sizes; 100 mm, 50 mm and 30 mm.

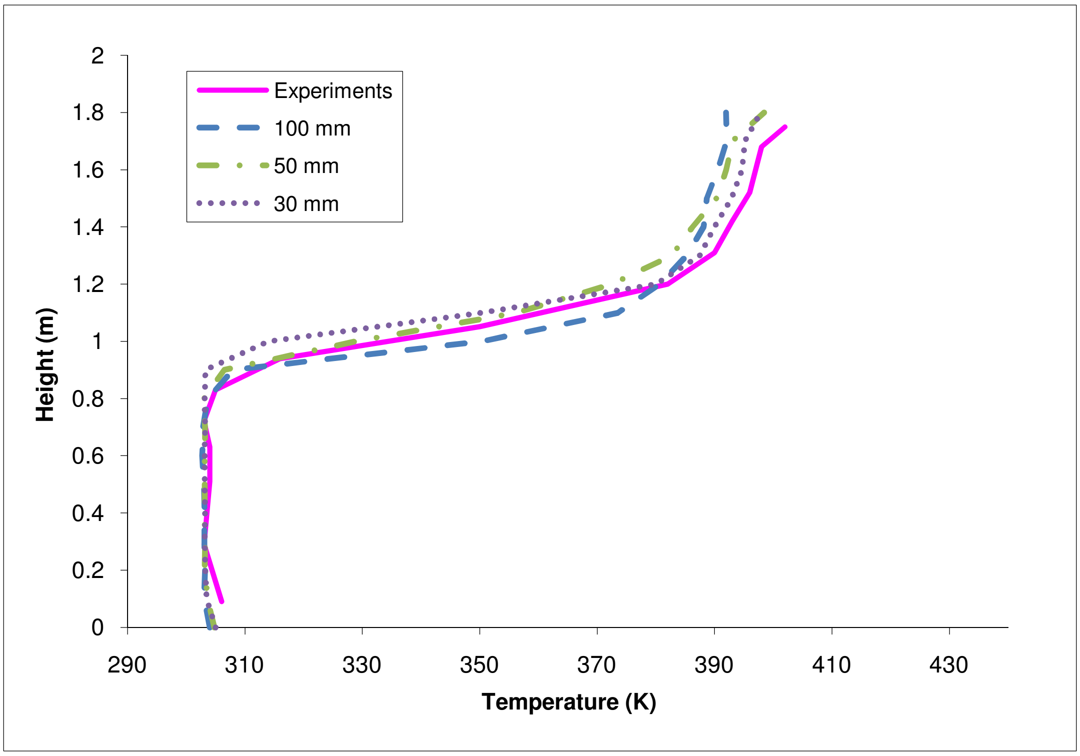

Figure 6-5: Temperature profiles in the doorway of the room comparing experimental results to three simulations with different cell sizes; 100 mm, 50 mm and 30 mm.

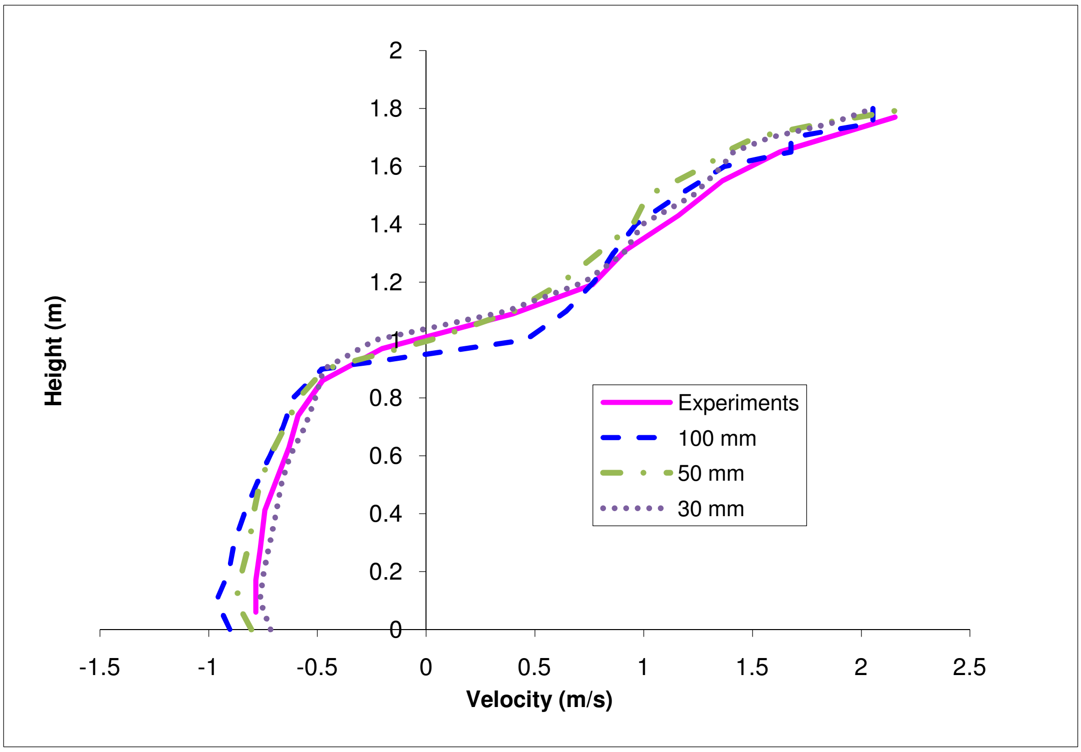

Figure 6-6: Velocity profiles in the doorway of the room comparing experimental results to three simulations with different cell sizes; 100 mm, 50 mm and 30 mm.

6.2.3 CFD Model – Fluent

6.2.3.1 Program Configuration

Fluent package is a multipurpose CFD software, hence the inputs were more demanding than those of the fire specialised software product FDS. Here, also the fire was treated as a volumetric heat source with a predefined heat release rate. Therefore, no combustion modelling was considered at all, just the fire effects and products, heat and smoke were considered. A separate cubical zone of dimensions (0.3m x 0.3m x 0.3m) was located in the centre of the room of dimensions 2.8m x 2.8m x 2.18m. An energy source was applied to the cubical volume generating a constant amount of heat equal to 62.9 kW. The height of the volumetric source height was assigned to 0.3 m in previous fire simulations like [Kumar et al., 2004] and [Grandison and et al., 2001]. Kumar conducted a sensitivity analysis for the height of the volumetric source in the range of 0.2 m to 1 m. It has been found that for the 0.3 m diameter and 62.9 kW fire, the volume heights of 0.2 - 0.3 m predicted room temperatures matching the experimental results. Although the flame height of the above fire can be found by empirical correlations to be around 0.9 m, it should be kept in mind that the flame temperature is not even. Therefore, a 0.3 m high volume is a very reasonable approximation of the real case. Unlike other fire specialised models, in case of modelling an intense fire in an enclosure by prescribing the free burning heat release rate, Fluent is unable to account for the oxygen supply deficiency in ventilation controlled fire case. Therefore, the energy in form of heat will be released as prescribed disregarding the oxygen availability in the enclosure. In this case the output heat release rate of FDS already constrained by oxygen availability is used as input of Fluent to allow fair comparison between the softwares. Otherwise, when the truncated HRR is not available from previous simulations or experiments, simple empirical correlations can also be used to determine the maximum possible heat release rate for a given enclosure and its vents in order to truncate the heat release rate to be used as input for Fluent.

The turbulence effects in the flow were modelled by solving the transportation equations of turbulent kinetic energy and dissipation, k-ε model (a Reynolds-Averaged-Navier-Stokes model). It should be mentioned here that also a laminar model was employed to calculate viscosity effects in order to study the sensitivity of turbulence effects on the flow. It was found that the laminar model over-predicted the upper layer temperature due to the under-estimation of air entrainment in the fire plume and the mixing between the hot and cold layer. Thus it can be said that beside buoyancy, turbulence is one of the main factors that control fire related flows. Noting that almost all of the accidental fires have turbulent diffusion flames and plumes [Quintiere, 1998].

Air properties were kept constant to the default ambient values except for the density where the ideal gas law was used. It should be noted as well that Fluent has the capability to account for density variations due to temperature through a feature called "incompressible ideal gas law" which considers the pressure as atmospheric when predicting density variations from the equation of state. Thus, the use of the ideal gas law or its incompressible version will not produce any significant difference in this open domain case where no pressure build up is expected. Air properties are listed in Table 6.1. The absorption coefficient was kept constant equal to 0.315 m^{-1} [Grandison and et al., 2001]. A more sophisticated method to define the absorption coefficient as temperature dependent did not improve the solution significantly in the test cases which made the assumption of constant absorption coefficient reasonable in this study [Grandison and et al., 2001].

Table 6.1: Air properties as used for the simulations.

Specific heat capacity	Thermal conductivity	Viscosity	Molecular weight
1006.43 J/kg K	0.0242 W/m K	1.7894 10^{-5} kg/m s	0.02896 kg/mol

6.2.3.2 Model Sensitivity and Simulation Results

All the input parameters that are sensitive to the model were studied to analyse their effects on the final results. To start, the computational domain was extended outward from the door soffit around 6 m in the vertical direction (Z-direction) and 5.6 m straight outward from doorway (in X-direction) and 3.8 m horizontally sideway from the door (Y-direction); see Figure 6-7 and Figure 6-8. The purpose of the excessive extension of the domain is; firstly for a better resolution of the doorway flow. Secondly to keep any outlet boundary conditions as remote as possible from the fire induced flow to facilitate the convergence procedure and to enhance a more accurate solution. The side boundaries of the extended domain were defined as walls with fixed ambient temperature (300 ^{o}K) and the top surface was set as an outlet with fixed atmospheric pressure and ambient temperature to allow air exit/entrainment from/to the domain. Ideally the boundaries of the extended domain are better set to be outlets with fixed atmospheric pressure and ambient temperature. However, due to convergence problems, the former implementation of mixed walls and outlets was applied. This was shown to be a reasonable engineering approximation of the real case. Another problem in posing realistic boundary conditions in Fluent was the thermal boundaries of the enclosure's walls, ceiling and floor. In concept these walls are supposed to allow heat dissipation to the outside. The rate of heat lost is subject to wall material properties, wall and gases temperatures and heat transfer coefficients. An accurate way to make Fluent calculating the above parameters without being defined in advance is to have all the walls inside the computational domain and not on the boundaries. In order to do so, an extension of the computational domain is required all around the room walls. This act of domain extension will increase the computational efforts and impose again a problem in defining the nature of the boundary conditions of the extended spaces around the room. A simpler way to account for heat lost through wall and ceiling is to have these walls defined as boundaries of the domain. However, to define these walls' boundary conditions, in addition to the material properties, a previous knowledge of the heat transfer coefficient or the heat fluxes through the walls is required. Also, the heat flux through a wall is never uniformly distributed in a stratified fire environment and not always in steady state condition, which makes any average value estimated for the heat transfer coefficient an approximation of the real situation even though the estimation is based on previous knowledge or experimental data for the case.

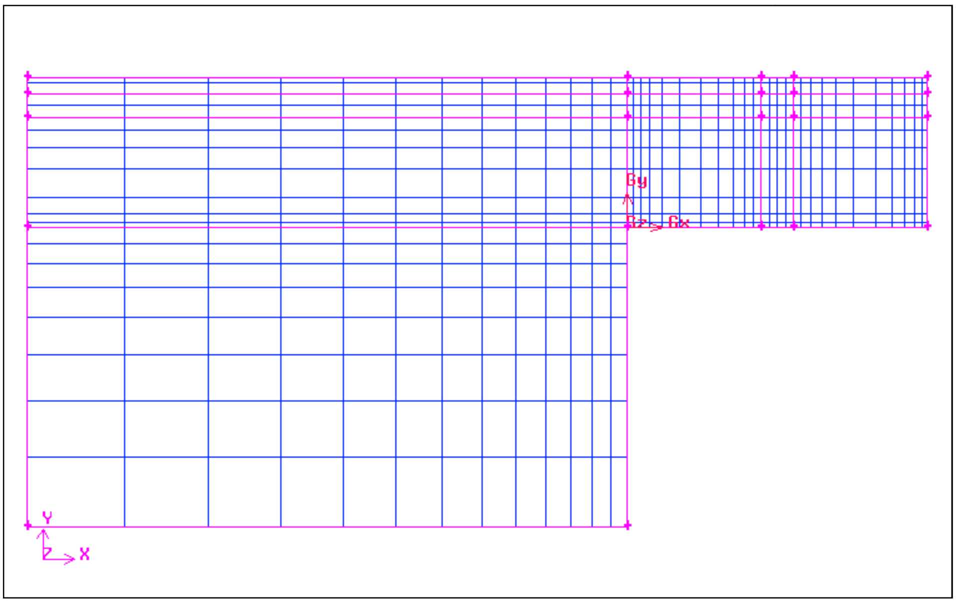

Figure 6-7: X-Y plane top view of the computational domain and mesh in Gambit

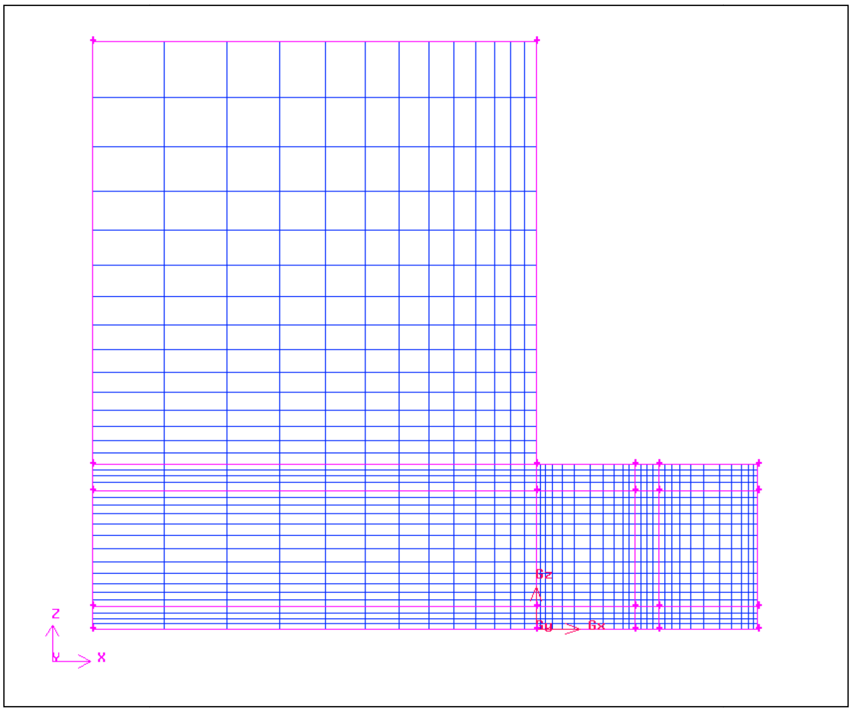

Figure 6-8: X-Z plane profile of the computational domain and mesh in Gambit.

In Figure 6-9, Figure 6-10 and Figure 6-11 depicted the predictions of Fluent for temperature profiles in the corner of the room and temperature and velocity profiles in the doorway, respectively. Velocity prediction agreement with the experimental data is better in the upper part of the door where the neutral plane is well predicted. There is a discrepancy between the experimental and predicted velocities in the upper part just below the door soffit. This is caused by the fact that, in the simulations, the velocity on the wall is nil and the adjacent cell is not close enough to resolve the shape of the boundary layer. However, this unresolved area is considered thin and no big influence is expected on the outcomes. The part of flow that lay below the neutral plane is overestimated by Fluent. Note that the velocity profile is not affected by the thermal boundary conditions used for the walls.

Temperature profiles predictions were closer to the experiments in the upper part more than the lower one where the layer height interface was not accurately predicted and stratification was weaker introducing an exaggerated mixing layer. Figure 6-9, Figure 6-10 and Figure 6-11 reveal two simulation types where in the first no previous knowledge is assumed to be available and the thermal boundaries of the room were defined by estimating the heat transfer coefficients. The heat transfer coefficients were estimated from the expression $h = C \cdot (T_{wall} - T_{out})^{1/4}$, where T_{out} is the temperature of outside, T_{wall} is the temperature of the outside wall and C is 2.49 for the ceiling and 1.77 for the walls [Kothandaraman and et al., 1977]. On the other hand, in the second simulation type the heat fluxes through the walls and ceiling were extracted from FDS calculations and introduced as thermal boundaries for the case. The upper layer temperature predictions were significantly improved by prescribing the heat flux through the walls and ceiling (0.2 kW/m^2 taken from FDS calculations). The lower part of the temperature profile predicted by Fluent does not match perfectly with the experiments. The layer interface is also found to differ from the measurements. A certain reason for these differences is the uniform and restricted thermal boundaries applied to the domain. However, other reasons like the turbulence and fire modelling can contribute to the deterioration of the predictions.

The mesh was refined in places where the flow is critical or high gradients were expected. The cell size was reduced down to 0.075 m and 0.05 m in the vicinity of fire and near walls respectively, (see Figure 6-7 and Figure 6-8). For grid sensitivity study, the cells number was doubled in all three directions x, y and z, i.e. the cell number of the mesh was increased eightfold (2 x 2 x 2). The results of the fine and coarse meshes did not show significant differences, hence it can be said that the results are mesh independent. Note that for the grid sensitivity study no radiation model was used in the calculation for computational capacity restrictions. The radiation model and its radiation mesh and their sensitivity to the results were studied as well. The radiation was modelled using the Discrete Transfer method described in Chapter 4. The sensitivity to the angular direction discretization (number of rays) was studied and found not very important in this case where the fire is considered weak. Thus, 4-Theta rays and 4-Phi rays were found sufficient for this simulation, however, 8-Theta rays and 16-Phi rays are recommended in cases where fires are more intense.

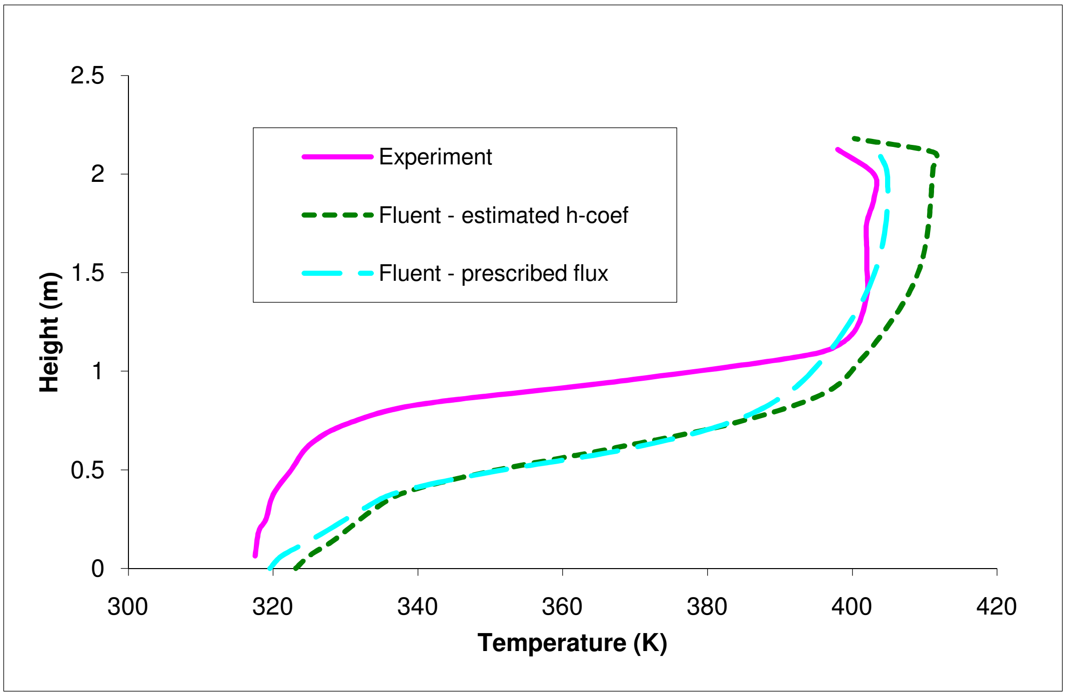

Figure 6-9: Temperature profiles in the corner of the room. The "estimated h-coef" is where the thermal boundaries are defined by estimating the heat transfer coefficient and "prescribed flux" is where the heat fluxes through boundaries are defined from previous knowledge.

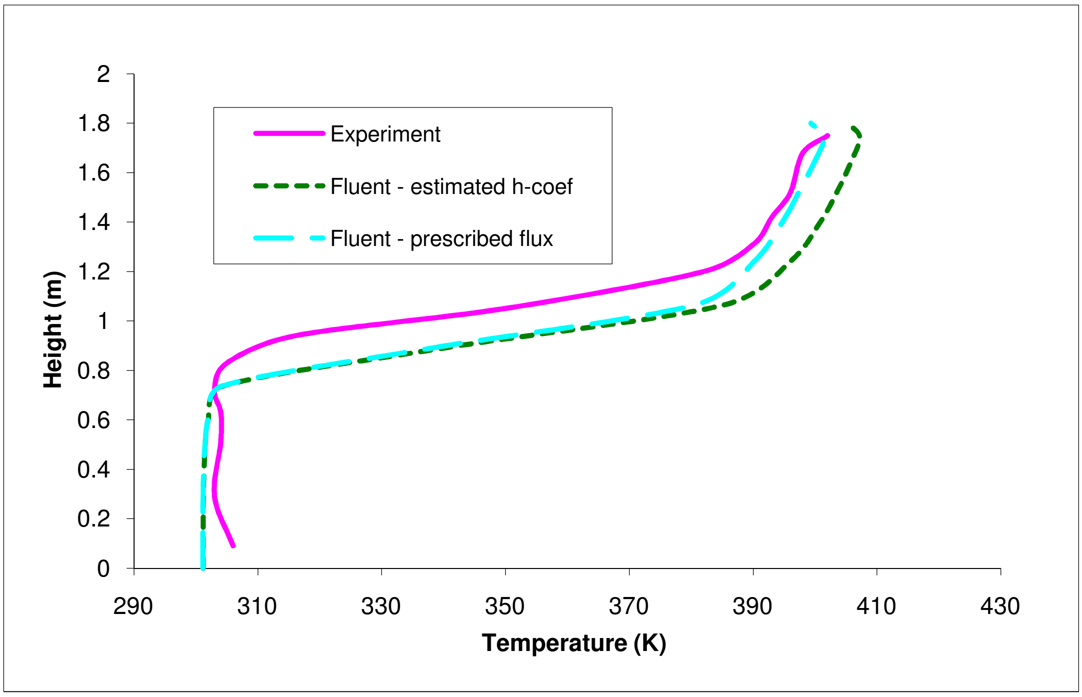

Figure 6-10: Temperature profiles in the doorway of the room. The "estimated h-coef" is where the thermal boundaries are defined by estimating the heat transfer coefficient and "prescribed flux" is where the heat fluxes through boundaries are defined from previous knowledge.

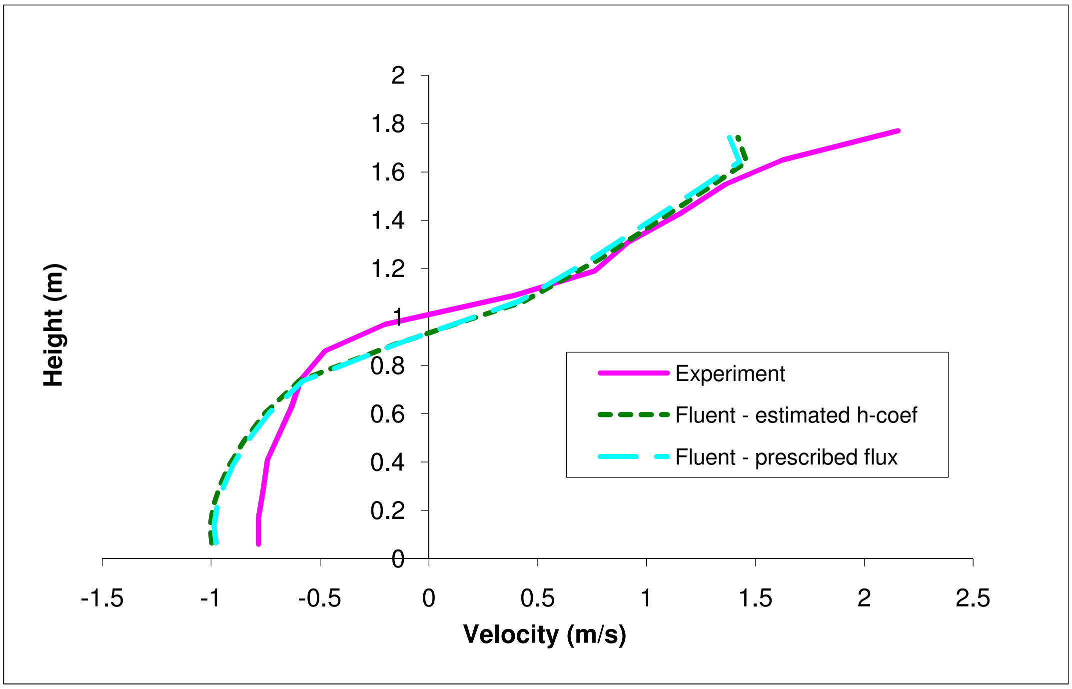

Figure 6-11: Velocity profiles in the doorway of the room. The "estimated h-coef" is where the thermal boundaries are defined by estimating the heat transfer coefficient and "prescribed flux" is where the heat fluxes through boundaries are defined from previous knowledge.

6.2.4 Zone Model – CFAST and Raeume

6.2.4.1 Programs Configuration

Two zone models were adopted of this study, namely CFAST and Raeume, as stated in Section 4.4.1.4. CFAST is a zone model developed at the National Institute of Standards and Technology [Jones and et al., 2005]. The main concept for zone models is described in Chapter 4. CFAST is widely used in the fire protection society. The model is well documented in its user guide and technical reference. CFAST computational domain is restricted to a maximum room number of 30. In zone models, care should be taken to check the applicability of the zonal approach to the scenario of interest and to analyse the sensitivity of the predictions to input assumptions. Among all the input parameters, the heat release rate is found to dominate the effects on the results predicted by the model. Same inputs and case specifications employed for the field models above were applied to zone models. The floor was set off, which means no heat conduction is calculated through the floor. Adiabatic status of the floor was found to be reasonably applicable and no significant differences in the results were observed by changing the floor material. The fire was modelled as a (0.3 x 0.3 x 0.3 m^3) cubical volume producing constant heat rate of 62.9 kW, where the fuel reaction is methane.

Raeume was developed in the Ship Stability Research Centre and has the same concept of zone models described in Chapter 4. Raeume was well documented and validated in [Shigunov, 2005]. The input parameters in this simulation were the same applied for the previous models and fire was also modelled as cubical volume (0.3 x 0.3 x 0.3 m^3) generating a 62.9 kW heat release rate for a methane fuel reaction. Raeume data taken for comparison are those when the solution became constant. Raeume is, unlike other zone models including CFAST, not restricted to a given number of items such as rooms or vents etc… but zone models approach should always be applied with caution considering the space of application and the nature of the flow.

6.2.4.2 Model Sensitivity and Simulation Results

Both zone models adopted in this study, CFAST and Raeume (Section 4.4.1.4), produced results which were found to be consistent with both the field models and experimental data. The data from experiments are presented in a form of temperature profile along the height of the room while results produced by zone models are in the form of uniform temperature for each of the upper and lower layers and an interface height between the two layers. Thus zone models results should be interpreted in a different way than field models. The upper layer temperature is observed to be around 401 ^{o}K in the experimental data temperature profile. CFAST predicted a hot layer temperature of 408 ^{o}K while Raeume estimated the upper layer temperature by 399 ^{o}K. The good agreement of upper layer temperature in this test case is achievable in the conditions of this scenario and should not be generalised. Different heat release rates and different boundaries where insulation is not employed might lead to different heat conduction and thus different results for the upper layer temperature.

Both CFAST and Raeume predicted a lower layer temperature of around 313 ^{o}K while the experimental estimated temperature was 321 ^{o}K. Both models showed good agreement with experimental results in temperature prediction especially for the upper hot layer which is of critical importance for safety study purpose. The layer height is not explicitly calculated in the field models neither the experimental tests, it is calculated afterwards from the temperature profiles. Two definitions are commonly known for the hot gases layer interface height. The layer height can be estimated as the base of the uniform hot layer where the temperature starts to cool sharply or it can be taken as the midpoint of the mixing layer where the changes took place rapidly between the upper and lower layer. Applying the first and second definitions to the temperature profile of the experiments resulted in 1.25 m and 0.97 m respectively for the layer interface heights. The models predictions for the layer interface height were 1.17 m for CFAST and 1.37 m for Raeume. Zone models predictions were more consistent with the second definition of the layer height. Finally it should be mentioned that the computational efforts for zone model did not exceed a minute for each run on a normal desktop.

6.2.5 Discussions on the Benchmarking Exercise

By the end of the benchmarking exercise, it was proven useful to perform a benchmarking exercise on the fire simulation tools at hand to comprehend the applicability of these models. Therefore, by developing a deep understanding of the models configurations and functionalities, it became practical to select a single model from each of the zone and field model types to conduct the intended simulations for this study.

For field models, the general purpose CFD package Fluent was found very demanding for input settings. The simulated results, although reasonably predicted, showed some deviations from the experiments at some places. On the other hand FDS, the fire specialised field model, could intake as input a well defined set of physical and numerical parameters that precisely describe the case of the intended simulation. The results produced by FDS were found in good agreement with experiments for the different locations and parameters used in the fire tests. Thus, it is obvious to favour FDS on Fluent for this type of fire applications conducted in this research.

As both CFAST and Raeume are of the zone models type, the input requirements were similar for both programs. The fundamentals of the two models are very similar concerning the governing equations and also the main sub-models like heat conduction through boundaries. However, CFAST is restricted to a given number of compartments whereas Raeume has no such restrictions. Both models showed good results matching the experiments especially regarding the critical parameters like the upper layer temperature and its interface layer height due to the similarity in the models' concepts. Away from the fundamentals and from usability point of view, it should be mentioned as well that Raeume was developed for the purpose of shipboard fire simulations and it possesses the possibility to export the general arrangement layouts of a ship in order to help in the creation of the fire scenario geometry. As a result, Raeume was found more useful for this study.

6.3 Application of Fire Models to Ship Geometry

Fire models are very widely used to deterministically predict fire resulting conditions in civil buildings, onshore transportation, aviation and many other applications. These models have also been applied to ship geometries in previous studies [Shigunov, 2005], [Salem, 2006]. Ship geometries are considered relatively complex comparing to other shore based geometries. The nature of space limit onboard ships necessitate the presence of uncommon shapes such as ceilings lower than usual, compact small cabins, hatches, and long narrow corridors. On the other hand, current passenger ships are required to have luxurious designs to attract the highest number of customers. These designs demand large public spaces like enormous restaurants and atriums among other shapes onboard. Field fire models are developed in a way that is scarcely affected by the shape of the geometry regarding smoke propagations, where the whole computed domain is divided into numerous small control volumes. For each volume the governing equations are solved and individual properties are derived (See Chapter 4). However, sub-models like ventilation controlled fires and heat loss through boundaries deserve more consideration especially in enclosures like the compact staterooms where air supply is very limited through a small door. Zone models are designed for compartments of moderate aspect ratios and where stratification is achieved. Applying zone models to the complex ship geometry imply high challenge to the main principles of these models. Therefore, the application of these models to different shapes of shipboard merit further testing and closer examination. Therefore, the aim of this chapter is to apply the selected fire models to ship geometries and examine the results closely. As accommodation areas were identified in Chapter 5 among the most hazardous onboard, the fire applications in this section are cabin fire, large space fire and corridor fire.

6.3.1 Cabin Fire

In general, a fire event is distinct in two stages from the safety point of view. First stage is the initial period of fire growth after ignition. The objective in this stage is to assure a safe escape for the occupants, thus the characteristics of interest in this situation is the heat and smoke release rate usually presented by the time history of mass and heat release rate. The time frame for the first stage is approximately 30 minutes. The second stage is when the fire reaches its peak heat release rate; this is assumed to last for some time and most probably flashover has occurred before reaching the peak of heat release rate. In this stage, the objective is to protect the structure from collapsing which will lead to fire escalation and might cause the loss of the ship or at least a vast area onboard. In this case the release rate of smoke is of less importance, while the temperature is of major interest for structure stability purpose; this is provided in a curve representing the time history of temperature in the influenced spaces. Both stages will be considered here with more focus on the first stage dealing with human life safety.

Design fires are defined by prescribing the time histories of heat release rates, where no attempts were made to model the combustion of the items present in a stateroom due to many difficulties. Firstly, the furniture present in a typical cabin is very complex and made of a wide variety of bulk materials which properties are not always available. Although the bulk thermal properties of these materials can be reasonably evaluated, combustion properties for some materials are not available at all. Secondly, a typical stateroom is relatively small and normally connected to other compartments via single door, hence a fire inside cabin will obviously be constrained (ventilation controlled). The combustion process is considered very complex where the various under-ventilated burning items release unburned fuel chars which will mix and burn wherever oxidant is available under the appropriate conditions.

6.3.1.1 Design Fire Scenario

Generally, fire protection engineers consider all the possible existing combustible items in determining a fire design of a building. When no combustion modelling is considered, the heat release rates of these items are usually obtained from separate experimental data. In the case of a stateroom onboard, the items found in such cabins are almost standard. Thus, the most convenient approach to model a complete cabin fire including all stages of fire development is to use the experimental data of existing cabin fire tests. The time histories of output heat release rates of such experimental data constitute the main input to study the effects of cabin fires aboard ship. In the European project SAFETY FIRST [Ramsdale et al., 2003], such fire tests were conducted. The burned cabin was an Internal Standard (IS) passenger cabin with the door wide open and without any mechanical ventilation or fire suppression. Two tests were carried out, where in the first one all the furniture normally present in a cabin were included in the experiment. Whilst in the second test one sofa and one bed were removed from the cabin to investigate the influence of fire load. Surprisingly the first test with higher fire load achieved a peak heat release rate of 3.05 MW while the second test resulted in a higher peak of 3.4 MW (Appendix B, Figure B - 1and Figure B - 2). It was also reported that the first test was aborted after 14 minutes due to high temperatures in the heat release measurement system. In both tests significant deformations were observed in the walls and ceiling while in the second test flaming occurred at joints in the back wall after 20 minutes. The flashover (See Chapter 3) was observed in the first test at 445 seconds while in the second test the flashover did not occur until 825 seconds. This discrepancy in flashover timing reveals the highly unpredictable variability of fire development. The smouldering period in the first test lasted for around 350 seconds before the fire started to grow up quickly. On the other hand in the second test, the fire smouldered and grew slowly but it was not until after 720 seconds when the fire started to grow up rapidly. This shows the difficulty in reproducing a fire with the same conditions to obtain identical heat release rates even in two similar experiments. The initial stage of fire growth is called the incubation stage and is highly dependent on the mode of ignition which is not clearly described for this experimental study. However, as a result the smouldering period made the big difference and influenced the flashover occurrence and consequently fire escalation. The difference seen in the delay time before the fire starts to grow until reaching its peak can be referred to smouldering propagation velocity and transition to flaming combustion. With all the aforementioned about unpredictability of fire growth and development, no attempts were taken to model the combustion in the simulations. Instead, the heat release rates as measured in the experiments were prescribed as inputs into computer programs.

The cabin height was 2.1 m and the plan surface was in "L" shape with a total area of 12.9 m^2 which was approximated by a rectangle of 2.6 m x 5 m for the model simulations. The door is located at 1.2 m offset from the corner on one of the 2.6 m walls and has dimensions of 1.98 m height by 0.655 m width rounded to 2 m by 0.7 m in the simulations (See Figure 6-12). The time history of the total output heat release rate measured in the experiments was provided as input for the computer model to account for the fire effects. Around 15 points were used to describe each heat release rate covering all the major deflections of the curves. The area on the floor where the heat release rate is distributed cannot be accurately modelled as in reality fire spread showed inherent variability. However, different cases with different distributions of heat release rates over variant areas were simulated and the final results were found to be weakly sensitive to this distribution area. Therefore, the heat release rate was prescribed on a volume of 1.5 m by 1.5 m plan area and 0.5 m height located on the floor in the centre of the cabin (See Figure 6-12).

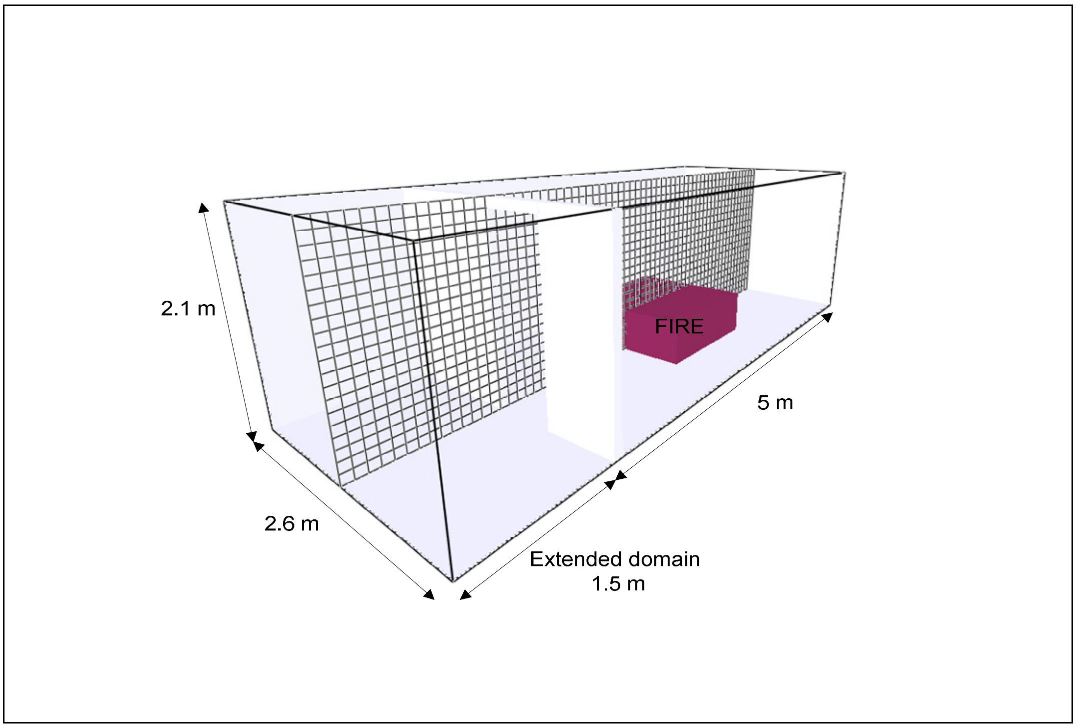

Figure 6-12: A Smokeview snapshot for the cabin fire configurations.

6.3.1.2 Numerical Simulations

The numerical simulations were conducted using the CFD model FDS and zone model Raeume. The input data for the models is similar including the geometry, vent and the heat release rates described above. In addition, the combustion reaction used was that of wood for both models. The thermal boundaries of the cabin were defined as a thin steel plate with 25 mm of Rockwool insulation; material properties are listed in Appendix C. The results compared in this section are those available from the experimental tests and these are the averaged temperature time histories at four different elevations; 10 cm, 30 cm, 90 cm and 150 cm below ceiling. For zone models the upper layer temperature was considered for comparison as this temperature is uniform in the whole layer. On the other hand, for the field model FDS the temperature considered at each height was taken as the average of four devices located on the same elevation at 0.3 m by 0.3 m from each corner of the cabin. The computational domain in FDS was divided in cubical cells with side size of 0.1m. In addition, the results were studied regarding their sensitivity to the grid and were found mesh independent.

In experiments, the heat release rates peaks measured were 3.05 MW and 3.4 MW in test 1 and test 2, respectively. FDS and Raeume both constrained and truncated the heat release rates in both fire tests (See Figure B - 1 and Figure B - 2 in Appendix B). Both models predicted that the oxygen supply for combustion sustain a heat release rate of a peak of around 2.8 MW in both tests.

Models predictions showed good agreement with the measured temperatures, especially in the first part of the curve before reaching the peak temperatures (Section B.1 in Appendix B). In general Raeume is showing matching results with the experimental results for the devices at high levels just below the ceiling, where the temperatures measured do not have big differences and can be considered as an upper layer temperature. However, Raeume in both tests showed a faster temperature rise comparing to the averaged temperature at 150 cm below ceiling (see Figure 6-13). The reason is that a single upper layer temperature of Raeume is compared to the average temperature measured at different heights of the cabin. When measured at low height the gas temperature, affected by mixing with the cold lower layer, rose slower than the single uniform temperature of Raeume (Figure B - 6 and Figure B - 10). FDS, before reaching flashover and peak temperatures, showed results in very good agreement with the experiments even for the devices located at 150 cm below ceiling; bearing in mind that the prediction of temperatures at this elevation is affected by the fire plume entrainment, layers mixing and thermocouple device locations with respect to fire bed.

At the moments when flashovers were observed (at 435 seconds in test 1 and at 810 seconds in test 2) both models started to show discrepancies from measurements as illustrated in Figure 6-14. These differences between measured and simulated results are more pronounced when the temperature curves reach their peak values. The models are observed to have results closer to each other but higher than the measured results. The peak temperature over-prediction by models comparing to experiments can be referred to many reasons. Firstly, the experimental tests showed significant deformations in the walls for both tests and failures in the back wall were observed after 20 minutes in test 2. As a result, heat loss from the cabin to the outside is increased. Test 1 was aborted after 14 minutes due to high temperatures in the heat release measurement system otherwise failures might have happened in the walls. Hence, the difficulty in modelling the deformations and failures in the boundary conditions can be referred as the main reason for the differences between the measured and simulated results after the flashover accompanied with high temperature in the cabin. Secondly, the approximation made in modelling the physical aspects might have contributed to the difference in results. The cabin was reshaped from an "L" shape to a rectangle, which can have an influence on the air entrainment mechanism and gases flow in the compartment. In addition the door dimensions were rounded to avoid unaffordable computational efforts implied by an extremely refined grid (order of 10^{-3}). This might have affected the air entrainment into the compartment. Not to mention all the errors resulting from averaging, thermocouple measurements in experiments and numerical errors in simulations.

Finally it can be concluded that both models predicted reasonable results comparing to the experimental data though the post-flashover stage showed some differences due to all the reasons stated above.

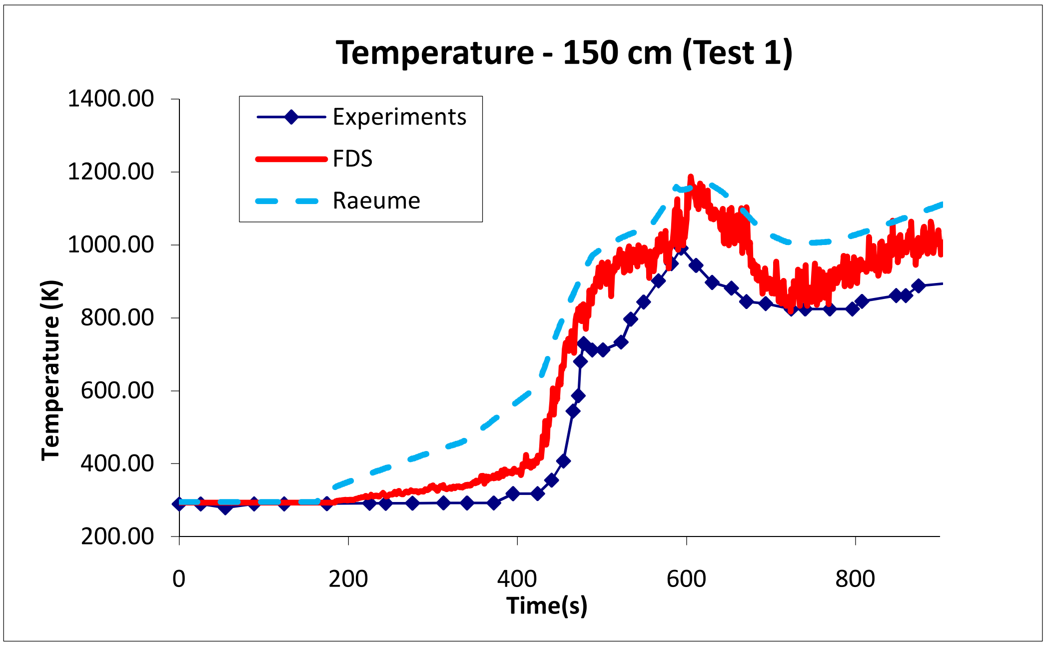

Figure 6-13: Comparison of the temperature as measured in experiments and predicted by FDS and Raeume at 150 cm below ceiling for cabin fire test 1.

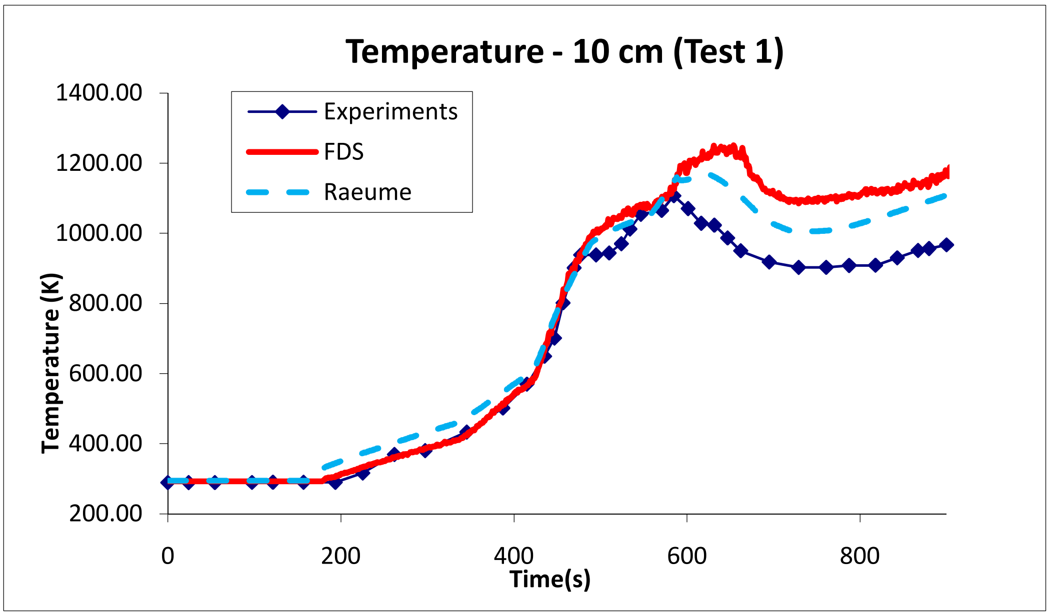

Figure 6-14: Comparison of the temperature as measured in experiments and predicted by FDS and Raeume at 10 cm below ceiling for cabin fire test 1.

6.3.2 Large Space Fire

Luxury designs of recent passenger ships contain all kinds of attractive large public spaces such as immense restaurants, cafeterias, malls and atriums. In general, most of these spaces are similar and they all present vast areas without compartmentation or barriers that can prevent or limit smoke propagation allowing fast spread of toxic gases. Although the geometries of these spaces can be near cubical which is suitable for zone models, these large spaces still pose some challenge on numerical simulations and worth further investigation. Therefore, a typical large public space represented by an atrium is considered in this section for further examination of the model predictions. It should be mentioned also that no experimental data is available for this simulation case; hence just the results predicted by both the zone and field model are compared and interpreted.

6.3.2.1 Design Fire Scenario

The atrium has a squared plane horizontal area of 30 x 30 m^2 where these dimensions are very common for atriums onboard ships. The height is taken as 15 m spanning more than three decks according to SOLAS regulations for an atrium definition. The atrium has four doors of 2 m width and 2 m height each. These doors are located symmetrically in two opposite walls 2 meters from the corners (See Figure 6-15). The fire is located in the centre of the atrium and considered to be a pool fire of 2.5 m diameter. The fire is of fast growth category as illustrated in Figure 3-11. The fire load can vary depending on the combustible materials present in the fire scenario. The design fire of this scenario grows fast and reaches 3 MW in 253 seconds then levels off until the end of simulations. The boundaries of the atrium are constituted of thin steel plates isolated by 75 mm of Rockwool; material properties listed in Appendix C.

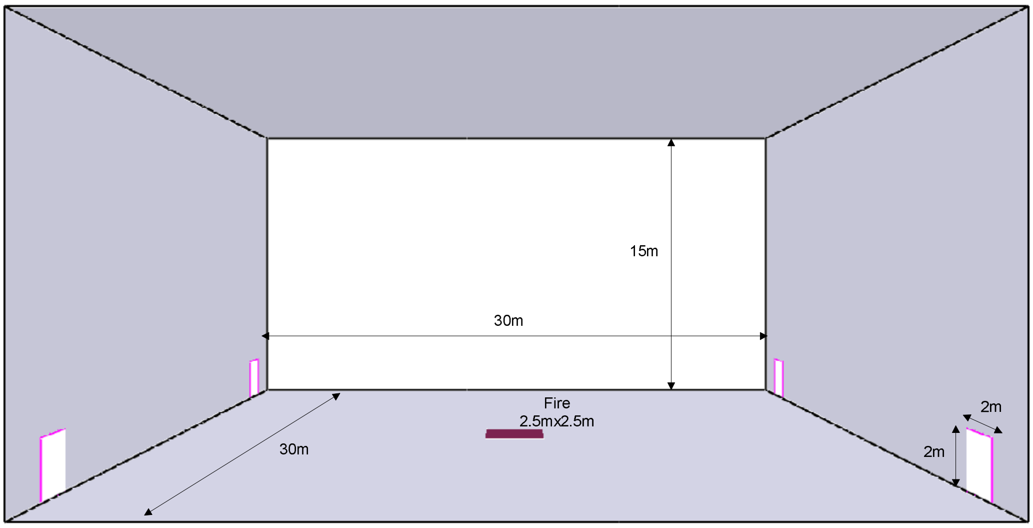

Figure 6-15: Atrium geometrical configuration.

6.3.2.2 Numerical Simulations

The numerical simulations have been conducted using the CFD model FDS and zone model Raeume. The fire in the simulations is generated by a squared vent (2.5 x 2.5 m^2) located in the centre of the room and releasing the heat release rate described above. The combustion was considered to react as burning wood.

The computational domain in FDS was divided in cubical cells of different size. A volume of 6 x 6 m^2 plane area and spanning the whole computational domain vertically was developed around the fire and its plume impingement on the ceiling. The rest of the computational domain was divided into four symmetrical meshes surrounding the fire plume mesh. In the fire plume mesh where the highest temperature gradients are expected fine control volumes were used whereas the surrounding meshes were divided into relatively coarser cells (see Figure 6-16).

Using equation (Eq 6-1) for the design fire levelling at 3 MW, it was found that the characteristic fire diameter D^* is around 1.5 m. The recommended ratios for the characteristic fire diameter to cell size $(D^*/\delta x)$ are between 5 and 10; hence cell sizes of 0.15 m to 0.3 m are reasonable to be used in the fire plume area for this application. Three grid configurations were used for the atrium computation to study the mesh dependency. Firstly, a coarse grid of 30cm cells around the fire plume mesh and 60cm cells for the surrounding meshes were used. Secondly, a finer grid of 20cm cubes was deployed around fire plume and 60cm cells for the other meshes. Finally, the finest mesh implemented 15 cm cells around the fire plume and 30 cm cells elsewhere. The results showed minor changes in the results of coarse and fine grid configurations. The results shown in this study are those produced by the finest mesh configuration.

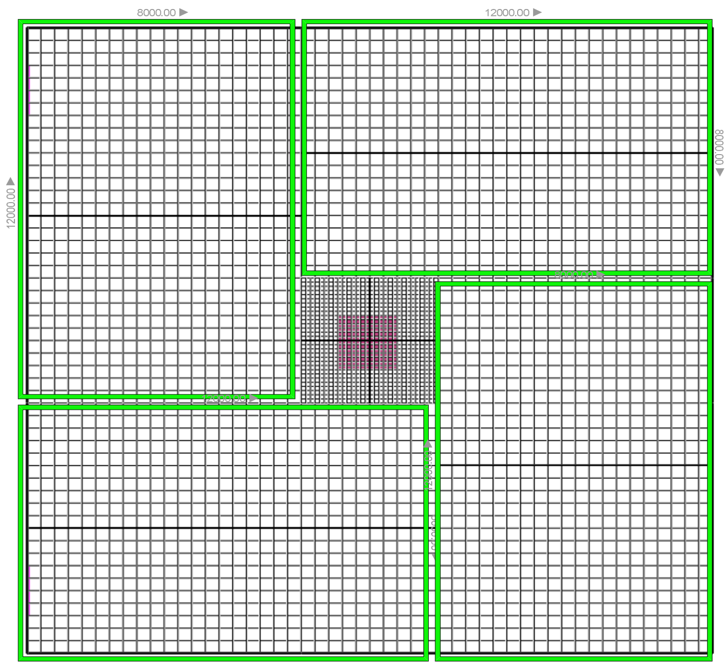

Figure 6-16: Top view for the grid configuration of the atrium, showing the fine mesh in the centre surrounded by four symmetrical coarser meshes.

The comparisons between the field model FDS and zone model Raeume are represented as time histories of the upper layer temperature, gases concentrations, radiation and layer height. The numerical simulations results are presented in (Section B.2 in Appendix B). As all zone models including Raeume predict a single value for each parameter of the upper layer in a compartment, FDS results should be processed in order to be compared to Raeume predictions. However, the devices measurements are found not very sensitive to the horizontal and vertical locations providing that the devices are not located inside the fire plume. Therefore, FDS results compared to Raeume are extracted from devices distributed in the corners of the compartment and averaged to produce a single value for each parameter.

In general, the predictions of all parameters in the atrium are showing good matching between Raeume and FDS (Figure B - 11 to Figure B - 18). The temperature and carbon monoxide (CO) concentrations in the upper layer are in excellent agreement. However it should be stressed that the very good matching to temperature at this stage comes from the fact that the heat release rates in both models are exactly the same and that's what the transient phase is mainly depending on. Should the simulations run for much longer time where the boundaries has the dominant effects this great matching might not be observed between the two models.

Carbon dioxide (CO_2) concentrations are showing minor difference where FDS predicted slightly higher concentration than Raeume (see Figure 6-17). The same exactly applies for the predictions of optical density (OD) where Raeume predicts slightly higher smoke obscuration than FDS. Oxygen (O_2) predictions are also in good agreement despite the little hump in the early seconds of Raeume simulations. This numerical instability is just observed in large spaces with huge volumes and can be considered of minor importance as it is occurring in the first few seconds of the simulation.

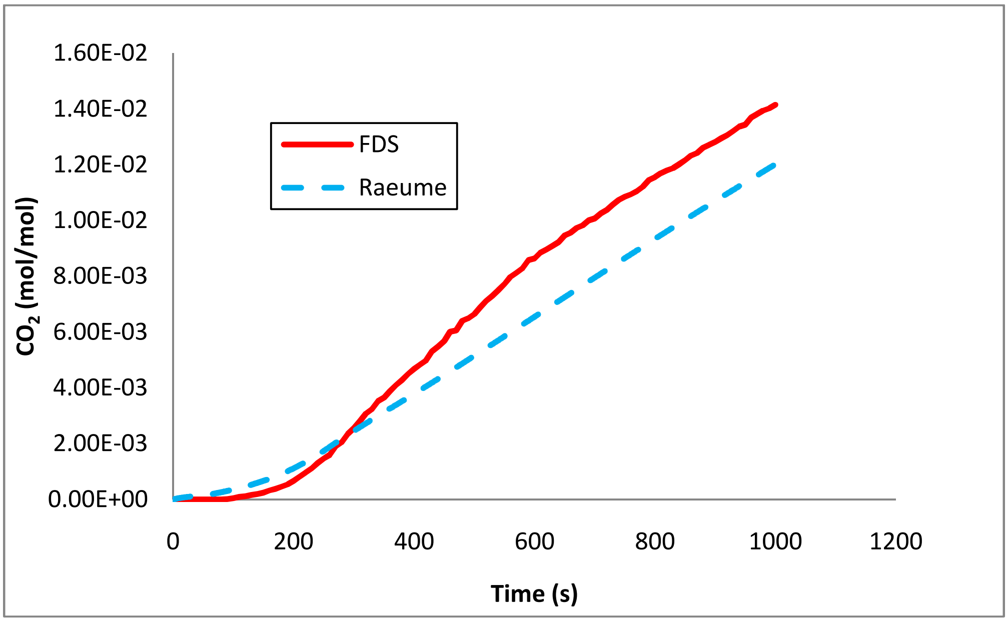

Figure 6-17: Carbon dioxide concentration in an atrium as compared between FDS and Raeume predictions.

For radiation measurements, more attention should be paid when comparing the results predicted by zone and field models as these models may use different methods to calculate the radiative heat fluxes. Two similar calculation methods were used for both Raeume and FDS. Radiation is measured in the zone model Raeume by calculating the incident radiation from the upper layer on a sphere located at 1.5m above the floor. FDS has many different measurement devices to predict various types of heat radiation. To allow the most convenient comparison between Raeume and FDS, a device that integrates the incident radiative heat flux over a 2π solid angle around a vector pointing upward in a selected location is used on an elevation of 1.5 m. Therefore, the field model FDS potentially computes different radiation values for every cell even in the same compartment whilst zone models predicts a single radiative flux value for each compartment. This should be kept in mind when comparing radiant heat flux predictions for zone and field models. FDS radiation measurements compared to Raeume are the average of device readings distributed in the atrium outside the fire plume. Comparing the predictions of Raeume and FDS for this case, the results are found in good agreement with slightly higher radiation fluxes predicted by Raeume. FDS records an initial radiative heat flux of 0.419 kW/m^2 which corresponds to the integrated heat flux radiated by an ambient temperature of 20 °C. On the other hand, Raeume calculates the heat flux radiated by the upper layer despite what the temperature of this layer is. Thus, for a room where the upper layer thickness is still very thin, the radiative heat flux is in the vicinity of zero. This mechanism affects just the first stage of the radiation predictions where heat flux values are very low and has no effects on human safety.

When the predictions of smoke layer heights for field and zone models are to be compared, the results should be treated with caution. While zone models assume a sharp interface layer between two layers of uniform temperatures, field models do not have two distinct zones but a continuous temperature profile instead. Hence, field models use a variety of ways to calculate the smoke interface location. Different methods of calculations lead to somewhat differing results in the layer height prediction for field models. FDS solves for the interface height, upper and layer temperatures by integrating the gas temperature along a vertical column of cells and equates it to the corresponding averaged upper and lower temperatures. Assume z is a height above the floor starting from 0 on the floor up to H at the ceiling and z_{int} is the height of smoke interface. $T(z)$ is the temperature in function of height where T_u and T_l are the averaged upper and lower layer temperatures, respectively. Thus, to find the required parameters (z_{int}, T_u and T_l), FDS solves for the following quantities [McGrattan, 2008b]:

$$(H - z_{int})T_u + z_{int}T_l = \int_0^H T(z)\,dz \qquad \textbf{Eq 6-2}$$

$$(H - z_{int})\frac{1}{T_u} + z_{int}\frac{1}{T_l} = \int_0^H \frac{1}{T(z)}\,dz \qquad \textbf{Eq 6-3}$$

$$(H - z_{int})T_u = \int_{z_{int}}^H T(z)\,dz \qquad \textbf{Eq 6-4}$$

Thus, the smoke layer height, upper layer and lower layer temperatures have different values for each different cell in the horizontal plane of the computational domain just like all the previous parameters predicted by FDS. Hence, once again the results of FDS used for comparison are the average of device readings distributed in the atrium outside the fire plume.

Keeping all the above in mind, it is clear that both models predicted a similar trend for the descending phase of the layer interface (Figure 6-18). However, Raeume predicted an interface that descended faster than the one predicted by FDS. This is mainly because Raeume is a zone model that allows instant smoke propagation vertically toward the ceiling and then horizontally toward the walls. In addition, FDS devices located in the fire plume predicted a fast and sharp layer descent; however it was found inconvenient to place devices in the fire plume considering the method used in FDS to calculate the interface height. After the decay phase both models predicted layers that level at close heights. The interface predicted by FDS levels off at around 1.7 m while the layer calculated by Raeume levels at around 1.2 m. Bearing in mind the sensitivity of interface calculation method and that the atrium total height is 30 m, the predictions of both models can be considered in fair agreement.

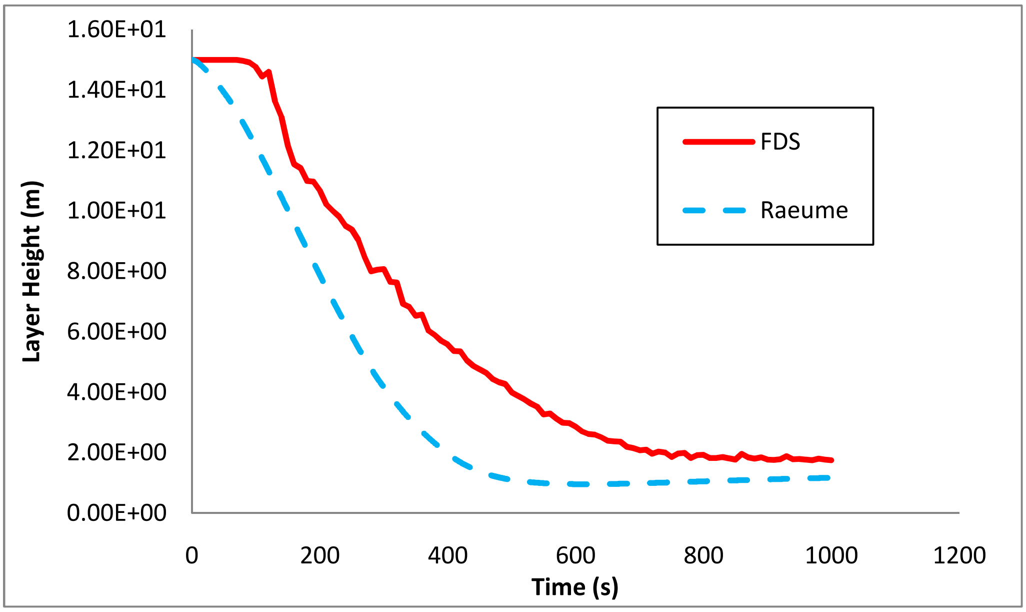

Figure 6-18: Layer height interface in an atrium as compared between FDS and Raeume predictions.

6.3.3 Corridor Fire

General arrangements onboard ships are known to be very complex and compact in order to make the most benefit of the floating space. In particular, the accommodation areas in passenger ships are designed to accommodate the highest number of passengers onboard. The numerous cabins are connected together and to other facilities through narrow long corridors. These paths allow fast spread of smoke and gases in case of a fire incident in the accommodation area or similar spaces aboard. On the other hand, these corridors represent the main egress route for passengers onboard escaping the hazardous conditions resulted from fire effects; hence, the great interest in smoke propagation predictions in corridors. It is found important then to apply fire models on this type of geometries and to interpret the predictions of the fire models closely.

Corridors or long compartments in general were always the subject of a dispute for zone models users. These models assume an instantaneous propagation of hot gases from one side of a compartment to another without accounting for the smoke travelling speed along the corridors. In addition, the assumption of uniform temperature for the upper layer of a single compartment results in the same temperature predictions in any location of this compartment. Whilst in a fire scenario taking place in a corridor the temperature might cool down along the path due to mixing with adjacent cool air and heat loss to boundaries. Therefore, the two main assumptions for zone models predictions in long compartments are; neglecting the time required for smoke propagation and the assumption of uniform gas properties throughout the whole corridor. As those assumptions do not suit some fire applications in the fire protection society, some ways were proposed to get around those assumptions. One common way to address this issue is to divide the long corridor into virtual smaller compartments by virtual barriers. The virtual partitions can be seen as a wide open door spanning the whole cross section of the corridor. This method is adopted by many zone models. Moving the smoke from a compartment to another instead of propagating in a single corridor delays the spread of this smoke and hence reduces the speed of instant filling. In addition, in zone models hot gases are transported from a compartment to another by a virtual plume equivalent to the vent jet between the two adjacent compartments. This plume entrains fresh air and hence cools down the hot gases moved between compartments. This cooling occurring in the virtual plume reduces the temperature of gases propagating from a compartment to another due to mixing with the adjacent fresh air underneath the smoke jet in a long corridor. It is always required that great care should be taken in applying this virtual partition method to corridors especially in choosing the number of virtual compartments and their sizes in order to predict the most realistic results. The possible drawbacks associated with the virtual partitions are obvious and several. Having several compartments instead of one corridor may result in different smoke layer heights in the same corridor which should not be the case in a well developed fire scenario. In addition, creating virtual plumes between compartments may result in over-cooling of the smoke temperature, over-slowing smoke propagation and alterations in the gas concentrations. The following sections will consider these issues in more details to investigate the sensitivity of the two aforementioned assumptions regarding this research study in order to judge whether the compartmentation method is suitable for the fire application conducted in this study and to draw some conclusions based on the conducted investigations.

6.3.3.1 Design Fire Scenario

A very typical geometry is used for the corridor scenario simulation. The layout consists of a fire room connected to a corridor via a door. The height of the ceiling is very similar in shipboard accommodation areas and is taken to be 2.4 m. Width of corridors vary slightly in different accommodation spaces. However, a corridor that is 1.6 m wide represents very well a common path between standard accommodation staterooms. The corridor is allowed to be sufficiently long to allow a reasonable spread of smoke. A length of 30 m is used for the corridor which is assumed to span almost the whole breadth of a ship. Fires in accommodation spaces are known to break out in cabins or similar compartments like storage rooms or laundries. For this scenario, the fire is ignited in a cabin of 3m x 4m area and same height as the corridor (2.4 m). Therefore, the general fire scenario of the accommodation area consists of a cabin of dimensions 3 m x 4 m x 2.4 m high and a corridor of 1.6 m x 30 m x 2.4 m high linked via a door of 1 m x 2 m high (See Figure 6-19). The corridor is open at its end by a door of 1 m width and 2 m height. The walls are all made of steel sheets isolated by 25 mm of Rockwool while the ceiling and floor are made of steel bulkheads. The design fire located in the centre of the cabin has a fast growth heat release rate reaching (Figure 3-11) levelling at 1000 kW for the rest of simulation time.

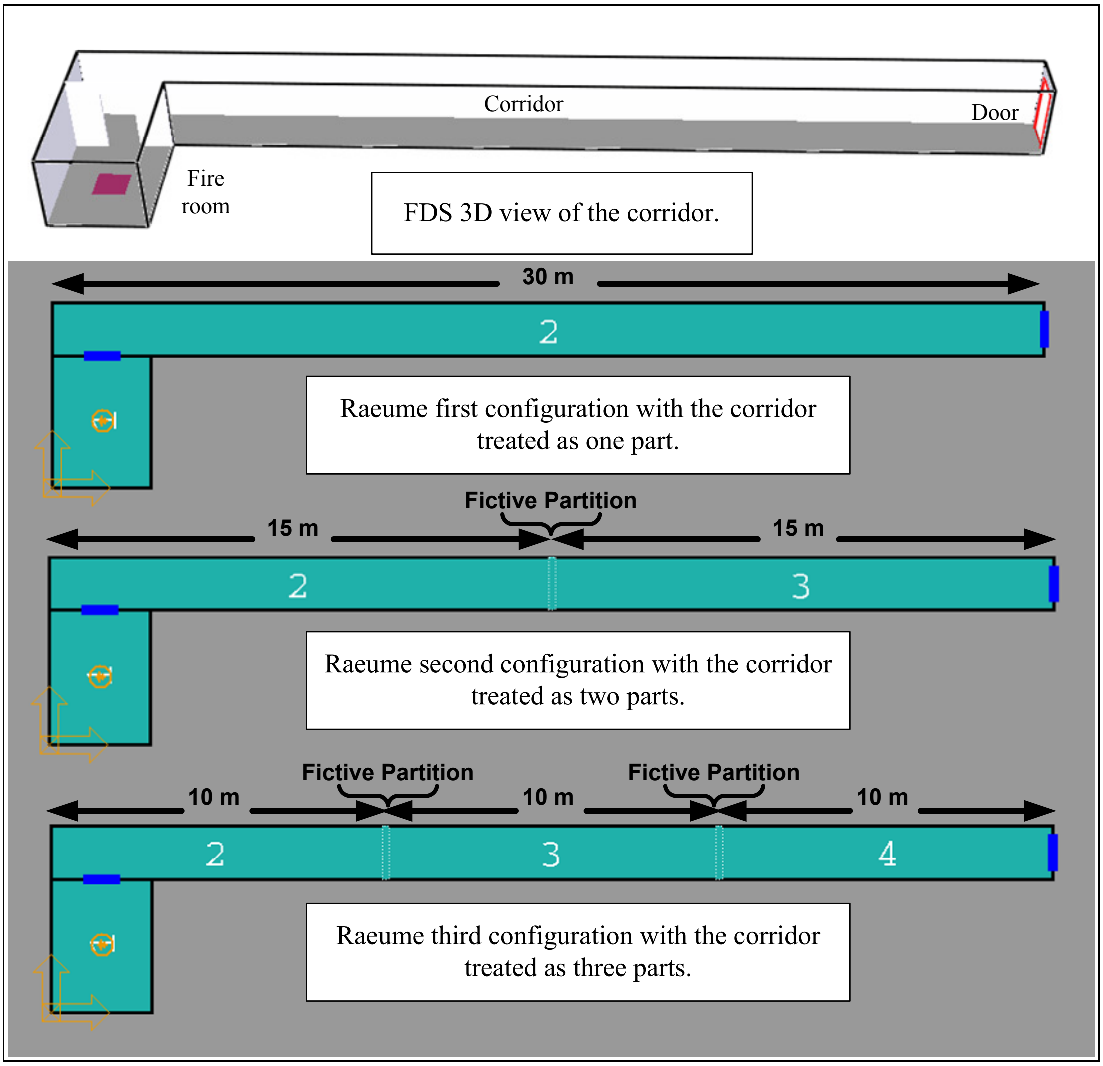

Figure 6-19: Snapshots illustrating from top to bottom; the corridor and fire cabin as shown by Smokeview the postprocessor of FDS, the three configurations of Raeume as taken by the pre-processor RamEditor for the corridor treated as one part, two parts or three parts, respectively.

6.3.3.2 Numerical Simulations

The computational domain was divided into equal cubical cells of 0.1 m side size. The grid was proven in previous simulations in this study to be sufficient for accurate predictions in cabin fires applications. In addition, the mesh was refined down to 0.75 m cell size and the changes in the results of the simulations were found insignificant.

The suitability of corridor compartmentation for this fire scenario application is analysed and interpreted in this section. As aforementioned, fast smoke propagation in long corridors is commonly slowed down by dividing the long corridor into smaller compartments allowing the formation of new virtual plumes that fill each new compartment with smoke. At the same time, the fresh air entrained into the new plumes cools down the hot air, therefore compensating for the cooling down occurring due to the mixing of the hot air in the jet with the adjacent fresh air. The corridor division should be done with caution to avoid the excess in cooling of gases reaching the compartments at the end of the corridor. Thus , to find out if it is a good practice to divide the corridor into small compartments for this fire application, three different configurations in the zone model Raeume were compared to the results predicted by the field model FDS (See Figure 6-19). In the first configuration, the long corridor was treated as one part forming a single compartment. In the second configuration, the corridor was split into two parts of 15 m each and hence treated as two different compartments. In the third configuration, the corridor was divided in three equal parts of 10 m each and which are dealt with as separate compartmentations.

The quantities compared are the upper layer temperature, carbon monoxide (CO), carbon dioxide (CO_2), oxygen (O_2), optical density (OD), radiative heat flux and layer height. These quantities are compared for FDS predictions and the calculations of Raeume with three different configurations treating the corridor as one compartment, two compartments or three compartments. The complete set of results is presented in Section B.3 in Appendix B. The results are compared in four locations; the fire room, first part of the corridor, second and third part where each part is 10 m long. For the field model FDS a number of measurement devices were distributed in the fire room and along the corridor. Then the measurements for each quantity were averaged for the cabin and for each of the three parts of the corridor. These averaged results are compared to the single uniform values predicted by Raeume for each part of the corridor and the cabin. Each of the quantities measured is illustrated in four figures; the room fire, first, second and third part of the corridor. Every figure depicts a comparison of FDS with the three configurations of Raeume where the corridor is treated as one compartment, two compartments or three compartments respectively (See Figure B - 19 to Figure B - 47 in Appendix B).

FDS and Raeume in its three configurations are showing great matching for the upper temperature in the fire room. However, in the first part of the corridor, the temperature is somewhat under-predicted comparing to FDS results by the first configuration of Raeume with the corridor as a single compartment (see Figure 6-20). For the second and third configurations the temperatures calculated by Raeume were closer to FDS predictions. For the second part of the corridor, the results of Raeume calculations are in agreement with FDS. In the third part of the corridor Raeume shows good agreement with FDS for the corridor treated a single compartment while it tends to predict lower temperatures than FDS as the corridor is divided into parts (see Figure 6-21). The reason for the low gas temperatures in the last two parts of the corridor is the entrainment of fresh air through the virtual plume imposed by the compartmentation of the corridor. The reason is that in zone models, gases are transported from a compartment to another by applying virtual plumes in each new compartment. Appendix B, Figure B - 23 to Figure B - 26 depict the results of the predictions of carbon monoxide. The results of Raeume with different configurations show minor differences between them and are in good agreement with FDS predictions. However, in the last part of the corridor FDS predicted lower CO concentrations than Raeume in general. The results of carbon dioxide concentrations are illustrated in Appendix B, Figure B - 27 to Figure B - 30. All Raeume predictions match well with the results of FDS apart from the fire room where the CO_2 concentration predicted by FDS is higher than Raeume predictions. Depicted in Figure B - 31 to Figure B - 34, are the comparisons of concentration predictions of oxygen O_2. FDS predicted lower concentration of oxygen than Raeume in the fire room while the predictions tend to be closer in all parts of the corridor. The results of optical density (OD) illustrated in Figure B - 35 to Figure B - 38 show good agreement between FDS and Raeume predictions in the fire room. However, in all parts of the corridor FDS predicted higher optical densities than Raeume, with closer results predicted by Raeume first configuration treating the corridor as a single compartment.

Before comparing the radiation results it should be reminded that the methods of calculation differ for the two models. Radiation is measured in the zone model Raeume by calculating the incident radiation from the upper layer on a sphere located at 1.5m above the floor. FDS integrates the incident radiative heat flux over a 2π solid angles around a vector pointing upward in a selected location on an elevation of 1.5 m. Thus, FDS computes different radiation values for every cell even in the same compartment whilst zone models predict a single radiative flux value for each compartment. This should be kept in mind when comparing radiant heat flux predictions for zone and field models. The results of radiation predictions for the cabin and corridor geometry are illustrated in Appendix B, Figure B - 39 to Figure B - 42. The predictions of the radiative heat fluxes can be interpreted similarly to those of the upper temperature. The predictions are close in the fire room. While in the first part of the corridor, Raeume and in particular the configuration with the corridor as single compartment under-predicts the radiative flux comparing to FDS results. In the second part of the corridor the results of Raeume are closer to FDS predictions. Finally, in the last part of the corridor, Raeume configuration with a single compartment corridor produces results in good agreement with FDS while the divided corridor configurations predicts lower radiative heat fluxes.

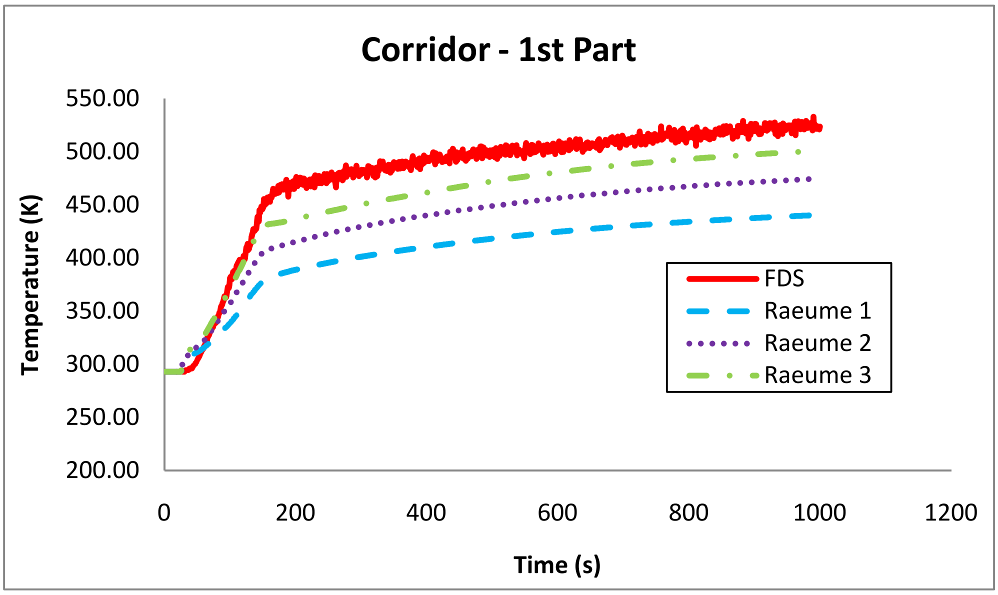

Figure 6-20: Temperature (K) as predicted by FDS and Raeume (different configurations) in the first part of the corridor.

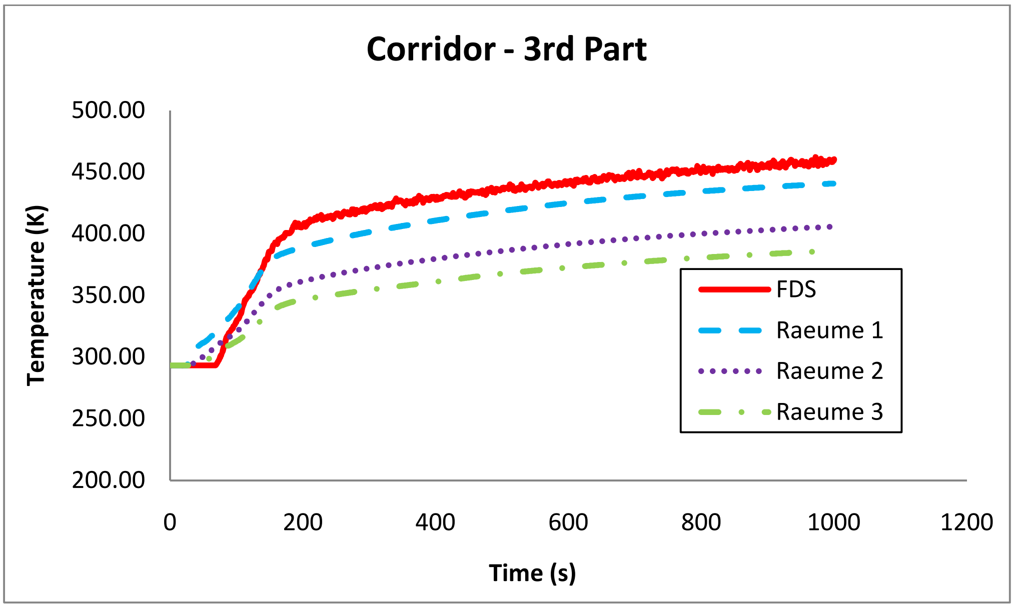

Figure 6-21: Temperature (K) as predicted by FDS and Raeume (different configurations) in the third part of the corridor.

As discussed in Section 6.3.2 the layer height predictions should be treated with caution when zone and field models results are compared. Firstly because field models unlike zone models do not have two distinct zones with a sharp interface layer in between but use various methods to calculate this interface. Secondly, a single layer height is predicted for each compartment by zone model whereas this height has different values at each device location for field model predictions. Raeume assumes a sharp interface layer between the two layers of uniform temperatures; FDS do not have two distinct zones but a continuous temperature profile instead. Different methods of calculating the smoke interface location lead to somewhat differing results in the layer height prediction for field models. FDS solves for the interface height, upper and layer temperatures by integrating the gas temperature along a vertical column of cells and equates it to the corresponding averaged upper and lower temperatures (See Eq 6-2, Eq 6-3 and Eq 6-4). FDS results in the cabin and three parts of the corridor are averaged and compared to the single layer height value predicted by Raeume in each of the four locations. The results of these comparisons are illustrated in Appendix B, Figure B - 43 to Figure B - 46. In the cabin, the predictions of both models are in good agreement as the layer interfaces level at 0.5 m height. In the first part of the corridor, even though the layers calculated by Raeume descend further than the one predicted by FDS, all layers level off at the same height at around 0.8 m. In the second part of the corridor, the first phase of the layer profile (decay phase) shows agreement between FDS and the prediction of Raeume configured with the corridor as a single part. In the second phase of the layer profile, FDS levels off at the same height as Raeume calculations with the corridors treated as three parts while the whole corridor configuration predicts a slightly higher layer interface. Similarly in the last part of the corridor, Raeume configurations with the corridor partitioned in two or three parts show good agreement with FDS while the single compartment corridor configuration of Raeume predicted a slightly higher smoke layer interface.

6.3.4 Discussions on Modelling Ship Fire Applications

Both CFD and zone models predicted reasonable results comparing to the experimental data of the cabin fire though the post-flashover stage showed some differences which can be mainly referred to the deformations and failures in the boundary conditions that followed the flashover stage in the cabin fire. In the large public space both models showed good agreement in most of the parameters. Some discrepancies were observed in some parameters like CO_2, radiation and especially the layer height which proved to be challenging for zone models. The descending stage predicted by zone model was faster than that predicted by field model, mainly due to the instantly impingement and spread of the hot gases on the ceiling. However, it should be stressed that the good agreement of results achieved here were mainly observed in the transient phase of fire and should not be generalised as these results depend on the design fire scenario conditions. The models are considered to predict close results for the scenarios provided in this study though there were no attempts to extensively study the sensitivity of all model parameters such as toxicity production, heat loss through boundaries etc…

Regarding smoke propagation in the corridor, it was clear that the division of a corridor into smaller compartments excessively reduced the temperature of propagating hot gases. The toxic gases concentrations were found less sensitive to the virtual compartmentation of the corridor. The optical density measurements showed some changes for different Raeume configurations, where the single compartment corridor predicted closer results to FDS. Radiation results were interpreted similarly to the temperature comparisons where the compartmentation of the corridor resulted in reduced radiative fluxes in the remote parts of the corridor. The smoke layer height was calculated slightly higher by Raeume configured with single compartment corridor as compared to other Raeume configurations and FDS results. After all what have been discussed above about the different methods used in Raeume and FDS to calculate the compared quantities and provided that FDS is taken as benchmark, it can be said that there is no single approach that can be applied to all corridor fire simulations computed by Raeume. Considering the simulation where the corridor was treated as a single compartment, unlike in the divided corridor case, temperatures were not excessively cooled in the corridor parts remote from the fire room. In addition the toxic gases concentrations were not markedly altered which is giving closer results to FDS predictions. The smoke layer height was not found significantly affected in the first phase (the decay phase). Therefore, to slow further the smoke descent, a higher number of virtual compartments were required and which obviously would result in extreme reduction in the temperature and marked alteration in the gases concentrations. However, if virtual division of the corridor is to be done, this should be done with a very moderate number of compartments taking into consideration all the analysis, observations and interpretations discussed above. Therefore, whether these virtual barriers should be applied in a corridor or not totally depend on the scenario conditions and need to be investigated for each different application.

6.4 Concluding Remarks

This chapter focused on the fire models and their applicability. CFD and zone models were both compared with experimental data to ensure the proper use of models and select the suitable ones of the study. Thereafter, the selected models were applied to specific ship geometry where the results of zone and field models were compared and interpreted. Generally speaking, fair agreement was shown between the compared models.

In the following chapter, the predicted fire results are evaluated in the way they affect human safety. Integration of fire model results with the evacuation models and methods of fire effects' quantification predict the health status of people affected by fire effluents.

7 Integration of Fire and Evacuation Models

7.1 Introductory Remarks

Chapter 6 above illustrated the application of fire models to ship geometries in order to predict fire effluents in the spaces of interest. In addition, the effects of exposure to the predicted fire effluents were analysed and quantified in Chapter 4. In this chapter, the fire effluents calculated by fire models (Raeume and FDS) in given fire scenarios are integrated with the evacuation model (Helios) and the associated quantification methods to assess the effects of exposure to fire products on the passengers. The effects of evacuee's exposure to fire effluents are quantified as a final output form in terms of fatalities and injuries with different severities. Therefore, this chapter is a Integration of the previous findings and analyses presented in the preceding chapters to demonstrate the holistic assessment approach and its outcomes.

7.2 Calculation Procedure

The procedure of calculation adopted in the consolidated model is described in this section and the different tasks conducted by each model in the software collection are explained as well (Also see Figure 4-2). First the general arrangements layout of the ship, shown in Figure 7-1, is imported into RamEditor where the three dimensional geometrical arrangement of the fire scenario is generated (See Figure 7-2).

RamEditor acts as a pre-processor for the zone fire model Raeume thus the design fire scenario inputs are set up on this level of the algorithm. These inputs consist of the design fire which defines the fire characteristics, and all the conditions driving the fire and smoke development. These conditions are mainly; the geometric configuration including all vents and obstacles; material properties of ceilings, floors and walls; and initial conditions in addition to all forms of fire fighting and containing activities like sprinklers and smoke extraction fans etc… The defined design fire scenario is simulated in the zone fire model Raeume to simulate fire development and smoke propagation in order to predict the resulting conditions in the domain (See Figure 7-2). Thereafter, the three dimensional geometrical arrangements and predicted fire resulting conditions are imported into Helios to produce the environment of fire scenario. In Helios, the evacuees are allocated and their properties are assigned; walking speed, response time and escape route. On this level, two kinds of simulations are performed; the pedestrian dynamics and the quantification of fire products effects on evacuees. Finally, the outcome of Helios is the number of causalities with the level of severity, location, time, and conditions that caused the casualty (heat, toxicity and visibility). The lethality or level of injury severity of a given evacuee is defined in correspondence to the resulting FED calculated for the evacuee.

In addition, for comparison purpose, the fire scenario was simulated with the field model FDS and the results of fire conditions were integrated to Helios in order to predict the number of evacuees affected by the fire incident. The same calculation procedure used for Raeume – Helios integration is adopted for FDS and Helios to predict the final outcome of affected passengers. The same three dimensional geometric arrangements generated by RamEditor are used as inputs for Helios for evacuation purposes (See Figure 7-2). However, the design fire scenario in FDS is defined through special scripts which are simulated by the software (See Section C.4 in Appendix C). FDS fire and smoke propagation simulations can be visualized in the software post-processor Smokeview (See Figure 7-3).

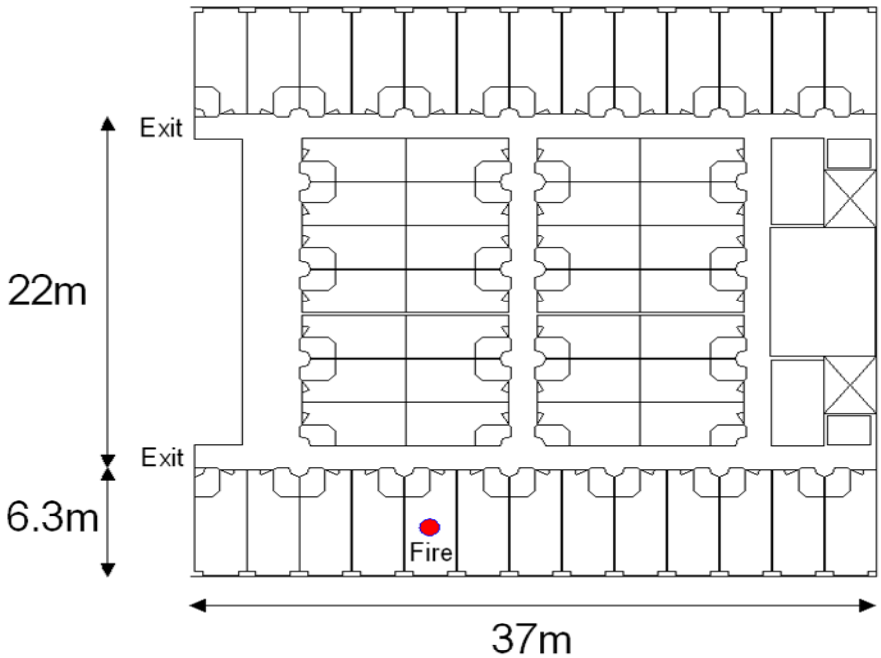

Figure 7-1: General Arrangements of the accommodation spaces fire scenario.

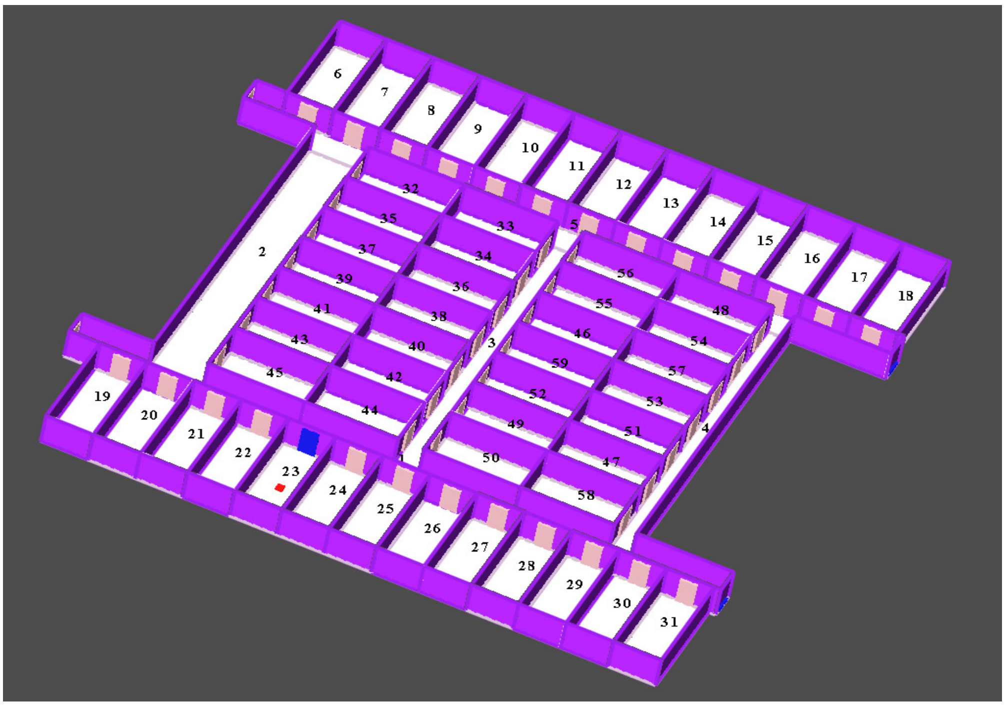

Figure 7-2: Snapshot from RamEditor (pre-processor of Raeume) illustrating the accommodation spaces including all the cabins and corridors where the evacuation process takes place.

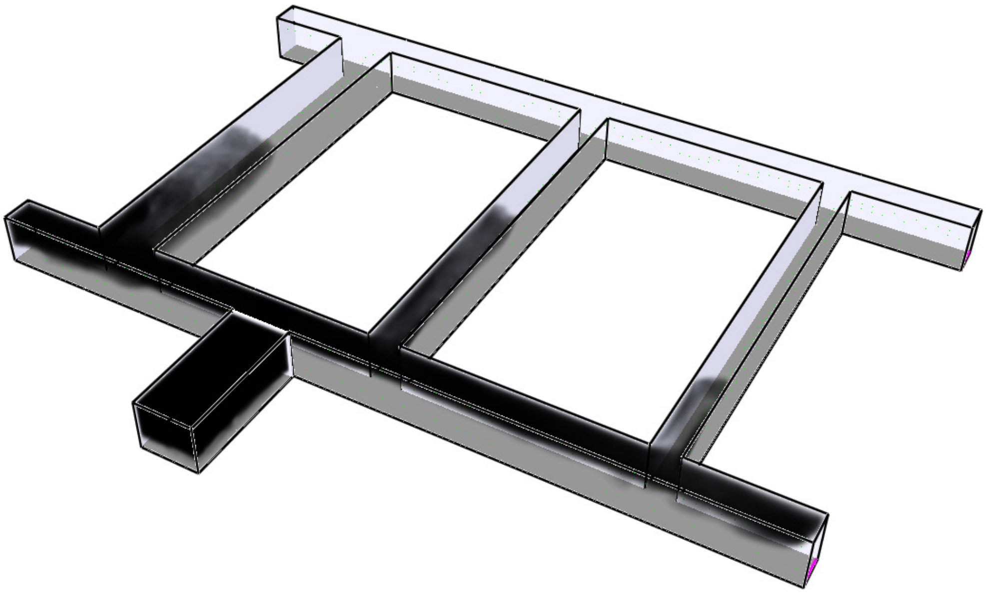

Figure 7-3: Snapshot from Smokeview (post-processor of FDS) illustrating the accommodation spaces corridors where the smoke propagation is predicted.

7.3 Fire Scenario in Accommodation Spaces

7.3.1 Description of the Design Fire Scenario

The fire scenario is mainly located in the accommodation spaces where fires even small ones can pose high threat on human lives. Fires in such spaces can be the reason of numerous events such as cigarettes, equipments failure or arsonist. In this case, the fire is assumed to be originated in a piece of furniture and considered unaffected by any fire fighting activities. The heat release rate is considered fast growing levelling at 1000 kW until the end of simulations (see section 3.4.3). The furniture is considered to be made of upholstered material and releasing toxic products such as carbon monoxide, carbon dioxide and soot (See Appendix C). Fire is started in a cabin having standard dimensions of 6.3 m by 2.7 m and 2.4 m height (see Figure 7-1 to Figure 7-3). The cabin is connected to the corridor via a 1 m wide and 2 m high door which is assumed to be fully open throughout the whole scenario. All the other doors are of self-closing type and considered closed during the entire simulation time. The staterooms are interrelated through two long corridors spanning the entire main vertical zone and shorter paths of 22 m length connecting the two corridors. Based on the analyses conducted in Section 6.3.3, all the corridors are treated in Raeume as a single compartment each and no partitioning is applied to these corridors (see Figure 7-2). The four exits used for escape are located at both ends of each of the two long corridors, which doors are also assumed of self-closing type. The decks including all floors and ceilings are made of 10 mm thick steel plates while all the bulkheads are made of thin steel plates and 25 mm of Rockwool insulation. The physical properties of Steel and Rockwool insulation are listed in Appendix C. The fire fighting system represented here by the sprinkler in the cabin is assumed inactivated to consider the worst case regarding fire fighting in a scenario. However, in case the sprinkler is to be considered activated this can be accounted for by modifying the heat release rate according to the correlation in equation (Eq 4-5). The interaction between sprinkler and smoke is not considered in zone fire models. The ventilation system does not interfere in driving the conditions of the fire scenario as the system is assumed shut upon fire detection and ventilation openings blocked by smoke dampers. Natural leakage in the domain is accounted for by "lumping" the leakage areas into two openings with estimated dimensions of 1 m wide and 0.3 m high at the end of each corridor.

The cabins are assumed at full berthing capacity with two people in each cabin apart from the fire room accommodating a total of 106 people in the fire scenario area. The evacuation procedure is assumed to start after accounting for the time spent for fire detection and passenger's response. The fire detection time is considered from fire ignition until the alarms sound. The evacuee's response time starts with the sound of alarms and includes issues such as cue perception provision and interpretation of instructions, individual reaction times, and performance of all other miscellaneous pre-evacuation activities [IMO, 2002b]. The response times assumed are stated and discussed of the scenarios in the numerical simulations below. The initial walking speed of the people is assigned a mean value of 1.1 m/s with a standard deviation of ±0.1 m/s. This walking speed value is an average value for different genders and different ages [IMO, 2002b]. However this speed is reduced by smoke obscuration according to equation (Eq 4-31).

7.3.2 Numerical Simulations

Fire simulations were run in both zone and field models, Raeume and FDS, respectively. The results were integrated to the evacuation model Helios along with all the evacuation information required. The number of evacuees affected by visibility, heat and smoke along with the time and location is predicted and visualized in Helios. Different indicators over the head of each evacuee show the level of impairment by heat, toxicity and visibility (See Figure 7-4). The cube stands for toxicity impairment, the sphere for heat and the cone for visibility, where the colours of indicators change from blue, green, yellow to red according to the ascendant FED of the person. In addition, the level of impairment (FED) due to different fire products effects are recorded for each evacuee as time history. FED is the measure of impairment experienced by the exposed person; see equation (Eq 4-11). An FED greater than zero means that the person considered is exposed and very mildly affected. While FED is still between 0.3 and 0.7 the injury can be considered as minor. For FEDs greater than 0.7 the injury gets more serious until reaching fatality when the FED attains unity. These estimations are made in order to illustrate the numerical values of the obtained FEDs as realistic hazardous situations to human life in a fire scenario.

First Fire Scenario

The cabins are at full berthing capacity as mentioned above. This is typical situation during night time where all passengers are sleeping. The response time for passengers in cabins at night time is normally distributed between 7 and 13 minutes as according to IMO regulations [IMO, 2002b]. The response time of passengers is assumed to begin after fire alarm sounds. The alarms sound upon fire detection which in a normal case takes around 1 to 3 minutes if the detection system works perfectly. In a first scenario, assuming the detection time is one minute therefore the evacuation process will take place between 8 and 14 minutes after fire ignition. With the above conditions for this scenario, both simulation models did not detect any injuries at all in the fire domain. All passengers had and FED greater than zero but less than 0.3 which means they were all exposed to some smoke on their escape route from cabins to exit doors but without reaching injury level. They all managed to evacuate the fire domain, without any minor injury, using the four available exits on the end of corridors illustrated in Figure 7-1.

Second Fire Scenario

In a second scenario, assuming the cabins at full berth and also the evacuation procedure takes place between 8 and 14 minutes. However this time the two exit doors on the right hand side of the domain are blocked (See Figure 7-1 and Figure 7-6). All passengers will then use the two exits on the left hand and especially the one which is further from fire room. Like in the previous scenario all people were exposed to smoke as their FEDs were greater than zero. However in this scenario both models predicted some minor injuries with FEDs higher than 0.3 but less than 0.7. Zone and field models, by predicting respectively 19 and 15 mildly injured evacuees, leaded to the same conclusion that the fire scenario did not show any serious hazard even with two blocked exits.

Third Fire Scenario

In this scenario, it is assumed that automatic fire detection in the cabin failed and fire was discovered when smoke was seen by passengers in the corridors, and then alarms were sounded manually. Thus a period of 10 minutes is considered between fire ignition and alarms. In addition, as all passengers were notified of the presence of an actual hazard, they are all assumed to respond in similar time. Therefore, the evacuation takes place between 17 and 19 minutes. These assumptions are aimed to push the evacuation process toward congestion as part of considering the worst scenarios.

The cabin fire, though not very intense, produced smoke that filled all the corridors in the scenario domain. The upholstery combustion produced dense smoke that impaired the visibility of almost all the passengers. Heat did not seriously affect the evacuees assuming that they are prevented to cross in front of the fire room door. Raeume results did not show any minor injuries from heat but FDS predicted 18 people with minor injuries from heat having FEDs greater than 0.3 but less than 0.7. These injuries were observed in areas of the corridor in close distance to the fire room. The field based model by simulating localised temperatures in different parts of the corridor enabled the prediction of minor hazards due to hotter gases close to fire room. Nonetheless zone models tend to predict one average temperature for the whole corridor and hence no minor injuries predicted.

Toxicity constituted the major treat for passengers. Although the combustion filled the domain with killing smoke, evacuees with close distance to the exits escaped the hazardous situation. The passengers who had to travel a longer distance to the exit doors were expected to be more affected and have minor injuries with FED>0.3 due to toxicity. Fire resulted conditions predicted by Raeume showed 46 people with minor injuries while FDS results predicted 41 minor injuries (See Figure 7-5). Noting that in the time history graphs of the affected evacuees, the lines presenting FEDs greater than zero are coloured in blue, FEDs greater than 0.3 in green, FEDs greater than 0.7 in yellow-orange and FEDs equal unity in red. The exact matching of the blue lines of (FED>0) for Raeume and FDS just implies that both models predicted that all the passengers present in the domain were exposed to smoke, which is very obvious. All passengers were severely affected by the poor visibility since soot concentration was high hence the light extinction coefficient (K_{ext}) was also high and consequently the walking speed was reduced according to equation (Eq 4-31). Most of the evacuees were slowed down by smoke obscuration to the minimum walking speed of 0.3m/s. The aforementioned can also be seen in Figure 7-4 where the indicators above the evacuees' heads show their situations. The blue sphere indicates that heat effects are insignificant at this stage, while the red cones reveal the severe impaired visibility for all the evacuees. Finally, the green cubes illustrate the toxicity effects which are mild in this situation.

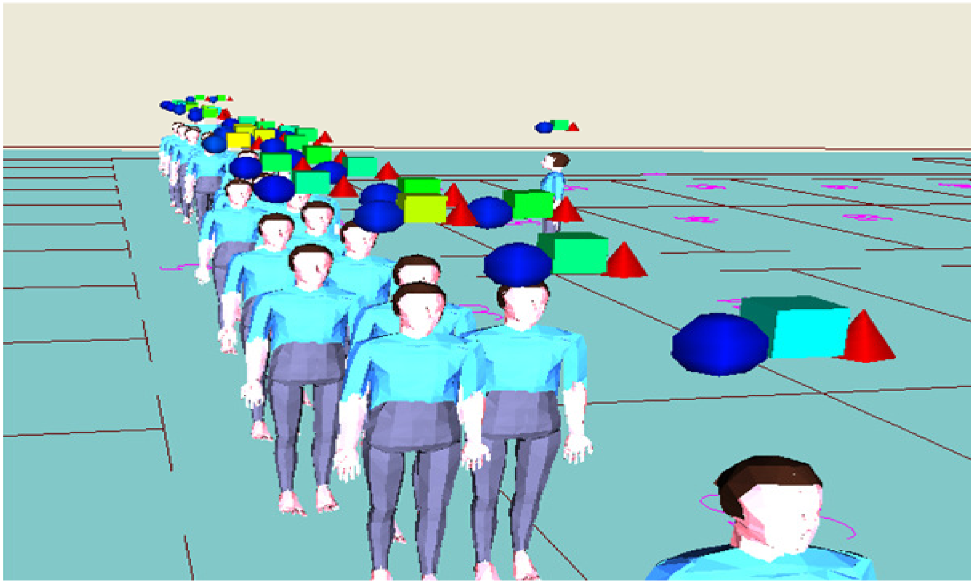

Figure 7-4: Snapshot from the evacuation model Helios showing the indicators over the head of each evacuee (sphere for heat, cube for toxicity and cone for visibility).

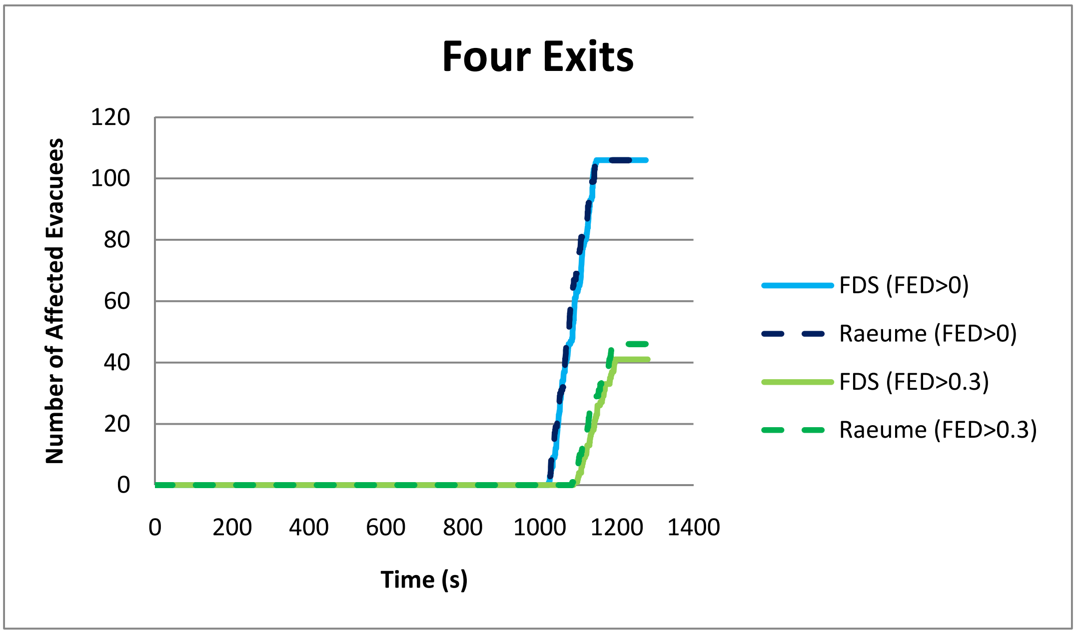

Figure 7-5: Time histories of the affected evacuees with different severities of toxicities assuming four exits are used for escape. Solid lines ___ represent the prediction of FDS results integrated with Helios. Broken lines _ _ _ represent the casualties predicted by the integration of Raeume results with Helios.

Fourth Fire Scenario

Now with the same response times as in the third fire scenario above, assuming the two exit doors on the right hand side of the domain are blocked (See Figure 7-1 and Figure 7-6). Thus, all passengers will be evacuating the area through the two exits on the left hand. In addition, the evacuees are not expected to cross in front of the door of the burning room. This will obviously result in a higher number of passengers escaping the fire domain through the door on the upper left corner. This change in the escape route in addition to the short interval during which evacuation took place (between 17 and 19 minutes) causes congestion on the mainly used exit door (See Figure 7-6). This is responsible to hold the evacuees longer in the fire domain, and hence expose them for a longer time to the hazardous fire resulted conditions. Similarly to the third scenario and for the same reasons stated above, Raeume results did not show any minor injuries due to heat while FDS results predicted 19 evacuees with minor injuries because of heat. These were passengers with close distance to the fire cabin. Toxicity was shown to have effects on most of the present people but with different severity levels. In the absence of hydrogen cyanide (HCN), carbon monoxide (CO) was found to be the main asphyxiant responsible of toxicity casualties, in addition to the depletion of oxygen (See equations Eq 4-14, Eq 4-18 and Eq 4-19). Carbon dioxide (CO_2) was acting as a stimulator of respiration rate as described in equation (Eq 4-16) but did not reach a high concentration to become an asphyxiant itself. Passengers evacuating the cabins located remote from the exits, particularly those who responded late to the alarms and were hold back by congestion, were exposed to the toxic smoke for longer time and hence reached incapacitation towards the end of the corridors (see Figure 7-7). Figure 7-8 illustrates the time histories for the evacuees affected by toxicity in different levels of fractional effective doses. The number of dead people, those whose FED reached unity, at the end of the evacuation process was predicted to be 12 by Raeume results and 9 by the results of FDS integrated with Helios. Evacuees with FEDs greater than 0.7 are considered at least seriously injured and are including the dead people with FED=1. The number of these seriously injured people was predicted as 31 by Raeume and 27 by FDS results consolidated with Helios. Finally, the passengers whose FEDs were greater than 0.3 are considered at least to have minor injuries. Raeume resulted in 75 people falling in this category while FDS estimated 73 people. The numbers computed by Raeume – Helios and FDS – Helios integrated models are in a good agreement as regarding toxicity effects predictions. On the other hand Raeume failed to detect the localised high temperature close to the fire room where FDS results showed that these might cause some minor injuries for people evacuating in close distance to the fire room. Noting that to overly compare zone and field model predictions, numerous sensitivity analyses should be conducted for different spaces, material properties, fire scenario conditions etc… however this is not the aim of this study. Therefore, the good coincidence regarding the agreement of field and zone model results are considered specific for this fire scenario and should not be generalised for all engineering applications.

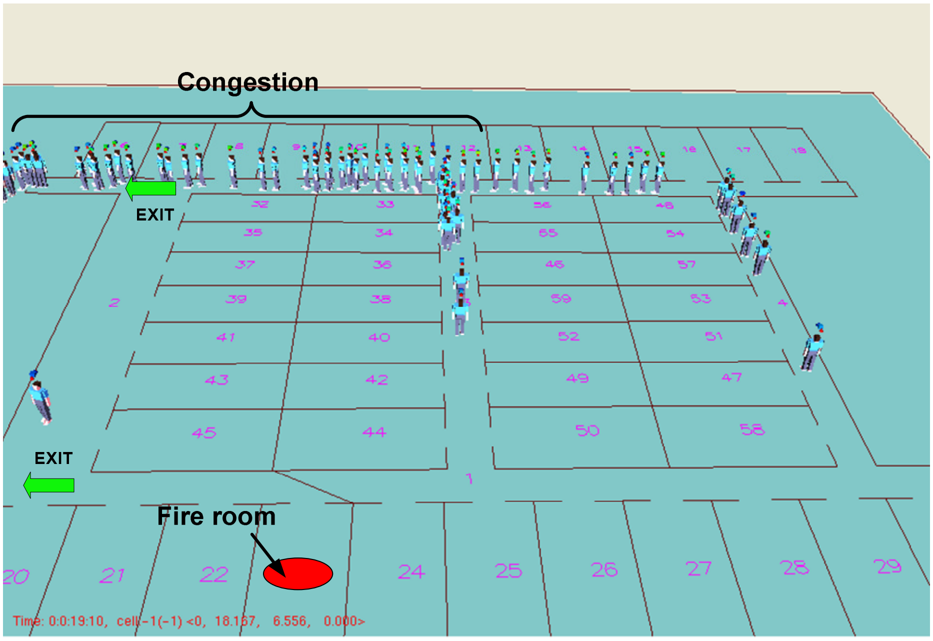

Figure 7-6: Snapshot from Helios showing the congestion occurring in the fire scenario with two blocked exits.

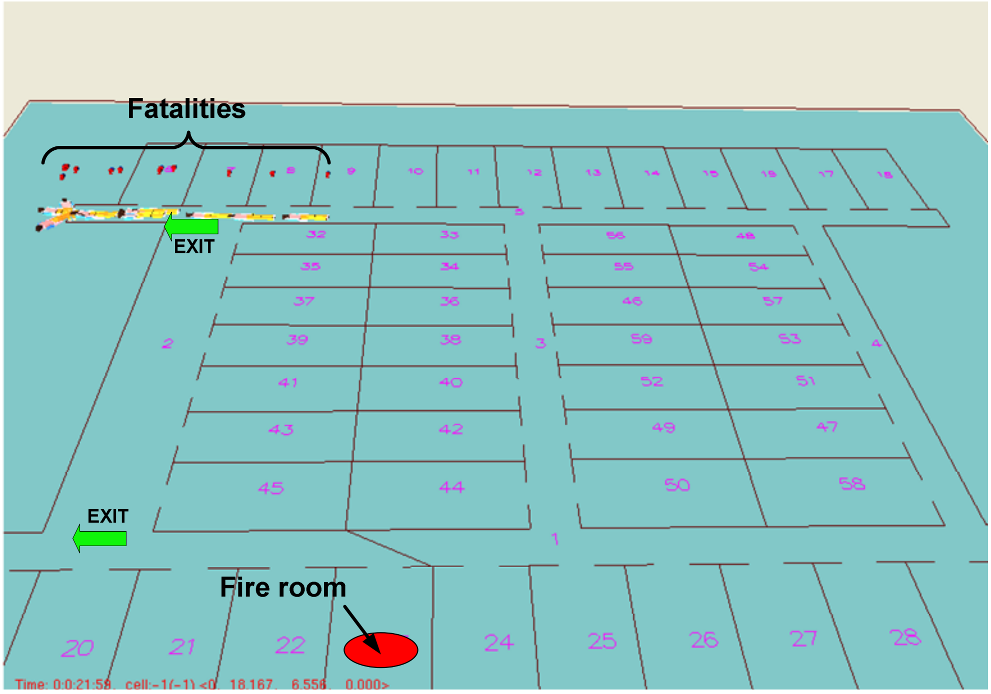

Figure 7-7: Snapshot from Helios showing the fatalities at the end of the corridor near the exit.

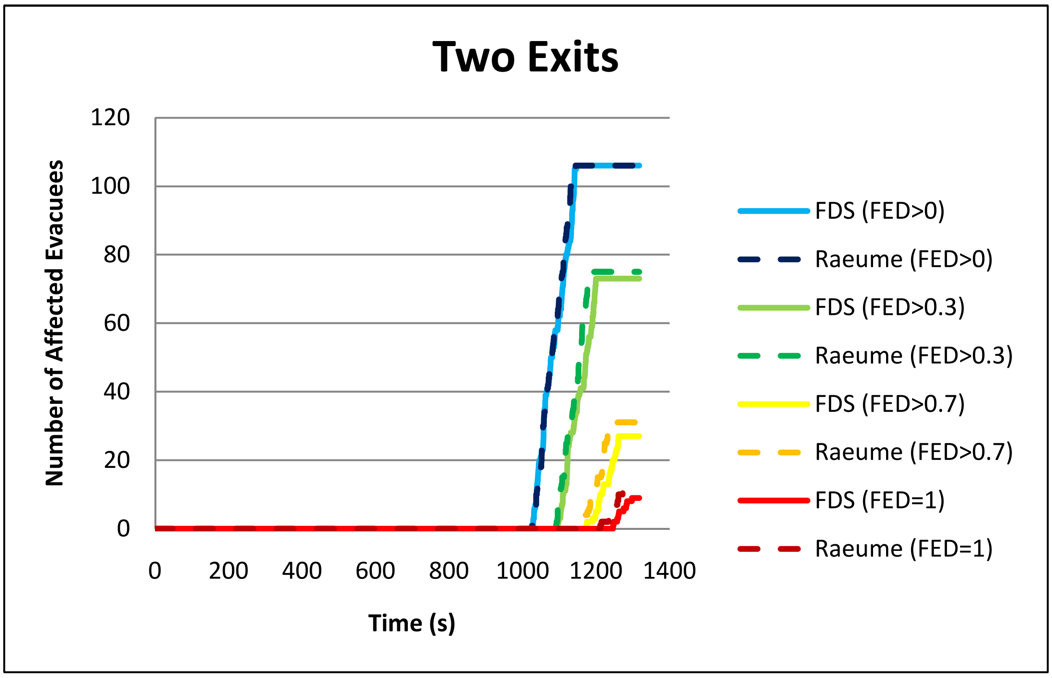

Figure 7-8: Time histories of the affected evacuees with different severities of toxicities assuming two exits are used for escape. Solid lines ___ represent the prediction of FDS results integrated with Helios. Broken lines _ _ _ represent the casualties predicted by the integration of Raeume results with Helios.

7.3.3 Effects of Subdividing Long Corridor into Virtual Compartments

In Section 6.3.3 above, the effects of dividing a corridor into smaller virtual compartments in the zone model Raeume was analysed and interpreted. It was shown that the significant differences between Raeume configurations with whole and partitioned corridors were in the temperature reduction while the gas concentrations were very slightly affected by the compartmentation. Also, the layer height predictions were somewhat influenced by the subdivision of the corridor. In this section the effects of corridor compartmentation are interpreted differently by comparing their influence on the final number of casualties in a fire scenario. For this purpose the corridors of the fire domain were subdivided into smaller compartments (See Figure 7-9). The long corridor adjacent to the burn room was divided into three parts of 7 m, 16 m and 14 m while the upper parallel corridor was divided into two parts of 18 m and 19 m. The three paths between the two long corridors were divided each into two parts of 8.5 m and 10.5 m. This subdivision is considered moderate where just the adjacent corridor with high velocity gradient was divided into three compartments and the rest of corridors were split into two compartments. The new configuration of Raeume with divided corridors was simulated and the resulted fire conditions were integrated to Helios in order to obtain the final number of affected evacuees. The final results as time histories of affected evacuees were compared to the previous results of FDS and those of Raeume with corridors treated as single compartments. Considering the evacuation takes place between 17 and 19 minutes after fire ignition. The comparisons of results for the fire scenarios with four and two open exit doors are presented in Figure 7-10 and Figure 7-11, respectively. The fire conditions predicted by Raeume with the configuration treating the corridors as subdivided compartments predicted a final number of casualties very close to the numbers previously predicted by FDS and Raeume with corridors as single compartments. First it should be mentioned that the compartmentation did not improve the refinement of temperature prediction and zone model did not predict any minor injuries due to heat as was done in FDS results. In the fire scenario with four exit doors, Raeume configuration with divided corridors predicted 37 people with

FED > 0.3 comparing to 41 people predicted by FDS and 46 by Raeume with whole corridors(See Figure 7-10). The fire scenario with two exit doors also showed results in good agreement between the two Raeume configurations and FDS. The number of evacuees with FEDs greater than 0.3 as predicted by Raeume with divided corridors was 68 comparing to 73 and 75 for FDS and Raeume with whole corridors, respectively. Evacuees with FEDs greater than 0.7 were 22 for Raeume with divided corridors, 27 for FDS and 31 for Raeume with whole corridors. Finally, the evacuees with FEDs equal unity, those who are considered dead, were predicted as 7 persons by Raeume with divided corridors, 9 by FDS and 12 by Raeume with whole corridors. Taking into account the randomness of time when different occupants start the evacuation procedure, initial speed and visibility target, the results of both models with different configurations are considered in a fair agreement between each other and with FDS. However, it can be noted that the results of Raeume with the divided corridors configuration always predicted the number of casualties slightly lower than the one predicted by FDS results. In contrary, the configuration of Raeume with undivided corridors tended to predict a slightly higher number of casualties than FDS. Thus, FDS predictions were sandwiched between the two different Raeume configurations. This should not be taken as a general rule though it was the case for this scenario. The comparisons implies that both configurations compare fairly to FDS results however it was clear that the compartmentation of corridors did not add any benefit to the accuracy of final results predictions. On the other hand, the slightly higher predictions of Raeume with the corridors treated as single compartments can be considered more conservative than the divided corridor configuration. It is therefore acceptable in this case to keep the corridors as single compartments when the zone model Raeume is used to predict smoke propagation in a fire domain for human life safety purposes as done in this study. This should be done, bearing in mind that in some other applications the subdivision of corridors may have different effects to improve or worsen the required results, hence the necessity of testing the sensitivity of each application to the compartmentation of corridors. However, for the human life safety assessment applied in such accommodation spaces, it was made clear in this section that the final consequences did not show big differences between the two different configurations of Raeume.

When the corridors were treated as a single compartment each, Raeume was capable of producing results in good agreement with the results of the field model FDS.

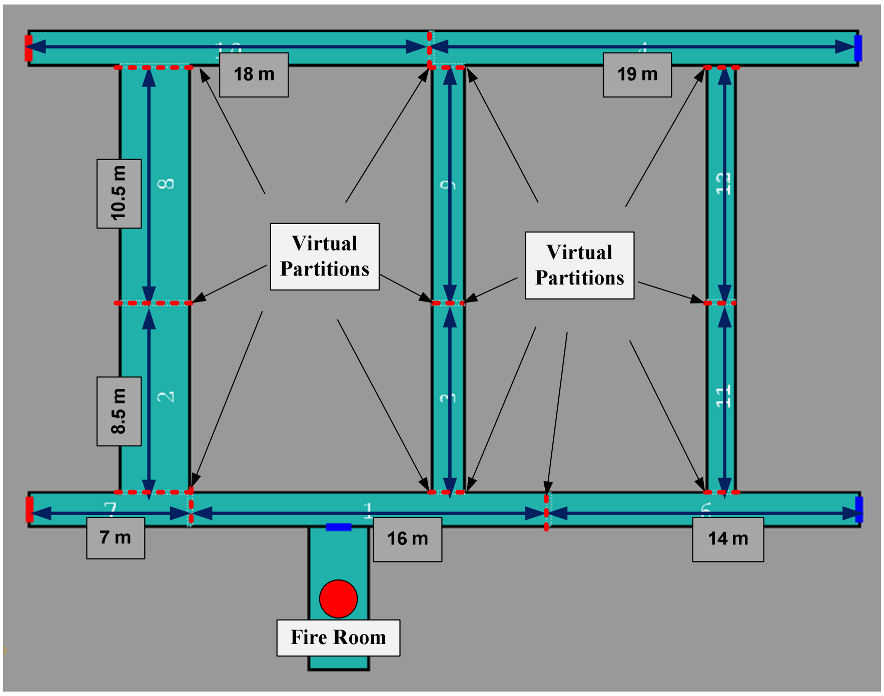

Figure 7-9: Snapshot from RamEditor showing the subdivision of the corridors.

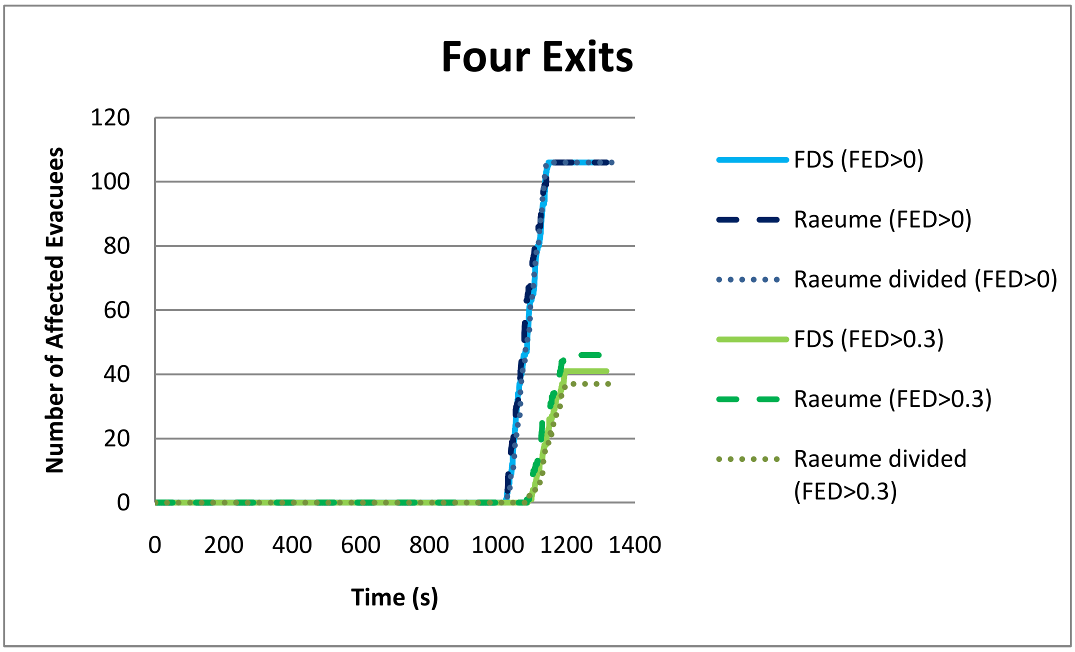

Figure 7-10: Comparison of the affected evacuees time histories assuming two exits are used for escape. Solid lines ___ represent the prediction of FDS results integrated with Helios. Broken lines _ _ _ represent the casualties predicted by the integration of Raeume results with Helios. Dotted lines …… represent the results of Raeume when the long corridors are divided into smaller compartments.

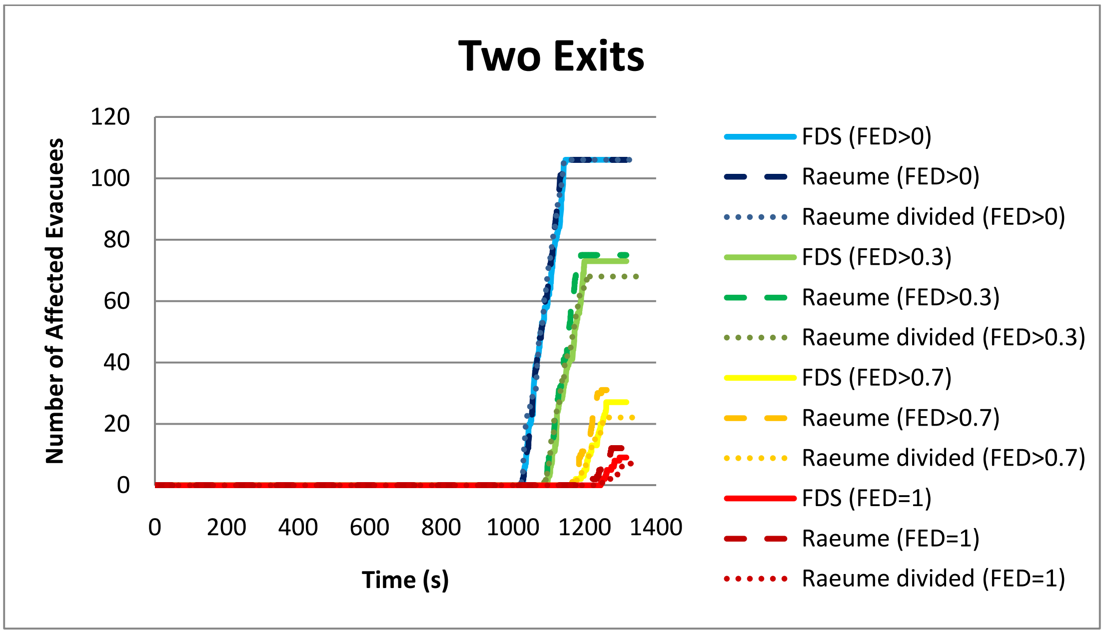

Figure 7-11: Comparison of the affected evacuees time histories assuming four exits are used for escape. Solid lines ___ represent the prediction of FDS results integrated with Helios. Broken lines _ _ _ represent the casualties predicted by the integration of Raeume results with Helios. Dotted lines …… represent the results of Raeume when the long corridors are divided into smaller compartments.

7.4 Concluding Remarks

In this chapter the use of the collection of integrated computer programs was demonstrated by simulating different fire scenarios. The fire resulted conditions in the domain were predicted by the zone model and transferred to the evacuation model to evaluate their effects on human life. The same procedure was also done for the field model FDS for comparison purposes. The hazards are quantified in form of casualties affected by different fire effects like toxicity, heat and visibility in order to assess the fire safety performance of the required scenarios. The effects of dividing the corridors in zone model simulations on the prediction of final consequences (fatalities and injuries) were also analysed in this chapter and it was found acceptable to keep the corridors as single compartments for the case applied here.

By identifying the potential hazards and measuring them in the early stages of a design, shipboard fire safety adopts a proactive approach that quantifies hazards before they occur. Unlike the reactive safety approach that tends to improve ship safety as a reaction to a disaster and by learning from the resulting growing experience. Numerous fire scenarios can be simulated for a novel design in order to identify the possible hazards associated with this design. Further analysis can be conducted for the identified critical hazards to provide possible solutions or amendments to the design. This all can be done in the early stages of the design to judge its safety performance which illustrates the benefit of using such simulation tools. The following chapter will present a design case study that makes use the simulation tool and illustrate the usability of the whole fire safety assessment approach in ship design.

8 Design Case Studies

8.1 Introductory Remarks

The aim of this chapter is to demonstrate the use of the computer software-suite in a fire safety assessment approach for novel ship design challenging SOLAS rules. In Chapter 7 the work procedure of the suite was illustrated and results of zone and field models were compared. In this chapter the tool is used from the design perspective as part of the whole assessment approach. An unusual modified design violating safety regulations is compared to another design complying with the existing rules. The fire scenario is located in the accommodation spaces where fire incidents have high life loss potential. For this comparison exercise conducted through the chapter the zone based model was used for fast predictions of fire conditions in the extended zone. The outcomes of the simulated scenarios are analysed and interpreted to indentify the positive and negative consequences of modifying the existing design. Some methods to improve the safety of the new design are implemented and analysed in the final part of this chapter.

8.2 Case Description

Shipboard fires have the potential to escalate and engulf large parts of the ship. Many large fires, reported to have broken out on different parts onboard ships, required enormous efforts to bring under control. However, surprisingly, very few or no injuries were associated to these fire incidents. On the other hand, much smaller fires brought under control in short time were reported to take many lives due to the fast toxic smoke spread (See Chapter 5). These fatal cases were mostly encountered in spaces connected through small paths and corridors like accommodation spaces where toxic smoke has rapidly reached all the areas in the domain and exposed all the occupants to a hazardous situation. Therefore the scenarios considered in this section are assumed to take place in the accommodation spaces, where a fire is originated in a cabin which door is considered open. In the absence of barriers, the smoke is assumed to spread all the corridors in the domain until reaching closed doors or dead ends.

SOLAS regulations state that the hull as well the superstructure of a ship should be divided into Main Vertical Zones by fire resistant bulkheads. The regulations also restrict the length and width of a MVZ to have a maximum of 48 meters provided that the total area of the zone on any deck is not greater than 1600 m^2 [SOLAS, 2004]. The size of a MVZ according to regulations was a subject of many discussions whether the length and area of the fire zone should be increased or not [ANSYS, 2007]. This issue is considered in this chapter of the research as a design case study. For this purpose, a general existing design with the dimensions complying with SOLAS regulations is extended to accommodate a higher number of passengers (See Figure 8-1). The original design has a length of 37 meters containing 54 cabins and can accommodate 106 passengers. The extended design has an added length of 17 meters which results in a total zone length of 54 meters which violates the restriction of 48 meters. The accommodation spaces are increased by 33 cabins to accommodate a total number of 172 passengers. In addition, the extended design presents a fire zone with an area of approximately 1900 m^2 which also breaks the 1600 m^2 rule of SOLAS. Extending the MVZ can be beneficial for designers and owners in different ways according to their interests. This can be to accommodate a higher number of passengers or to hold a fancy large public space of a novel design without partitions crossing the space. A larger MVZ can help in avoiding penetrations of ducts and pipes through the bounding bulkheads which can be costly complicated. It also helps in using the same units (like for ventilation or fire fighting) to cover large areas where the rules require different units to be allocated to separate fire zones. For the above reasons, it was found worthy to consider the case of a MVZ extended beyond the restricted dimensions for the comparison procedure conducted in this case study. The physical and numerical descriptions of the fire scenarios are illustrated in the following sections.

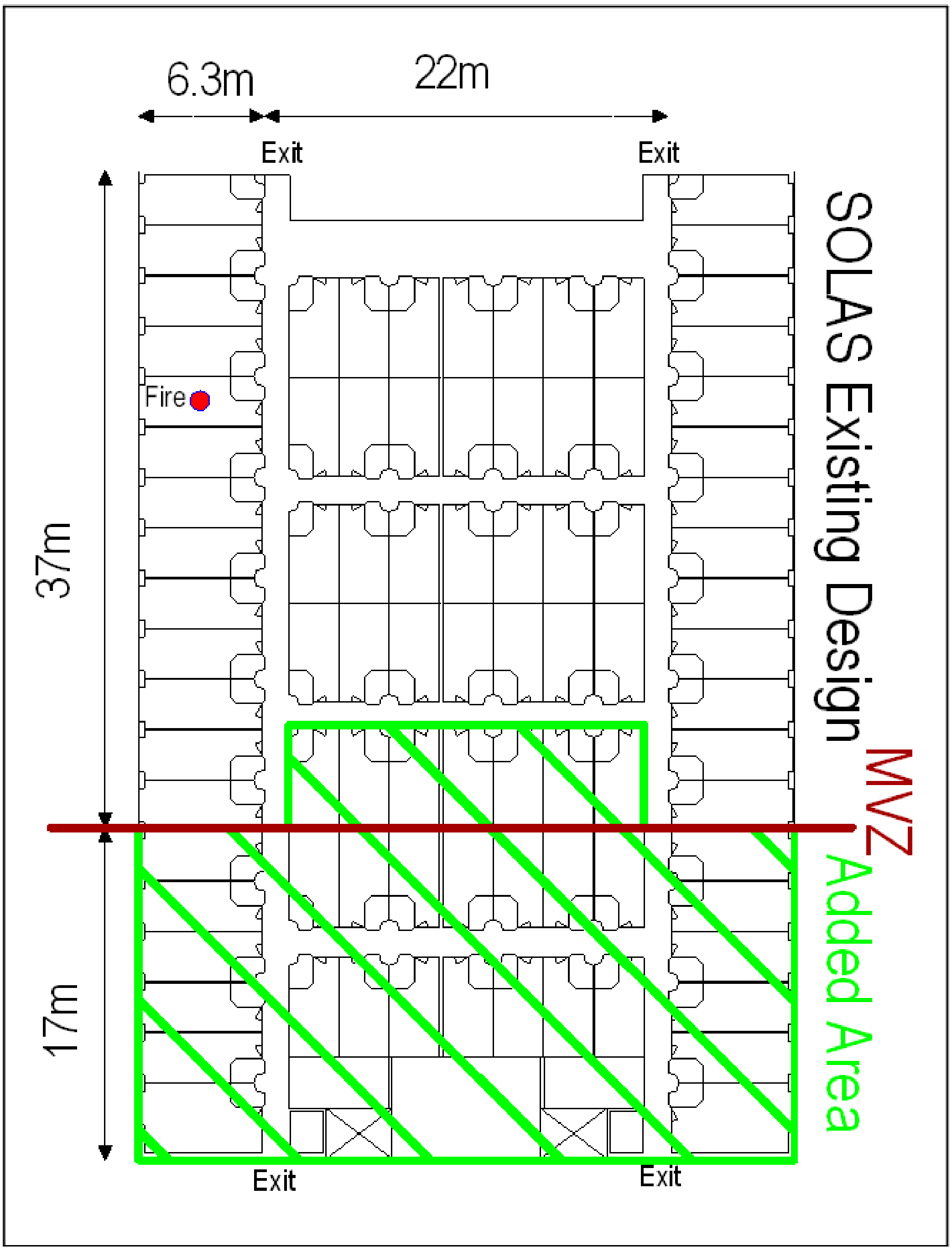

Figure 8-1: General Arrangements of the existing design complying with SOLAS and the additional area violating the rule restricting the size of a MVZ.

8.3 Design Fire Scenarios

Two identical fire scenarios are simulated and compared in this section. The differences between the two scenarios are the dimensions of the main vertical zone which outlines the fire scenario domain. The fire scenarios are mainly located in the accommodation spaces where fires even small ones can pose high threat on human lives. Fires in such spaces can be the reason of numerous events such as cigarettes, equipments failure or arsonist. In this case, the fire is assumed to be originated in a piece of furniture and considered unaffected by any fire fighting action. The heat release rate is considered fast growing (Figure 3-11) levelling at 1500 kW until the end of the simulations. The furniture is considered to be made of upholstered material and releasing products such as carbon monoxide, carbon dioxide and soot. This design fire is considered a good test of smoke effectiveness in threatening passengers' safety where fire escalation out of the cabin is not considered the major threat. Structure failure is not impossible in case of fire flashover to involve all contents of the cabin where very high temperatures can be reached. However due to the difficulties mentioned in Chapter 6, fire escalation and combustion of furniture and boundaries are not considered in this study. The main hazard considered here is that due to smoke propagation and its toxic effects on evacuees. Thus for this case based oriented to address mainly the fact that smoke is the main killer of evacuee in an accommodation fire, the moderate upholstery fire employed here is considered suitable.

Fire in each of the considered scenarios is started in the same cabin having standard dimensions of 6.3 by 2.7 m and 2.4 m height (See Figure 8-1). The cabin is connected to the corridor via a 1 m wide and 2 m high door which is assumed to be fully open throughout the whole scenario. All the other doors are of self-closing type and considered closed during all the simulation time. The cabins are interrelated through two long corridors spanning the entire main vertical zone and shorter paths of 22 m length each connecting the two corridors as shown in Figure 8-1. The two long corridors measure 37 m in SOLAS complying case while in the new design they are extended up to 54 m. The four exits used for escape are located at both ends of the two long corridors, which doors are also assumed of self-closing type. The decks including floor and ceiling are made of 10 mm thick steel plates while all the bulkheads are made of thin steel plates and 25 mm of Rockwool insulation. The fire fighting system represented here by the sprinkler in the cabin is assumed inactivated to consider the worst case regarding fire fighting in a scenario. However, in case the sprinkler is to be considered activated this can be accounted for by modifying the heat release rate according to the correlation in equation (Eq 4-5). The ventilation system does not interfere in driving the conditions of the fire scenario as the system is assumed shut upon fire detection and ventilation openings blocked by smoke dampers. Natural leakage in the domain on doors level, ventilation units and other openings are accounted for by "lumping" the leakage areas into two openings of 1 m wide and 0.3 m high at the end of each corridor.

The cabins are assumed at full berthing capacity with two people in each cabin apart from the fire room accommodating a total of 106 people in the SOLAS complying design and 172 passengers in the extended design. To account for fire detection time and passengers' response time, the evacuees are considered to start moving from their cabins toward the assembly point between 17 and 19 minutes after fire ignition, assuming that the fire scenario takes place during night.

8.4 Numerical Simulations

Fire effects are simulated by the zone model *Raeume* then integrated with the evacuation model *Helios* to predict the effects of evacuees' exposure to these fire effects. In both scenarios, smoke produced by the cabin fire filled all the corridors in the domain in a short time far before the passengers started the evacuation procedure. Most of the evacuees in both designs were exposed to smoke and the majority were at least very mildly affected. Levels of impairment due to different fire effects are recorded for each evacuee. All passengers were severely affected by poor visibility whilst the influence of heat on all the evacuees was considered negligible, provided that the passengers are prevented from crossing in front of the fire room door.

Toxicity was shown to have effects on most of the passengers present in the fire domain but with different severities. As shown in Figure 8-2 both fire scenarios, SOLAS complying design and the extended alternative design, resulted in approximately similar number of fatalities with FED = 1 (16 deaths for SOLAS and 14 for the extended design). The number of evacuees who were at least seriously affected with FED > 0.7 was found somewhat different for the two scenarios where 42 injuries were reported in SOLAS scenario and 61 in the extended MVZ scenario. Passengers who were at least mildly affected with FED > 0.3 were found more frequent in the extended MVZ scenario (132 passengers) comparing to 86 passengers in SOLAS scenario. This can be referred to the fact that the number of vulnerable persons present in the extended alternative design scenario is 172 which is much higher than the 106 passengers accommodated by SOLAS design. In both scenarios, the entire area of the fire domain was filled with smoke and hence all the occupants were exposed to the hazardous conditions. The difference in injury severities of evacuees is mainly the result of the walking distance these passengers had to travel between their cabins and the closest exit door. The total incapacitation of evacuees occurred at the end of the corridors near the exit doors. The long slow walk obscured by smoke from the far located cabins to the exit doors in addition to further slowing down due to congestion, all resulted in a longer exposure to smoke effects and hence death. In Figure 8-3 depicted the location of fatalities in both SOLAS and extended designs. Both fire scenarios show that all death cases occurred at the end of the corridors just at a short distance from the exit doors.

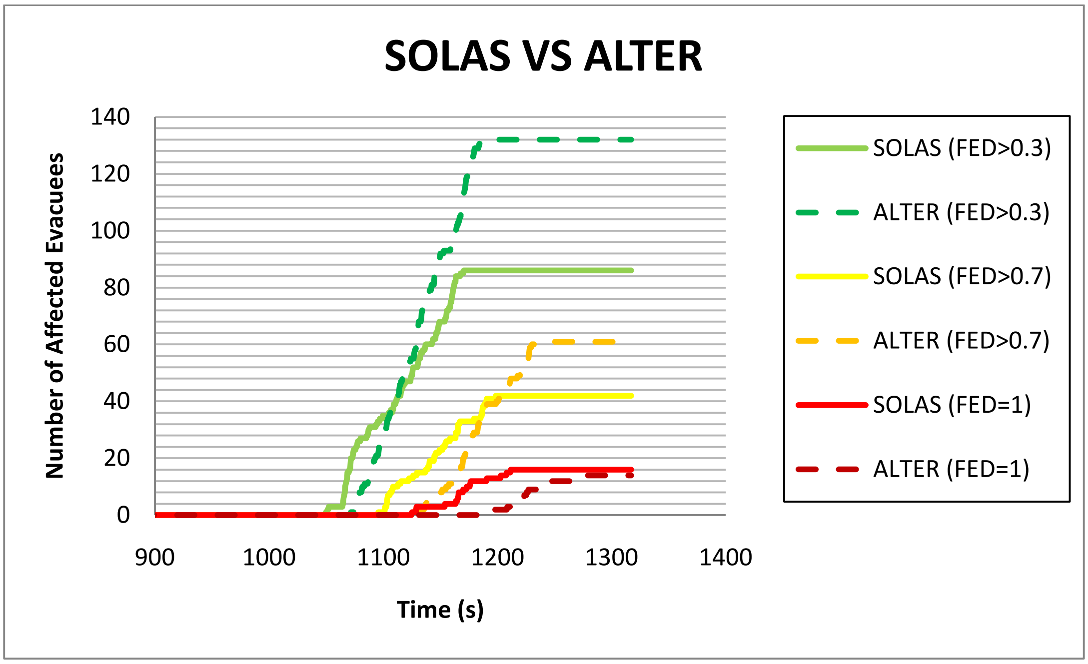

Figure 8-2: Time histories of the affected evacuees with different severities of toxicities. Solid lines ___ represent the casualties of SOLAS complying design while broken lines _ _ _ represent the extended alternative design.

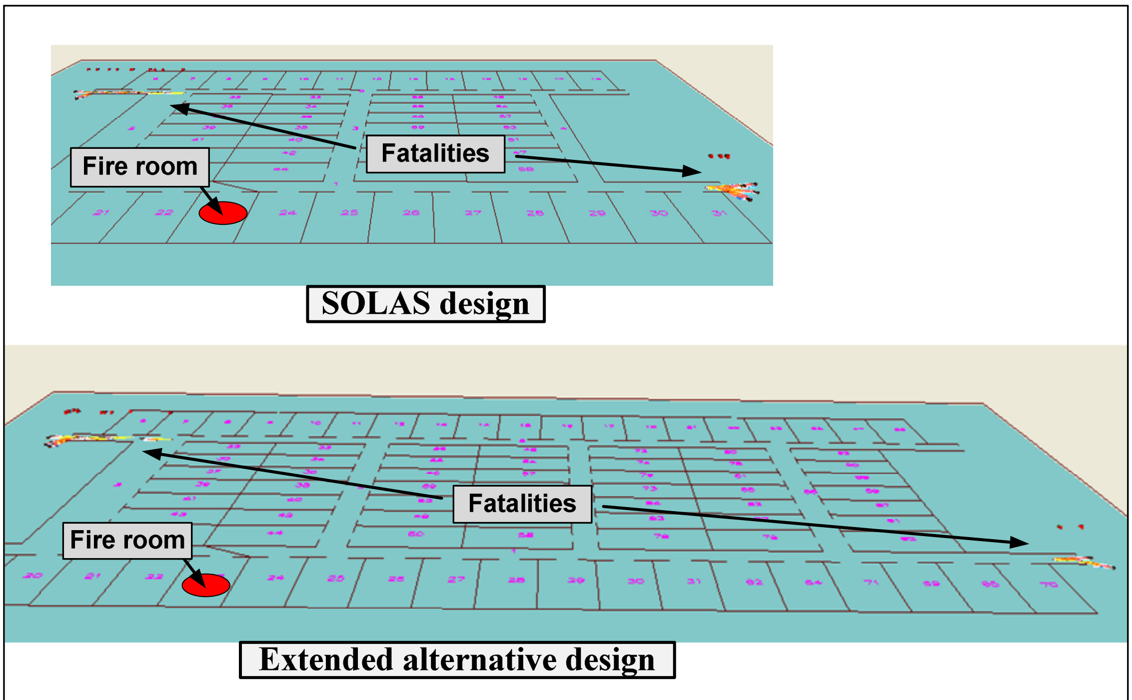

Figure 8-3: Layouts of the SOLAS and the extended alternative designs showing the locations of fatalities in both fire scenarios.

Considering the percentage instead of the absolute number of passengers affected in each scenario, the figures were found closer tending to be slightly higher for SOLAS design. Figure 8-4 shows that SOLAS complying design resulted in 81% of passengers at least mildly affected, 39% at least seriously affected and 15% dead. Note that the 81% mildly affected passengers with FED > 0.3 include the 39% of evacuees with FED > 0.7 and the 15% dead with FED = 1. On the other hand, the extended design fire at least mildly affected 76% of the passengers, at least seriously affected 35% and killed 8% of the total number of evacuees.

The results were presented in two forms of time histories; as number of casualties and percentages depicted in Figure 8-2 and Figure 8-4, respectively. The former illustrates the severity of consequences in each scenario while the later form shows the severity with respect to the present passengers. It was clearly observed that the higher the number of passengers exposed to the smoke the more affected and injured persons are expected. As the extended design could accommodate a higher number of passengers, more people were mildly and seriously affected. On the other hand, the number of people who were considered totally incapacitated or dead was similar for both designs. This can be referred to the tendency of having more severe conditions in a fire scenario with a smaller domain than a larger volume domain. The same toxic fire products filling a small and large volume implies higher toxic gases concentrations in the smaller volume and hence worse conditions. At the same time, it can be argued that the larger fire domain can supply fire with a bigger quantity of oxygen whilst the smaller design limits the supply of oxygen to fire and hence smothers it at an earlier time than the larger domain. Therefore, the main clear drawback of the extended domain in case of fire incident is that the affected area is larger. A larger area affected by smoke implies a higher number of exposed passengers and a longer escape route affected by smoke.

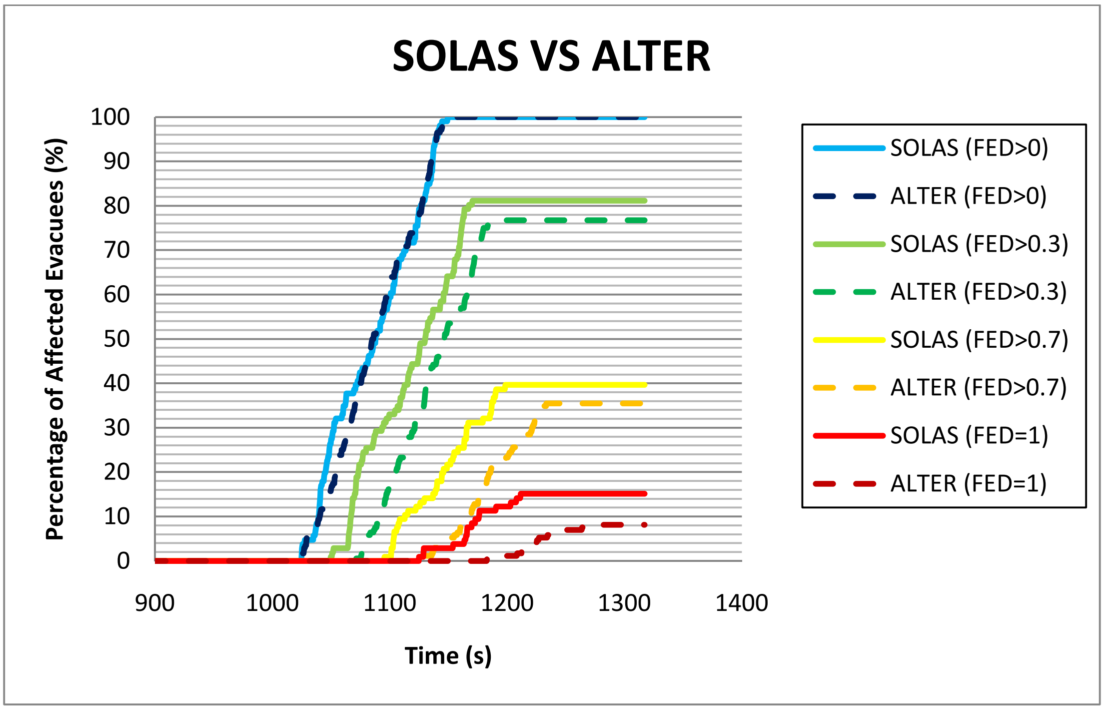

Figure 8-4: Time histories of the percentages of affected evacuees with different severities of toxicities. Solid lines ___ represent the casualties of SOLAS complying design while broken lines _ _ _ represent the extended alternative design.

8.5 Smoke Control

The comparison of the two fire scenarios in both fire designs and data analysis indicated that the lower the number of passengers exposed the lower are the affected people and hence, the resulted casualties. In each of the simulated scenarios, all the passengers present in the domain were exposed to the effects of smoke which filled all the corridors of the fire zone in the first few minutes of the scenario. The more people are present in the domain the more are exposed to smoke and hence, affected and injured. Smoke was found to quickly propagate in the corridors and spread over the whole domain in the absence of any barriers that can stop smoke propagation. The boundaries of the Main Vertical Zone are very important to stop fire escalation however, for smoke propagation those boundaries are apparently less useful as a large number of passengers are already present inside the fire zone boundaries and will obviously be exposed to smoke effects. The main purpose of a MVZ is to divide the vessel into separate parts where in case of a fire incident the escalation would not exceed a single fire zone in order to avoid the loss of the whole ship and provide a safe refuge area for the passengers onboard. For this reason, the boundaries of a fire zone are required to be of high fire integrity of A-60 class (See Appendix C) [SOLAS, 2004]. Nevertheless, smoke can easily propagate through the whole fire zone and expose the passengers present in the zone to hazardous conditions. Smoke propagation issue is crucial as smoke was found to be the only killer in the accommodation spaces scenarios simulated above. This is also consistent with previous fire accidents reports where toxic smoke was the most probable and effective killer in such accommodation spaces fires (See Chapter 5). Consequently, as the spread of toxic smoke which is the main killer is not directly addressed by the size of MVZ, different controlling methods can be sought. The high fire integrity required for the boundaries of fire zone is not essential for smoke barriers. The same way employed to keep the smoke outside the cabins and staircases by self-closing fire doors can be utilised to contain the smoke in small areas of the fire zone. Thus, an effective way to control smoke propagation through corridors is the compartmentation of these corridors into smaller parts by using self-closing fire doors. This can contain the lethal smoke in a smaller portion of the corridor and hence reduce the number of exposed passengers. However, the corridor compartmentation may imply that the conditions will be even more hazardous in the smoke filled part of the corridor as gases concentrations would be higher in the smaller volume. But at the same time, the escape route distance travelled by an evacuee while exposed to smoke effects would be much shorter in this case as smoke is contained in a small part of the corridor. The self-closing doors used for compartmentation can be widened up to the width of the corridors to avoid additional congestions during evacuation.

To manifest the above discussion and interpret the consequences of the proposed smoke control method, a compartmentation by fire doors was implemented on both designs, SOLAS complying and extended Main Vertical Zone. As shown in Figure 8-5, a self-closing door was employed in every vertical corridor to divide it into two parts. The horizontal corridors were divided by fire doors into two parts for SOLAS design and three parts for the extended design. Considering the fire scenarios above with the fire originated in the same cabin aforementioned, the simulations were conducted using the assessment suite to predict the consequences resulted in both fire scenarios. Clearly, in both designs, smoke was contained in the small portion of the corridor adjacent to the fire room and hence affected just this part of the domain (See Figure 8-5). Smoke propagation was stopped by the fire doors and was prevented from spreading to other parts of the corridors in the domain. The passengers who were affected by smoke were those occupants of the cabins connected to the corridor portion affected by smoke. The numerical simulation using the assessment suite produced similar results for both SOLAS and the extended alternative design. In both cases, all evacuees apart from the ten passengers occupying the cabins connected to the smoke affected area managed to accomplish a smooth evacuation without being exposed to any hazardous conditions. The ten passengers who had to pass through the smoke affected area were obviously exposed to smoke effects hence they all had FEDs greater than zero. Six of the exposed passengers suffered mild injuries with FED > 0.3. Two out of the ten evacuees were considered to have serious injuries with FED > 0.7. Although the smoke effects were considered hazardous in this part of the escape route used by the evacuees, the distance was considered short and therefore the exposure time was short as well. As a result, no casualties were recorded even though two of the evacuees were seriously injured. By containing the hazardous smoke, the number of people exposed to smoke effects became independent of the passengers present in the whole fire zone. In addition, the walking distance required to escape the hazardous conditions was shortened. Therefore, the hazard of smoke spread associated with an extended MVZ is reduced and the fire safety performance is improved. At this point, when the corridors are divided by fire doors, the extended design presented an equivalent performance to SOLAS design in the case of a cabin fire and evacuation of a fire zone. However, it should be clearly mentioned that the equivalency achieved between the SOLAS and novel design performances is totally dependent on the design fire scenario considered. This means, that the concerned hazard in this study was toxic smoke as this was identified the main killer in previous accommodation fire accidents and hence the fire scenario conditions were build on this basis. Other hazards, like fire escalation out of the origin space and fire damage to ship integrity can lead to disastrous consequences such as total loss of the ship.

Each of these specific hazards can have a range of scenarios to be simulated in order to prove the total equivalency between two designs. The case study conducted here was aimed to demonstrate the assessment approach rather than to prove equivalency and was based on the fact observed in previous accidents that toxic smoke is main killer in accommodation spaces.

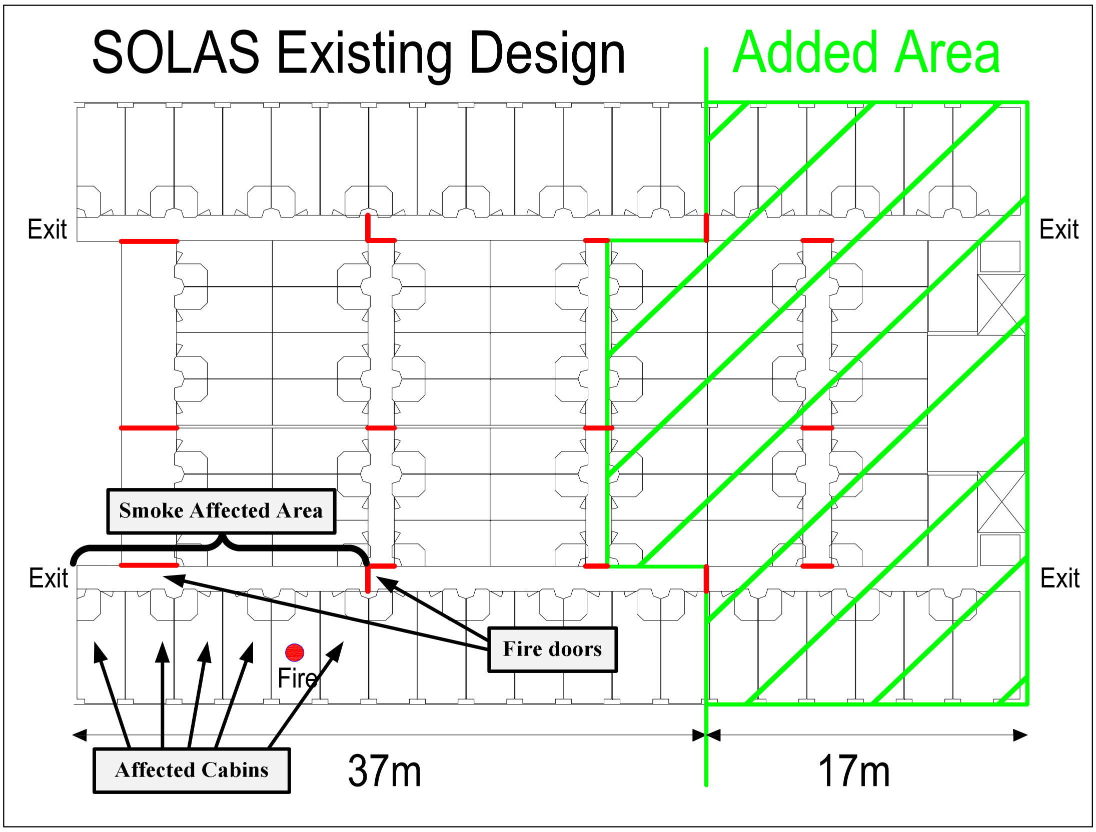

Figure 8-5: The compartmentation of SOLAS and extended design by self-closing doors for smoke controlling purpose. Compartmentation doors are indicated as red lines.

8.6 Discussion

It was clearly seen in the simulated fire scenarios that smoke was the main killer of evacuees in the accommodation spaces. The results of the numerical simulations showed that the uncontrolled smoke spread rapidly to fill all the corridors of the fire zone. Even though the smoke was not deadly hot, the gases were toxic and effective in causing serious injuries and death. The hot gases propagate in the long narrow corridors making the conditions untenable for passengers trapped in, or slowly evacuating the area. Sooty smoke obscures visibility and hinders evacuation by slowing down the walking speed. The longer an evacuee is exposed to toxic gases the higher the FED gets until it reaches unity when the person is considered dead. It can be deduced that the main hazards in the prolongation of a main vertical zone was that a higher number of passengers were exposed to the effects of the uncontained smoke which spread in the entire zone. In addition, the evacuees were required to walk a long distance to reach the exits and consequently exposed for a long time to the effects of lethal smoke.

The practice of dividing the long corridors into compartments by using self-closing fire doors can provide a useful mean to control smoke. It is certain that further analysis of the size of compartments and doors locations would be essential in order to achieve an effective smoke containment solution. However, at this stage it can be said that the compartmentation of corridors appears to be a successful method to control smoke propagation. This technique is considered a passive smoke control system in contrast to other active control systems like smoke extraction devices. The latter systems can be very efficient if well installed and operated. However, the reliability of such multi-component systems was always a subject of dispute due to the technology used to operate them. Quantification of the reliability of an extraction system is not an easy or even a possible task as the data about reliability of the components used is insufficient [Andersson and Daniel, 2002]. Self-closing doors can contain smoke propagation without facing serious reliability problems like active smoke control systems such as extraction devices. In addition, these latter automated devices are not very well developed and not extensively used onboard ships because of their complicated functioning procedure; where such control systems, if poorly designed, installed or used can present a hazard rather than a benefit. Not to mention, the experience and skills required to operate those automated smoke extraction systems where mistakes can just make the situation worse in case of a fire incident onboard. For instance, failure to detect correctly the exact location of fire and smoke initiation may unintentionally spread the smoke to undesirable places like the staterooms. Therefore, the operation of active smoke control systems such as extraction arrangements should be performed with great caution by skilled personnel.

Undoubtedly active control systems can provide a very efficient solution to address smoke effects in case of fire incidents, however as discussed above this is just after further development in reliability, installation and operation skills. For the present time, the division of corridors with self-closing fire doors is a relatively reliable smoke control solution comparing to automated devices and do not require any specific skills in installation neither in operation onboard. The compartmentation considered as passive smoke control system will not eliminate or prevent the hazard as other active smoke control devices would if they operate as supposed. But the fire doors will contain and minimize the consequences resulting from smoke propagation. Beside the passive control system provided by compartmentation other simple passive and active control systems should be in operation to assist the smoke control procedure. For instance, in case of a fire incident, the ventilation system existing in the accommodation area should be shut down and all openings closed by fire dampers in order to prevent smoke spread in the domain through ventilation ducts. This can be activated either by heat and smoke detection devices or manually, whichever occurs first. In addition, staircase should remain pressurised where the higher air pressure inside prevents smoke from propagating from the corridors toward the staircase and exit routes. These arrangements cover a wide range of flaws associated with smoke hazard but not all what can be possibly faced from a designer perspective.

With all the above being said about the proposed smoke control strategy as compared to other means of smoke control, it was clear that the application was bounded in a single fire zone. The focus on one zone was obvious as the main challenge to SOLAS was the extension of a main zone beyond the restricted length to accommodate novel design ideas. An extended zone does not imply to lessen the whole ship structural subdivision as this is mainly targeting the issue of total ship loss and consider other aspects such as damages stability and loss of propulsion. However this extension gives the flexibility for designers to utilise a larger zone where required in a condition that safety performance is maintained considering all aspects including but not limited to smoke toxicity. As in this demonstrative case study the main hazard in a zone extension regarding toxic smoke was recognized as long exposure of many people to toxic conditions for long time, a compartmentation smoke solution was employed. The self-closing doors are specific for narrow corridors connecting staterooms while in other spaces different control options are sought such as smoke curtains for atriums or large restaurants. The above case assumed that smoke is always contained in the zone due to pressurised staircases however in a different scenario the smoke may be assumed to extend to another and hence this should be included in the simulation domain. Different systems employed and different spaces implies that the performance assessment is required for the range of different scenarios resulted. Therefore when safety performance of the whole ship is in question, all proposed systems should be tested simultaneously and all shipboard spaces should be considered.

Finally, the results of this case study can be incorporated in the whole risk-based design approach by providing a risk index to different areas onboard ships. The risk index can be the product of probability (or frequency) index and consequence (or severity) index. For a certain space with different possible fire scenarios, the risk can be written as follows:

$$Risk = \sum_{i} (Probability)_i \times (Consequence)_i \qquad \textbf{Eq 8-1}$$

This is the summation of all probable fire scenarios where for each scenario (i) there are specific indices for probability of occurrence and quantified consequence.

The calculation of these indices is fully quantitative based on numerical values rather than qualitative based on judgement. The frequency index can be quantified from numerical values derived from previous detailed statistics of fire incidents onboard ships. However, the data collected about fire incidents should be extensive to provide details that allow the generation of frequencies for all the probable scenarios. For example, the scenario assumed in the study case was an extreme scenario with failure in fire suppression and smoke containment. Had values for the frequencies specific scenarios are readily available, the frequency of this scenario should be very low although accommodation fires are expected to be hazardous due to the dense population in those areas. Fortunately, the majority of shipboard fire incidents do not escalate and do not have severe consequences, why the severity indices were more based on judgment rather than numeral values. Hence, the use of computer simulations to predict the virtual consequences whether these incidents escalate and result in casualties. There are still challenges residing in the conversion of quantified fire consequences in terms of casualties (injuries and fatalities) into robust and consistent numerical values for the severity indices. Where in this study only human safety is examined, in general fire safety assessments the damage to property should also be quantified and included in the severity index calculations. However, structure failure and damage to properties are beyond the objectives of this study.

8.7 Concluding Remarks

In this chapter, the issue of increasing the size of a MVZ for an accommodation space was investigated from the fire safety point of view. Two fire scenarios, a SOLAS complying design and an extended alternative design, were simulated using the assessment suite and the outcomes were analysed. It was found that the higher the number of passengers exposed to toxic smoke the more affected and injured persons are expected. Also, the extension of a fire zone exposes evacuees to smoke effects for a longer time as they are escaping from the cabins toward exit doors.

As smoke propagation was deemed as the main hazard in an accommodation fire incident, the size restriction of a MVZ was found unable to contain the hazard of smoke spread. An approach to divide the corridors into parts by self-closing doors was implemented and tested. The numerical simulations showed that both SOLAS and alternative designs, if partitioned by fire doors, provided equivalent safety performances in the case of a cabin fire. Smoke was contained in a small portion of the corridor and hence the number of exposed evacuees was minimised and the escape route shortened. Finally it should be noted that there is no doubt that further studies and analyses would be required to achieve a higher effectiveness of the compartmentation method for smoke containment in accommodation spaces.

9 Discussion

9.1 Introductory Remarks

The research work presented in this thesis attempted to address the issues related to fire safety onboard passenger ships. The principal hypothesis of the research has been that the deficiencies in the reactive ship design approach based on prescriptive fire safety rules have resulted in the increasing interest in the proactive performance-based design. This interest was shown through the introduction of a new SOLAS regulation namely Reg. 17 in Chapter II/2 on the alternative design and arrangements, in addition to the rising calls to adopting the new design for safety concept based on the performance of the design. The evaluation of fire safety performance of a design requires the utilisation of a collection of engineering tools and methods. The working procedure of the computer-simulated tools collection has been laid down and its applicability to the area of interest has been demonstrated. An example of a novel design in form of a case study has been included to demonstrate the use of the proposed fire safety assessment approach.

This chapter presents the major results achieved in the research work undertaken in this thesis. This includes the contributions made to the field considered, difficulties encountered while achieving the aim of the thesis and finally the recommendations for further research.

9.2 Contributions to the Field

The research undertaken in this thesis provides a new perspective of the importance of the topic of fire safety onboard passenger ships. The research work mainly focuses on issues deriving from the need for a fire safety assessment approach of practical use for the new performance-based design concept. By defining the problems encountered in shipboard fire safety and by offering an integrated platform of computer simulated programs and an approach to evaluate the fire safety performance of a given design, this thesis was made a new contribution to the field of shipboard fire safety in particular and safety of life at sea in general.

Quantification of the consequences resulting from a fire event in a given scenario is considered the core of the new approach based on design performance. Therefore, the simulation tools used in the quantification methodology are of sound importance in order to predict reliable outcomes. The two main categories of simulation tools used are fire and evacuation models. As for fire models, the thesis tested and assessed the applicability of these programs in the field in question, particularly the accommodation spaces onboard passenger ships. The advantages and limitations were discussed and the factors considered in the selection of the suitable models for the study were mentioned. Where experiments were available, fire models were compared against these experimental data, otherwise comparisons were conducted between the two types of fire programs, zone and field models. In addition, a novel manner of comparison was carried out by consolidating each of the field and zone fire models with the evacuation model used in the thesis and compare the final outcomes resulting of each in from of injuries and fatalities. The final consequences in terms of life loss were the estimated realistic illustration of the numerical results obtained from the fire effects quantification methods. Considerable efforts were made to review discuss and define the proper set of quantification methods for human exposure to fire effects to be utilised in this research work. A novel correlation based on two different sets of experimental data was used to assess visibility impairment.

Finally, by providing a case study addressing real issues onboard passenger ships pertaining to ship design development and regulation requirements, the thesis demonstrates the applicability and utility of the proposed fire safety assessment approach.

9.3 Encountered Difficulties

This research work was aimed to be a boost for the “Design for Safety” philosophy from the fire safety point of view. Since the new design philosophy was initiated, numerous difficulties were encountered as the new concept is based on the design performance and the associated risk quantification rather than just complying with rules. Hence, the transition from the reactive approach based on the application of prescriptive rules to the proactive performance-based approach implied various challenges in all aspects of shipboard safety. This thesis was specifically aimed to meet the challenges associated to fire safety onboard including issues related to the design performance assessment algorithm, its application and the simulation tools.

Regarding the assessment of a design performance, the lack of well defined and validated acceptance criteria imposes the utilisation of a comparative approach to assess the performance of a given design. In this approach, the alternative design has to be proven at least equivalent to the prescriptive rules compliant design.

On the subject of simulation tools, the challenges encountered were numerous. To start with, the fact that fire experiments onboard ships are of very high costs made the availability of such experimental data very limited. Hence, the benchmarking against experiment measurements was just conducted for the simple available cases and comparison between models was carried out for the other cases. Defining the input data for the simulation programs was also considered challenging. As for general purpose CFD model, care should be taken in choosing the correct sub-models and parameters in order to set up the problem correctly (Chapter 4). As well, for the purpose of a proper problem set-up, sensitivity studies for different input parameters and numerical grids were conducted and found very time consuming regarding input data generation and computational efforts (Chapter 6). On the other hand, issues like lack of well defined data for materials available onboard such as fire characteristics (such as heat of combustion and fuel composition etc…) and physical properties of bounding material (such as density, thermal conductivity, heat capacity and emissivity etc…) left no choice but the adoption of simple and commonly known material properties throughout the thesis. The properties of these materials were adopted from fire engineering society references such as [SFPE, 2002], [NFPA, 2003], and data of [Jones and et al., 2005]. Challenges were also posed by the comparison methods adopted for the reason that different models predict different types of data which need to be manipulated in order to allow proper comparison (Chapter 6). Additionally, to allow fair comparison between models some of the input parameters were simplified and used through the thesis where for instance fire was predefined as heat release rate in function of time-squared rather than modelling the combustion of fuel. As for the equations used in the quantification of human exposure to fire effects, the information available was also very limited. These formulas were the results of some experiments done on rodents and monkeys for heat and toxicity effects, and on humans for visibility impairment. The available data was used without any attempt to conduct any comparison between correlations from different sources (Chapter 4).

As regards the identification of the most risky spaces onboard, the data collected in this thesis was not sufficient to determine the frequency of occurrence of fire incidents, thus information from different studies was used. As for the severity assessment, judgements were made to support the information provided by the data collected (Chapter 5). Therefore, the information regarding development of the design fire scenarios used for case studies was also limited. Knowing that development of these design fire scenarios is of great importance in the performance-based design approach, information from the shipboard fire incidents data supported by judgments and knowledge from previously performed fire simulations were collected and used in the development of the design fire scenarios.

Finally, it should be mentioned that due to time limitations, the design fire scenarios generated were not very various and numerous but standardised in a manner to represent the worse resulting consequences of a given scenario. As well, the design case studies accomplished were kept limited but covering the space category that was identified to be of high fire risks.

9.4 Recommendations for Future Research

As the subject of performance-based fire safety is considered novel in the ship design field, this research work is considered boosting but certainly not sufficient to be claimed as a complete and well established performance assessment approach. Many further actions can and should be taken in order to make the whole approach more robust and widely applied for different areas onboard. These recommendations for future research work involve among others:

- Detailed and extensive use of the historical data of fire incidents in a manner that provides reliable information on the frequency of occurrence and severity of consequences for all shipboard space categories.

- Development of a well established and validated set of acceptance criteria to be used for the evaluation of safety performance of novel designs.

- Conducting more fire experiments specific to the marine sector and involving issues such as burning of materials used onboard in various ventilating conditions, and smoke propagation through long narrow corridors.

- Accounting for the cases with structure failure (e.g. bulkheads) due to heat in the simulations via modelling the combustion of all flammable materials in the domain or through the integration of numerical methods that can account for these failures.

- Closer examination of the applicability of fire models used in the developed tool on different spaces onboard ship.

- Improvement of zone model performance in typical ship geometries possibly by developing specific correlations that account for the imperfections of zone model concept in shipboard geometries.

- Development and enhancement of the existing idea of hybrid fire modelling approach, combining the rapid simulations of zone models where suitable and the accuracy of CFD computations where needed, in order to provide quick and accurate fire condition predictions for all shipboard geometries.

- Improvement of the evacuation models to involve realistic passenger behaviour in an evacuation procedure based on experimental studies.

- Further development of the equations used in the quantification of human exposure to fire effects. For this purpose, more experimental data are required in this field especially on human visibility impairment.

- Generation of a well documented library of material properties for the items available onboard, in order to be used in the design fire scenario creation.

- Performing more various design case studies including different space categories and scenario condition configurations in order to better assess the performance of a design and provide severity indices. This also includes further investigation of the proposed smoke control method in the accommodation area.

- Integration of fire safety assessment tool and other devices for different safety aspects assessment onboard to provide a complete platform of simulation programs capable of assessing the safety performance of the whole ship.

9.5 Concluding Remarks

This chapter discussed the major findings of the research work undertaken in this thesis and including the main contributions to the field in question, the difficulties encountered throughout the thesis and finally the recommendations for further future research.

Even though the difficulties encountered were numerous due to the novelty of this research subject in the marine sector, however it is hoped that this thesis contributed significantly to the marine fire safety field in particular and life safety at sea in general. In addition, as the research topic is not mature enough, lots of further research and developments can be carried out in this field to add more values to the current research. Finally, it can be said that this thesis work can be considered as an important step in the achievement of a holistic approach in ship safety based on risk quantification and evaluation of a design performance rather complying with prescriptive rules.

10 Conclusions

The main conclusions drawn from the research work undertaken in this thesis are summarised and presented in chapter as follows:

- Experience-based prescriptive regulations governing fire safety were proven incapable to protect all aspects of the ship, particularly passenger ships where rules development is unable to keep up with the pace of design evolution and innovations. Consequently, calls were rising to shift from the reactive safety ship design approach triggered by disasters to a proactive performance-based approach where risk is quantified and evaluated in order to be reduced.

- The collection and analysis of shipboard fire incidents assisted in identifying the accommodation areas among the most hazardous spaces onboard passenger ships. The fire incidents data also facilitated the generation of possible fire scenarios evolving in these accommodation spaces.

- In consideration of the above, this thesis focused on firstly providing an approach to quantify the fire safety performance of a design in terms of life loss and secondly on demonstrating the applicability and usability of the proposed approach on shipboard spaces identified as most hazardous. This is the implementation of performance based philosophy and theories into real life applications. The implementation procedure involves all the reviews, research, integration, validation and improvements in order to reach the target.

- A critical review of the relevant fire programs, their main concepts and sub-models, in addition to a benchmarking exercise against existing experimental data helped in selecting the most suitable models for this study, namely Raeume for zone model and FDS for field model. On the other hand, Helios was used for simulation of the evacuation procedure. The effects of human exposure to fire effluents broken into three categories (heat, toxicity and visibility) were extensively discussed. Fractional Effective Dose concept from the literature was used for heat and toxicity. Particularly, visibility impairment was considered by reduction of walking speed according to smoke concentration based on experimental data.

- The application of fire codes (Raeume and FDS) to typical fire scenarios in accommodation areas onboard passenger ships revealed the functionality and limitations of these models. Both models predicted reasonable fire resulted conditions comparing to the experimental tests of a fire in a cabin. In absence of experiments, the results of both models were in a good agreement for an atrium fire. As regards smoke propagation in corridors, the virtual compartmentation of a long corridor in zone model did not show significant improvements to a single compartment corridor by comparing the results to field model predictions.

- The assessment tool, in form of consolidated fire and evacuation models with the associated fire effects quantification methods, was implemented in an accommodation area fire scenario to demonstrate the simulation tool work procedure and analyse its applicability. Fire models (Raeume and FDS) were integrated to the evacuation model (Helios) each in a time to compare the final outcomes in form of fatalities and injuries. Good agreement was shown between the compared models. Additionally, the compartmentation of long corridors did not show any improvements for zone model results as compared to the field model ones.

- With all the above at hand, an illustrative design case study of a Main Vertical Zone, extended in length and deviating from regulations, was undertaken to attest the usability of the proposed assessment approach in quantifying fire safety performance and evaluating it by comparison to other designs complying with regulations. As the design violating rules showed worse consequence than the prescriptive design, a smoke control method to contain smoke and hence hazardous condition was proposed and examined.

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Appendix A

Shipboard Fire Incidents

This Appendix cites the fire incidents collected from different safety and transportation boards supported by other sources for the purpose of hazard identification. The incidents are listed in the chronological order. For each incident, the name and type of vessel reported are stated in addition to a briefing of the available details on the fire event.

1934 – *SS Morro Castle* cruise ship disaster killed 137 people. The fire started in a storage locker within the first class writing room. The locker contained more than 100 blankets that had been cleaned commercially with a flammable substance. The highly polished panelling in the writing room, corridors, salon, stairways and other passenger accommodations favoured the rapid spread of fire. Smoke has been forced throughout the accommodations by the ventilation system which had not been shut down. *SS Morro Castle* was well equipped with fire extinguishers, long hose lines, more than sufficient lifeboats and life preservers. The cargo holds had a smoke detection and a fixed fire extinguishing system was installed in the engine room and cargo holds. Fire doors were installed every 40 meters in addition to such doors in the public spaces. However, the disaster happened as most of the above features were rendered ineffective by alteration to the equipment and lack of proper training. [Brady] [Cowley, 2006]

1942 – *SS Normandie* passenger and cargo vessel caught fire because of hot work of welding and cutting on shipboard. The presence of tons of kapok onboard made the fire spread rapidly and resulted in capsizing of the ship. [Brady]

1949 – *SS Noronic* passenger ship caught fire at the Pier of Toronto Harbour. Smoke was noticed by a passenger to be coming from a closed linen closet. When the closet was opened, the fire expanded immediately in the hallway and spread quickly fuelled by the oil-polished wood panelling on the walls. The fire escalated rapidly onboard of the ship resulting in 118 deaths. [CBC-Archives]

1954 – *SS Empire Windrush* engine room fire resulted in loss of lives and burn of the ship. This accident inspired the dispersal of fire pump controls. [Vassalos, 1999]

1962 – *MV Rio Jachal* is a cargo and passenger ship. Fire was detected in an unoccupied stateroom. Attempts to fight the fire using fire extinguishers and hose lines failed due to the growing intensity of fire. Fire propagated through passageways and stairways fuelled by the combustible plywood panels and wood studding covering the whole interior of the ship. However, due to the crew and professional efficient work, the fire was confined to the mid-ship section of the vessel. [Brady]

1963 – *SS Lakonia* cruise ship fire started initially in a hairdressing salon then spread into the hallway toward the staterooms disregarding the stewards' attempts to fight the flames using portable fire extinguishers. Most of the passengers have been rescued on lifeboats. However, 95 passengers and 33 crewmen lost their lives in this marine incident. [Brady]

1965 – *SS Yarmouth Castle* is a cruise ship whose fire originated in a storage room containing mattresses, chairs, panelling and other combustible materials considered as high fire loading for a small place. The fire alarms were not sounded at all. The flames spread through the stairwells fuelled by the wooden panelling and decks covered by oily paints. While most of the people onboard were rescued by two other ships, 87 others went down with the capsizing ship. [Brady] [Cowley, 2006]

1966 – The passenger vessel *SS Hanseatic* was docked when she caught fire that was originated in the engine room due to fuel leakage. The fire extended up an intake ventilator through seven decks before it could be brought under control by the city fire department. [Brady]

1967 – Onboard of *SS San Jose* a fire ignited in the vessel's boiler room resulted in power loss and forced the occupants to abandon the ship. No deaths or serious injuries were reported. [Brady]

1990 – Onboard of the ferry *Scandinavian Star* two fires has been reported ignited by an arsonist at the accommodation area. While the first fire was put out by the crew, the second one escalated quickly filling the corridors in different decks with toxic smoke. Failure in closing the fire doors allowed the fire to spread along the length of the ship. The highly combustible laminate fed the fire and made the smoke more severe and poisonous. Shutting the ventilation system down has resulted in lowering the high pressure in cabins and forced the smoke into the rooms. The ship generally was not fitted with either an automatic fire detection system or an automatic fire fighting system and the crew was poorly trained to handle the situation. The result was 158 death, 156 were passengers and two crew members. [SINTEF, 1990] [Fire.org]

1994 – The fire aboard the ro-ro passenger ship *Sally Star* was caused by the failure of a bolted flange joint on the low pressure fuel system of a main engine which allowed the fuel vapour to come into contact with a part of the engine exhaust system. The first attempts to extinguish the fire were unsuccessful due to failure of the auxiliary generators and the emergency fire pump. However, the fire was controlled within three hours by closing the fuel system and engine room ventilation. [MAIB]

1994 – *Al-Qamar Al-Saudi A-misri* ferry caught a fire because of an explosion in the engine room. Most of the passengers (around 505) and 63 crew members abandoned the ship. However the ferry sank causing the death of 21 people. [Divemagazine]

1994 – The cruise ship *Achille Lauro* caught a fire which rapidly went out of control. Almost 1000 people abandoned the ship, however, two persons died and 8 were seriously injured. The ship continued to burn for two days and then sank. [BBC-news]

1996 – The passenger ship *Universe Explorer* caught a fire in the main laundry. The lack of fast fire detection alarm and sprinklers allowed the spread of toxic smoke through the open doors into the crew berthing area resulting in the death of five crewmembers. [NTSB]

1997 – *Vistafjord* is a passenger ship who suffered a fire started in a store room in the crew area. The cause of ignition was thought to be a deliberate burning of combustibles. The room was protected by a fixed CO_2 fire fighting system which was very useful to help fire team bringing the fire under control. One crew member was reported dead due to smoke inhalation. [NTSB]

1998 – Onboard the passenger ship *Edinburgh Castle* a fire broke out on a fat fryer in the main galley. Fire damage was very limited and no injuries were reported. [MAIB]

1998 – The *Pride of Le Havre* (passenger/ro-ro cargo vessel) fire was caused due to a mistake by the electrical-technical officer in the engine room. The fire was brought under control by the fire parties within few minutes. However, the injuries of some crew members were serious. [MAIB]

1998 – *Ecstasy* is a passenger ship who suffered a fire in its laundry because of lint accumulation in ventilation ducts. The fire spread in the ventilation system causing the loss of propulsion power and steering system. The fire was brought under control after huge efforts and one serious injury due to smoke inhalation was reported with no fatalities recorded. [NTSB]

1999 – The *Pride of Le Havre* was sailing for engine trials when fire in the engine room was detected. When the first extinguishing attempts failed, the Halon total flooding extinguishing system was used successfully to put the fire out. [MAIB]

1999 – *Spirit of Tasmania II* (former *MS Superfast III*) is a fast RoPax ferry who was on route from Patras to Ancona when a fire broke out in a freezer trailer on the vehicle deck. The fire was controlled by the drench system and crew efforts. The evacuees were picked by nearby ships, however, during the investigations on the next day of the event 14 dead bodies were found in a truck. [SSRC, 2006b] [Cargolaw]

1999 – The Chinese ferry *Dashun* carrying more than 300 people onboard caught a fire on her lower vehicle deck. The fire was not controlled and developed rapidly and the weather was reported as strong wind and high sea. The result of this was that the ship capsized and over 280 lives were lost. [MAIB]

2000 – Onboard the passenger ship *Nieuw Amsterdam*, a fire broke out in a crew cabin. The fire was extinguished, however, the smoke spread to other decks of the ship resulting in an injured passenger by toxic gases inhalation. No fatalities were reported. [NTSB]

2000 – A fire broke out in the main switchboard in the engine room onboard the ferry *Columbia*. The fire was extinguished successfully by the fire fighting team with no injuries or deaths recorded. [NTSB]

2001 – *Stena Explorer* is a high-speed catamaran who suffered an engine fire caused by leaking oil from a compression fitting ignited on the hot exhaust system. The water hi-fog fire fighting system was activated in the area but the fire was later totally put off by the fire brigade. The evacuation was safe and efficient. [MAIB]

2001 – The fire onboard the ro-ro passenger ferry *Spirit of Tasmania* broke out in the photography shop due to electrical failure in a short circuit supplying power to a fridge. The fire was extinguished in five minutes and no casualties were reported. The mustering was generally effective and successful. [ATSB]

2001 – *MS Cinderella* (cruise ferry) was in its Helsinki port when a fire was discovered in a storeroom of tax-free goods. The fire was caused by molten steel drop resulted from flame-cutting in the vertical bulkhead of the ship. The fire spread was limited and the extinguishing procedure was successful. [AIBF]

2001 – The passenger vessel *Seastreak New York*, suffered a fire in her engine room due to lube oil in contact with the hot exhaust manifold. The fire was extinguished by the fixed CO_2 suppression system. The incident had no fatalities. [NTSB]

2002 – Aboard *MS Cinderella*, a fire broke out in the night club in an unidentified location. Although the fire escalated, it was possible to bring it under control within half an hour. No injuries were reported and the evacuation procedure of passengers in the night club and the cabins below and above the club went smoothly and successfully. [AIBF]

2002 – Onboard the ro-ro ferry *Norsea*, a fire was detected in the aft engine room. The fire was caused by fuel leaking from the low pressure fuel system which came into contact with the exhaust system of the engines. The engine room was closed and carbon dioxide was injected to control the fire. The propulsion power was lost as a result of the fire incident. [MAIB]

2003 – A fire was originated on the lower vehicle deck of the ro-ro passenger ferry *Joseph and Clara*. The water spraying system was activated and the ferry continued on its way. Upon arrival to the port the passengers were evacuated and the fire was declared under control in two hours then extinguished in one and a half hours. [TSB]

2003 – Onboard of the ro-ro passenger ship *Queen of Surrey* a fire started in the engine room. The fire was a result of fuel oil sprayed from the pressure gauge pipe onto the engine exhaust manifold. The engine room was evacuated and sealed then carbon dioxide gas was released into it. Despite the system failure and escape of gases, the fire was extinguished and no fatalities were reported. [TSB]

2003 – The passenger vessel *Columbia* had a fire in her engine room. The probable cause was referred to a failure in the generator's wiring insulation. The fire was easily brought under control by portable extinguishers and no injuries were reported. [NTSB]

2006 – *Al-Salam Boccaccio 98*, a ro-ro ferry capsized after suffering a fire onboard taking with her more than one thousand innocent lives. The fire possible origin was referred to the engine room. The fire extinguishing operations resulted in water accumulation on the car deck. The water excess free surface effects forced the ship to list sharply and capsize quickly taking with her more than one thousand innocent lives. [BBC-news] [IMO, 2008]

2006 – *Star Princess* is a passenger cruise ship who suffered a fire started on an external stateroom balcony. The probable cause was reported as a discarded cigarette end which heated the combustible materials on balcony. The fire rapidly spread to the adjacent balconies assisted by the wind and the combustible materials available on these balconies. When the fire entered the staterooms, it was contained by the fixed fire extinguishing system (where these were successfully activated), the restricted combustible materials and the thermal boundaries of the rooms. However, the combustible material on the balconies generated dense and toxic smoke that entered the ship and hampered the passengers' evacuation resulting in one life lost and 13 injuries. [MAIB]

Appendix B

Results of Application of Fire Models to Ship Geometry

This Appendix the results of fire simulations conducted by Raeume and FDS in the different spaces onboard; cabin fire, large space fire and corridor fire.

B.1 Cabin Fire

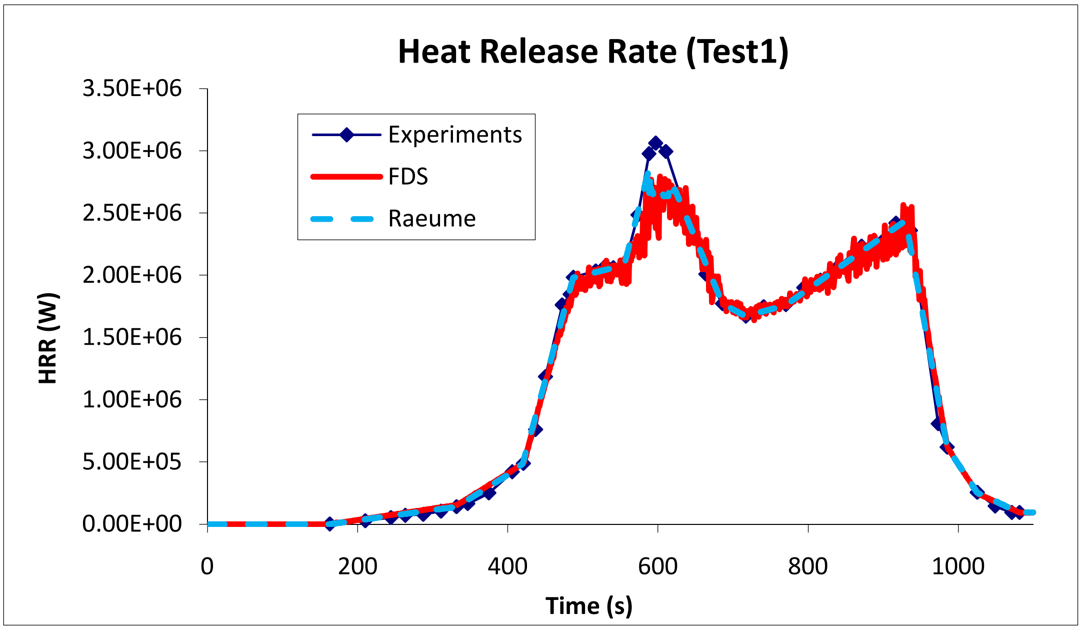

Figure B - 1: Heat Release Rates, measured and predicted for test 1

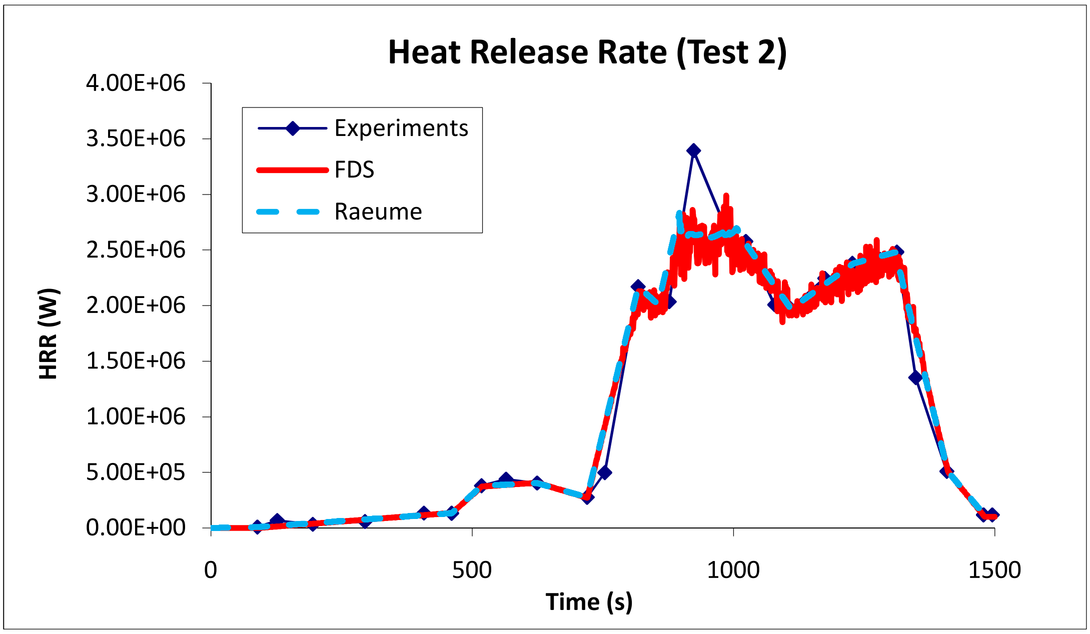

Figure B - 2: Heat Release Rates, measured and predicted for test 2

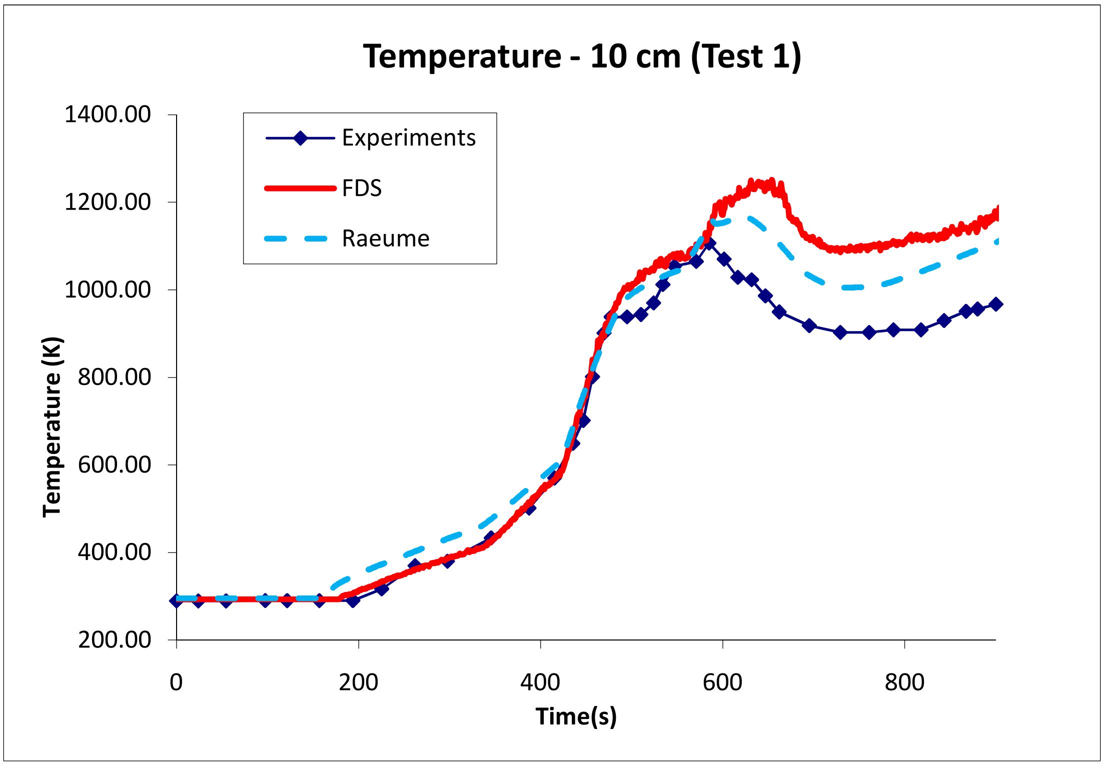

Figure B - 3: Temperature profiles, measured and predicted at 10 cm below ceiling for test 1

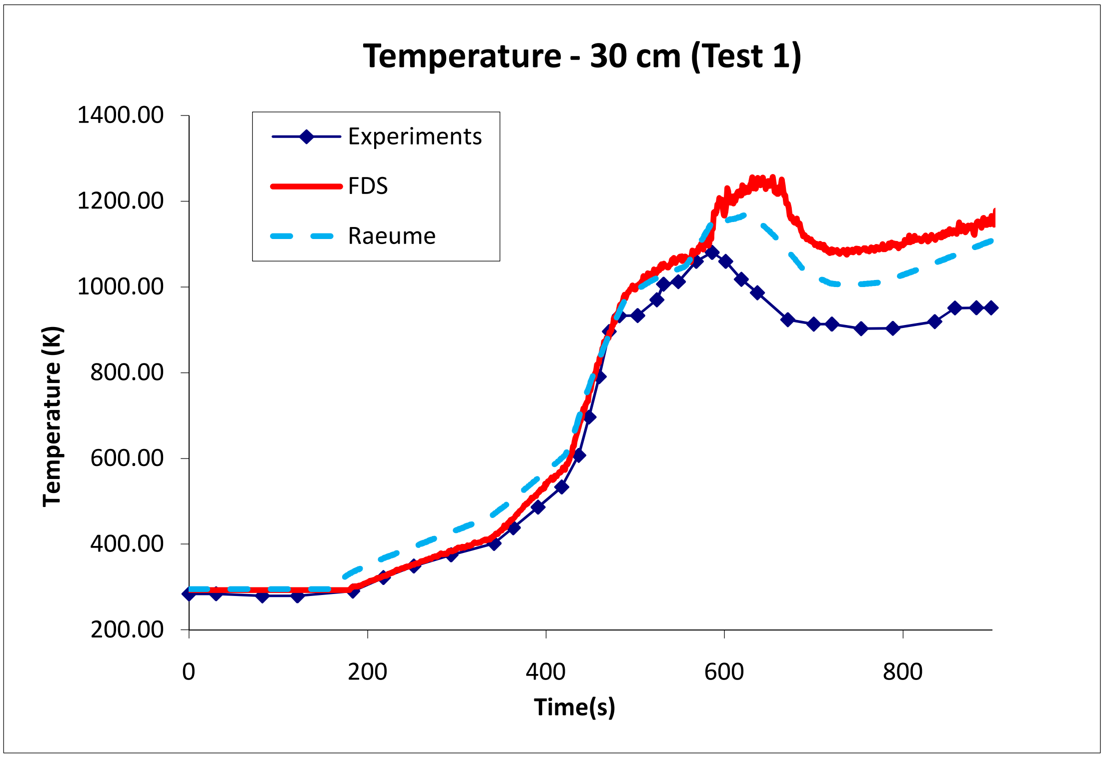

Figure B - 4: Temperature profiles, measured and predicted at 30 cm below ceiling for test 1

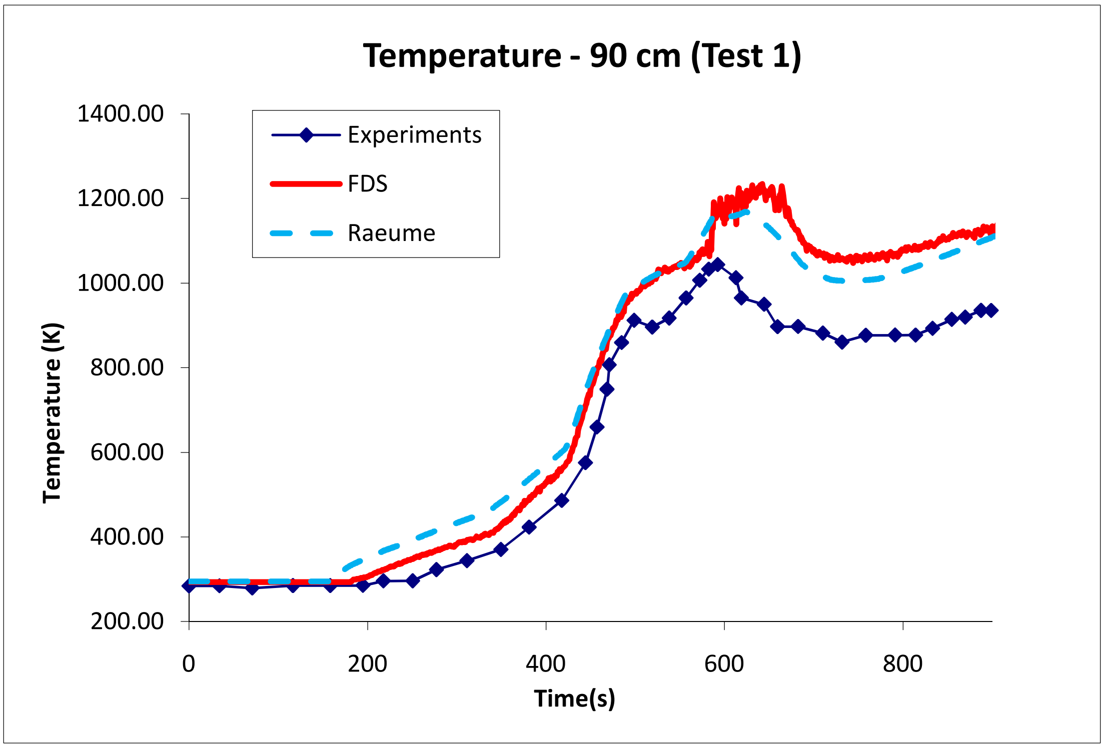

Figure B - 5: Temperature profiles, measured and predicted at 90 cm below ceiling for test 1

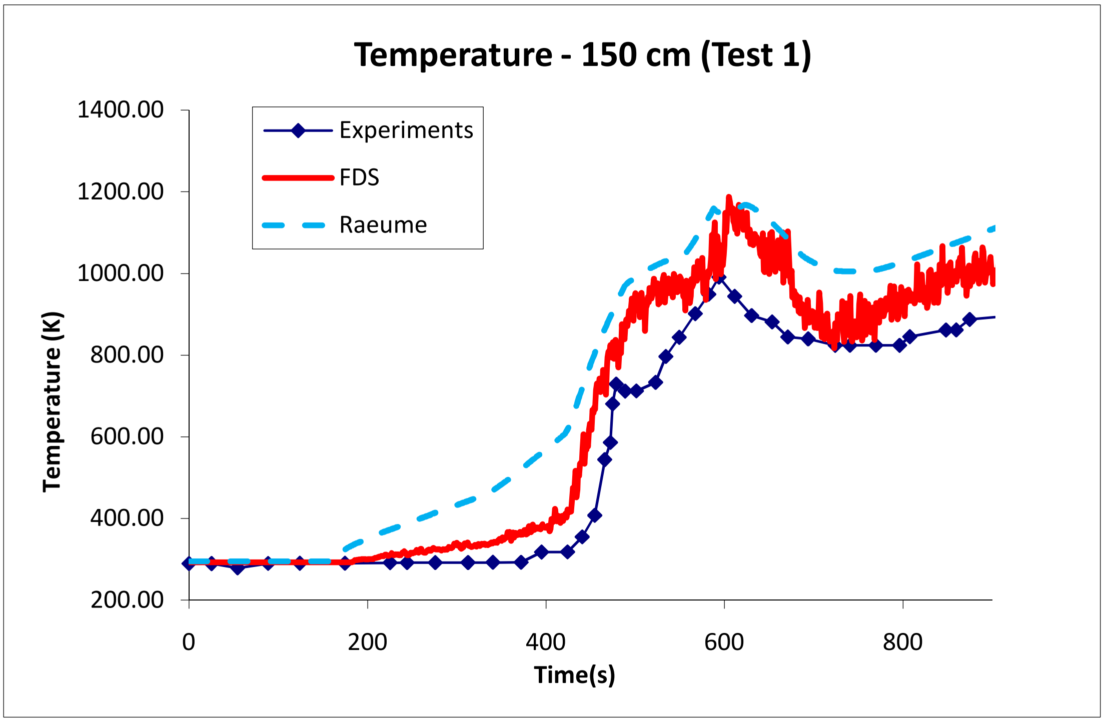

Figure B - 6: Temperature profiles, measured and predicted at 150 cm below ceiling for test 1

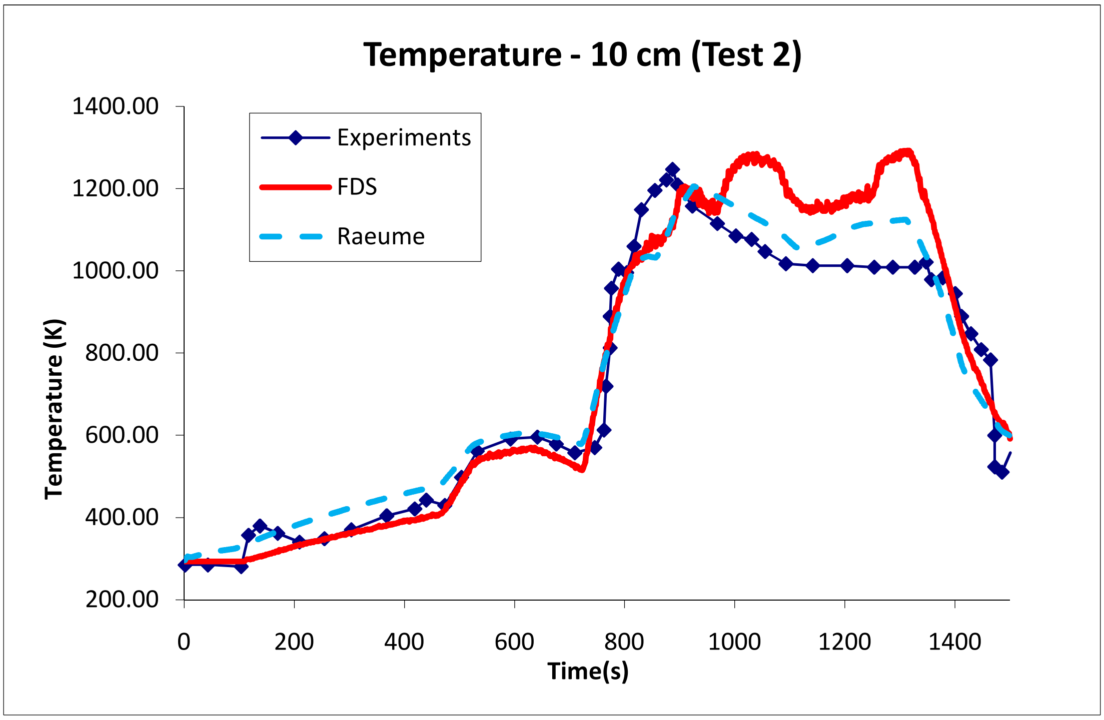

Figure B - 7: Temperature profiles, measured and predicted at 10 cm below ceiling for test 2

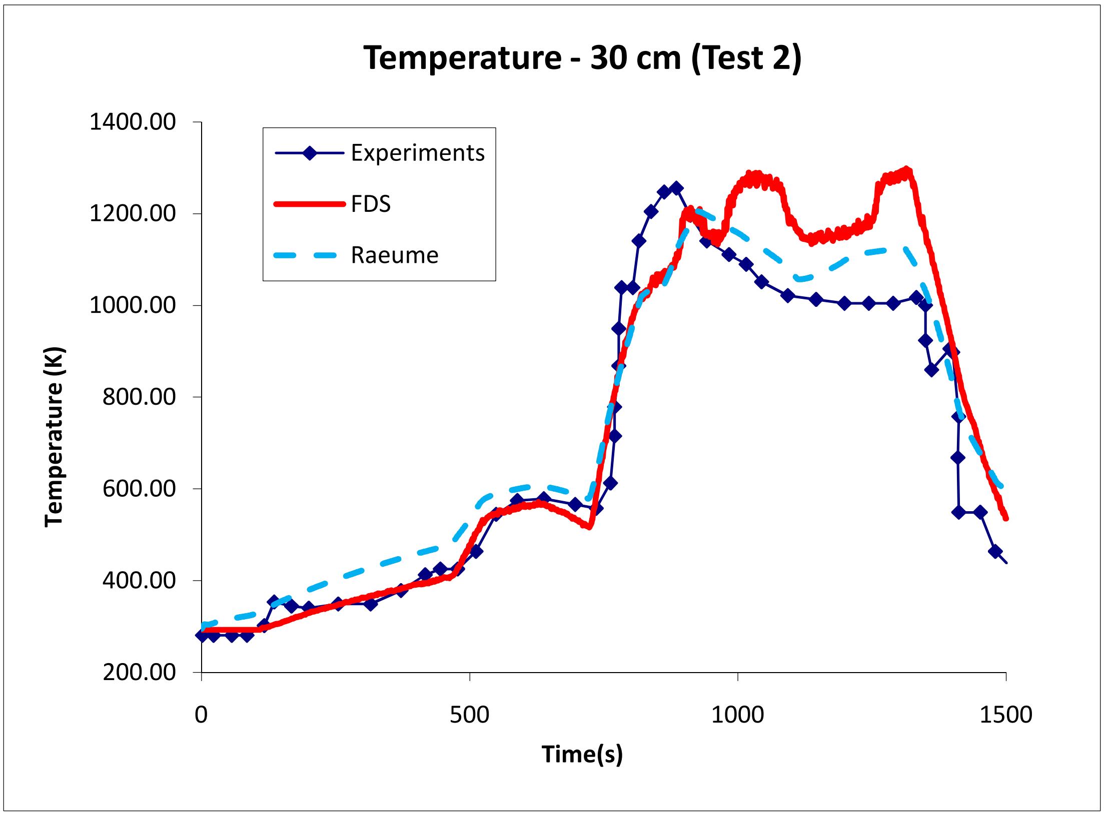

Figure B - 8: Temperature profiles, measured and predicted at 30 cm below ceiling for test 2

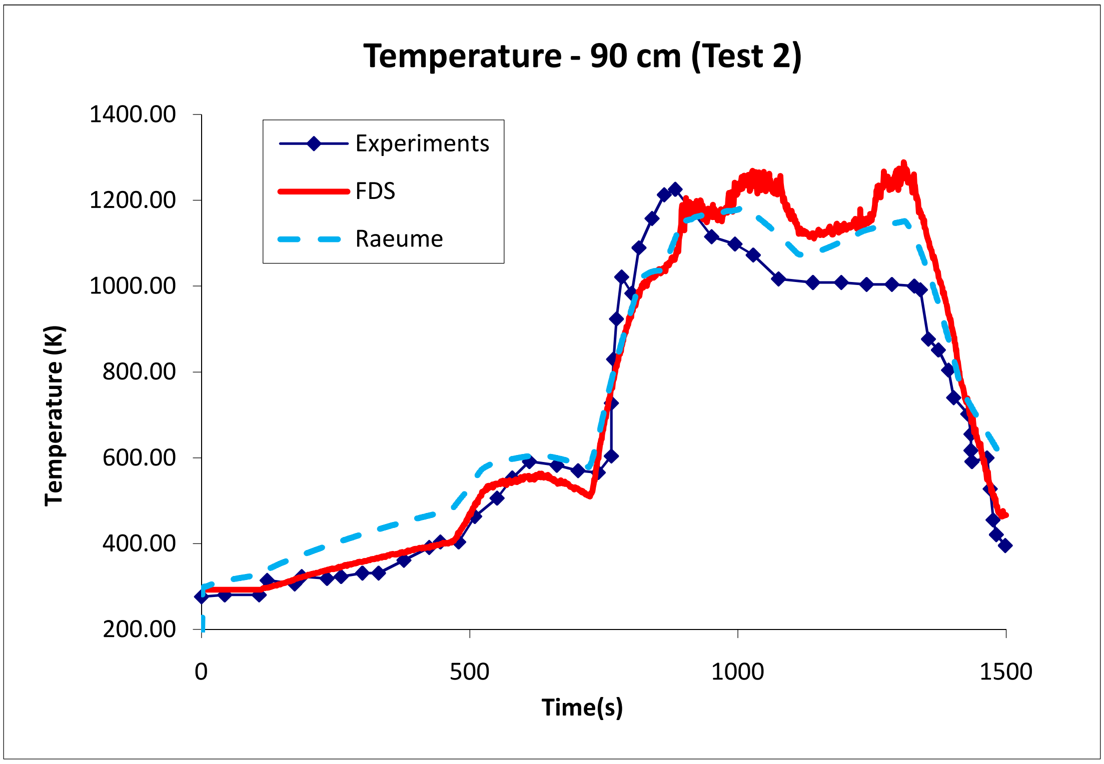

Figure B - 9: Temperature profiles, measured and predicted at 90 cm below ceiling for test 2

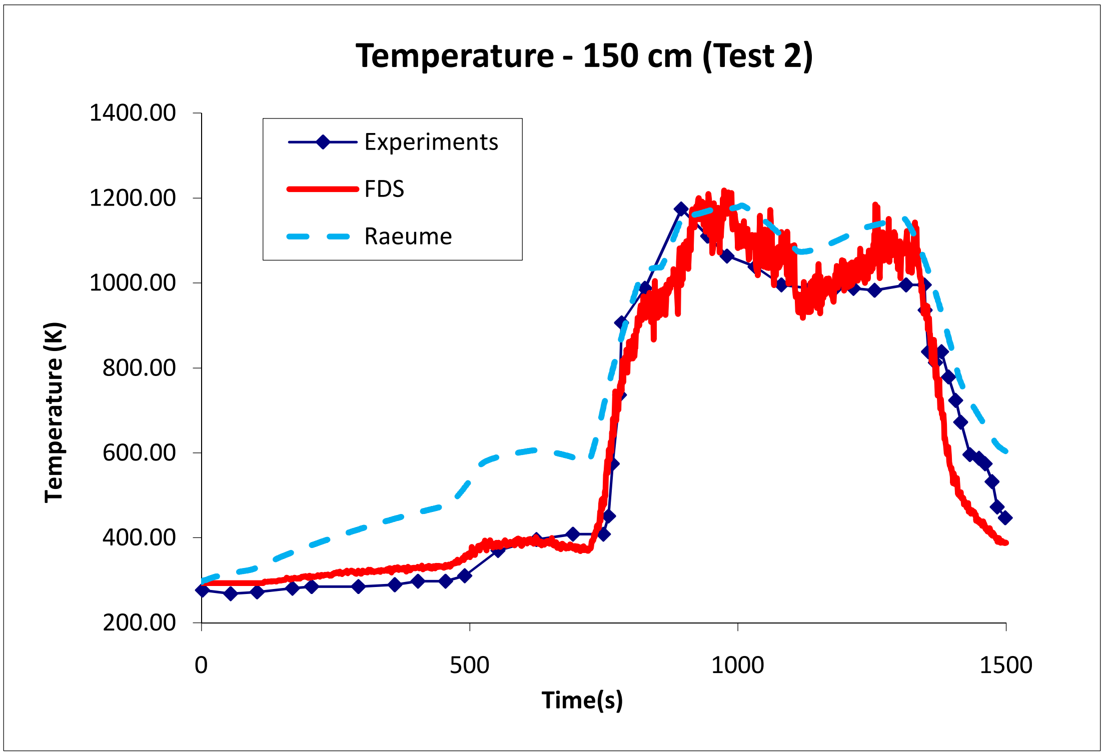

Figure B - 10: Temperature profiles, measured and predicted at 150 cm below ceiling for test 2

B.2 Large Space Fire

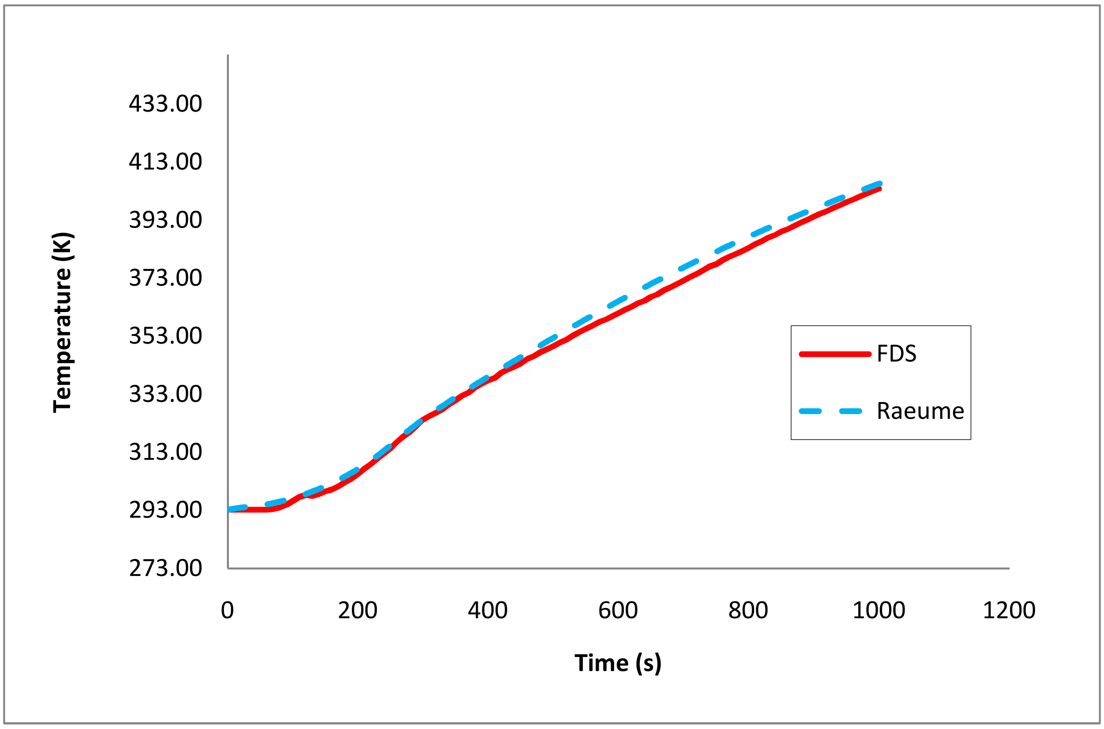

Figure B - 11: Temperature (K) in the atrium as predicted by FDS and Raeume.

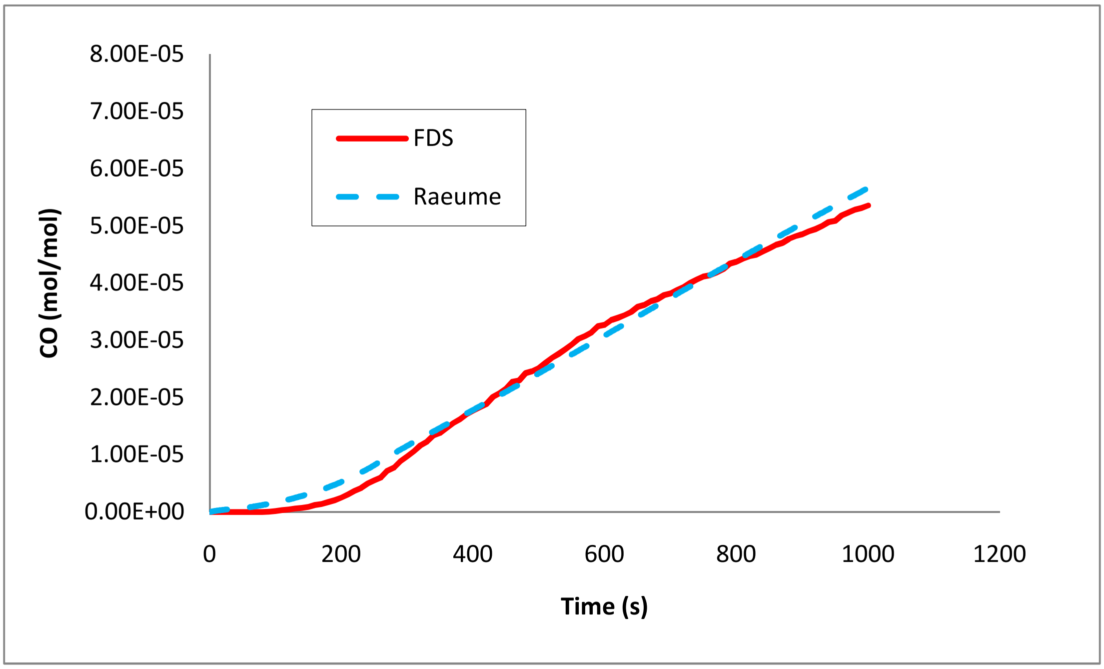

Figure B - 12: Carbon monoxide concentration (mol/mol) in the atrium as predicted by FDS and Raeume.

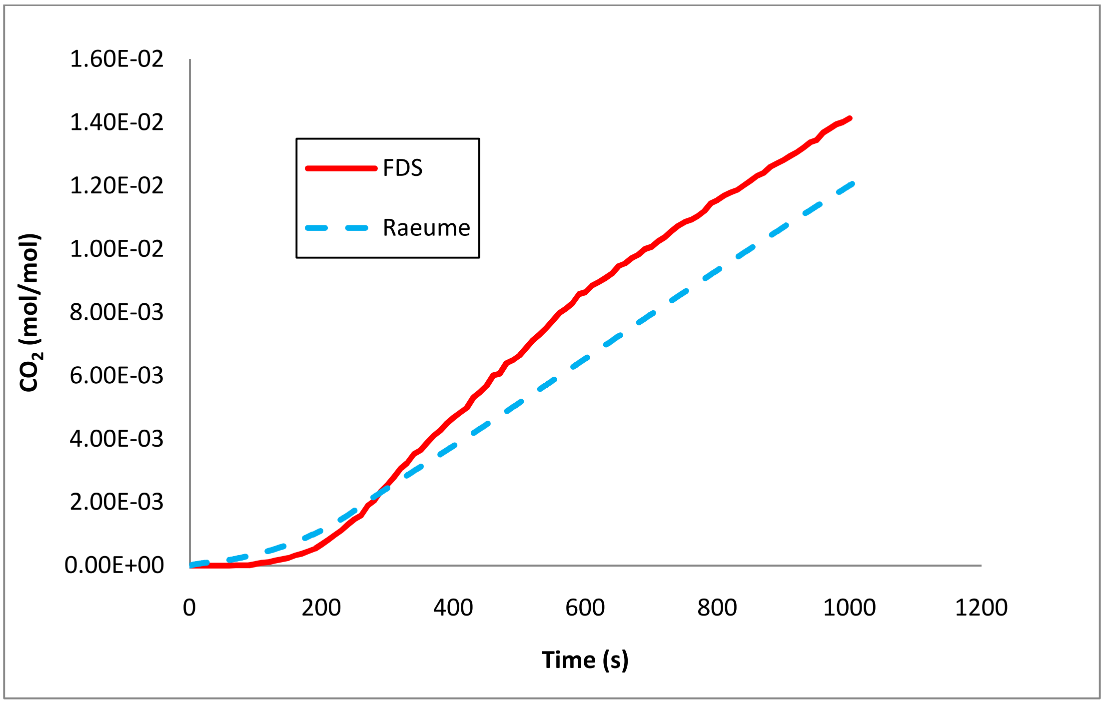

Figure B - 13: Carbon dioxide concentration (mol/mol) in the atrium as predicted by FDS and Raeume.

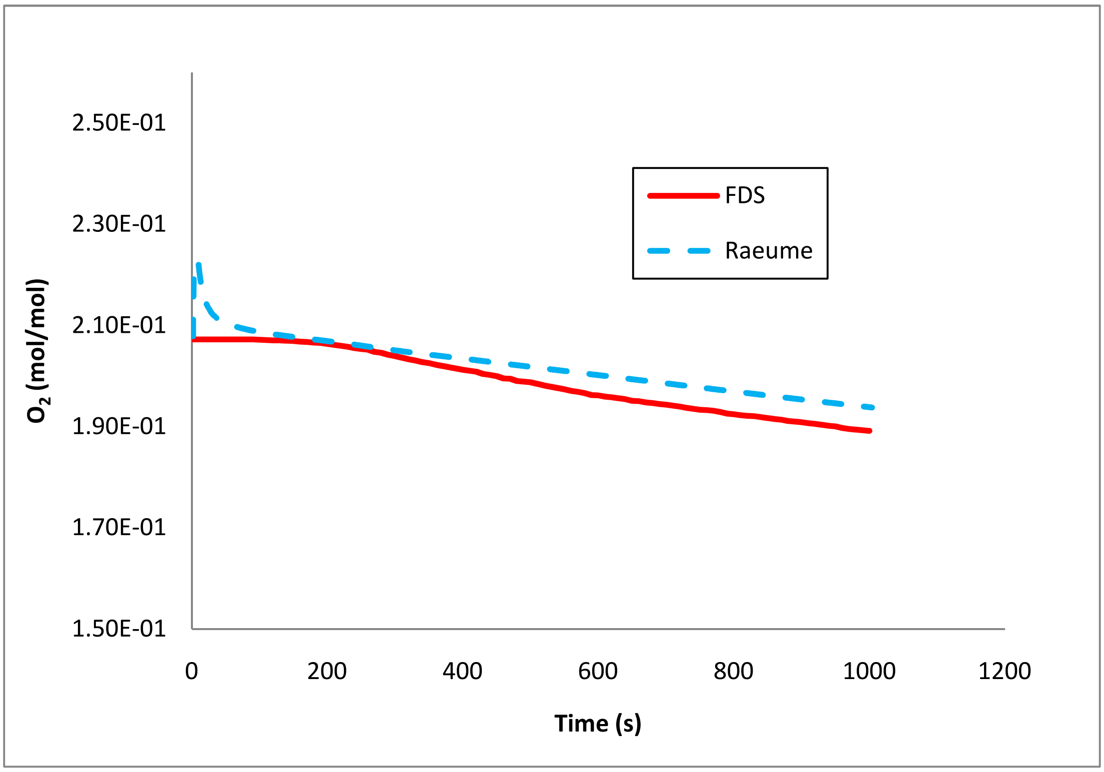

Figure B - 14: Oxygen concentration (mol/mol) in the atrium as predicted by FDS and Raeume.

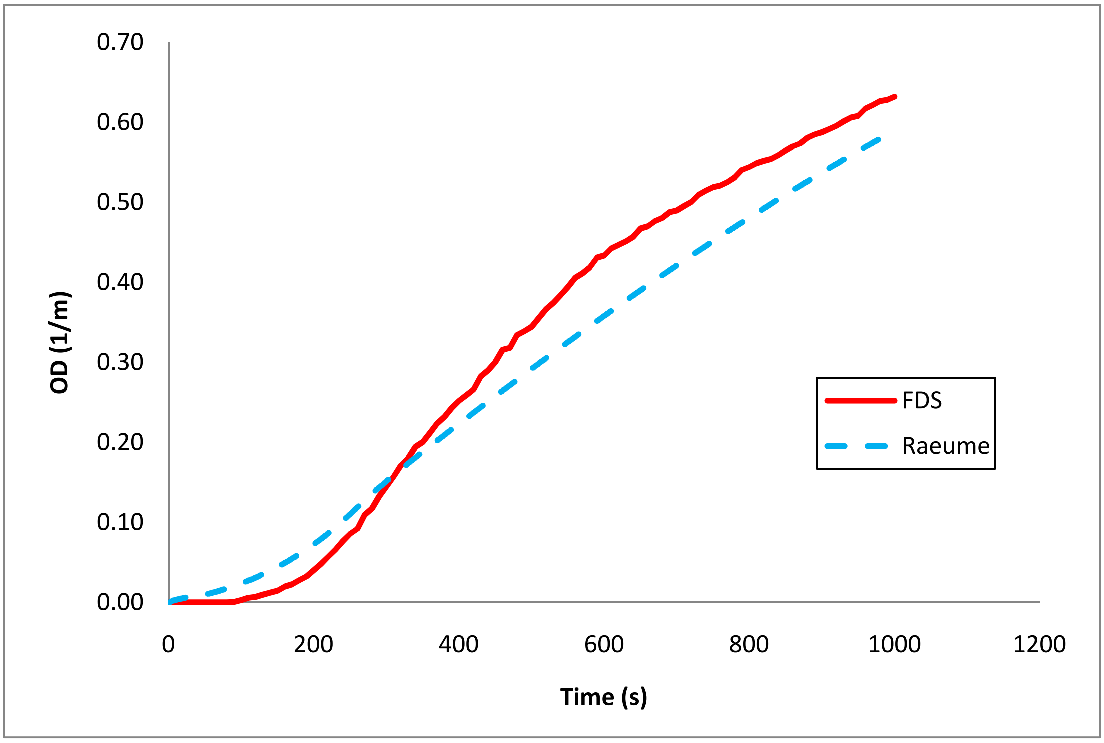

Figure B - 15: Optical density (1/m) in the atrium as predicted by FDS and Raeume.

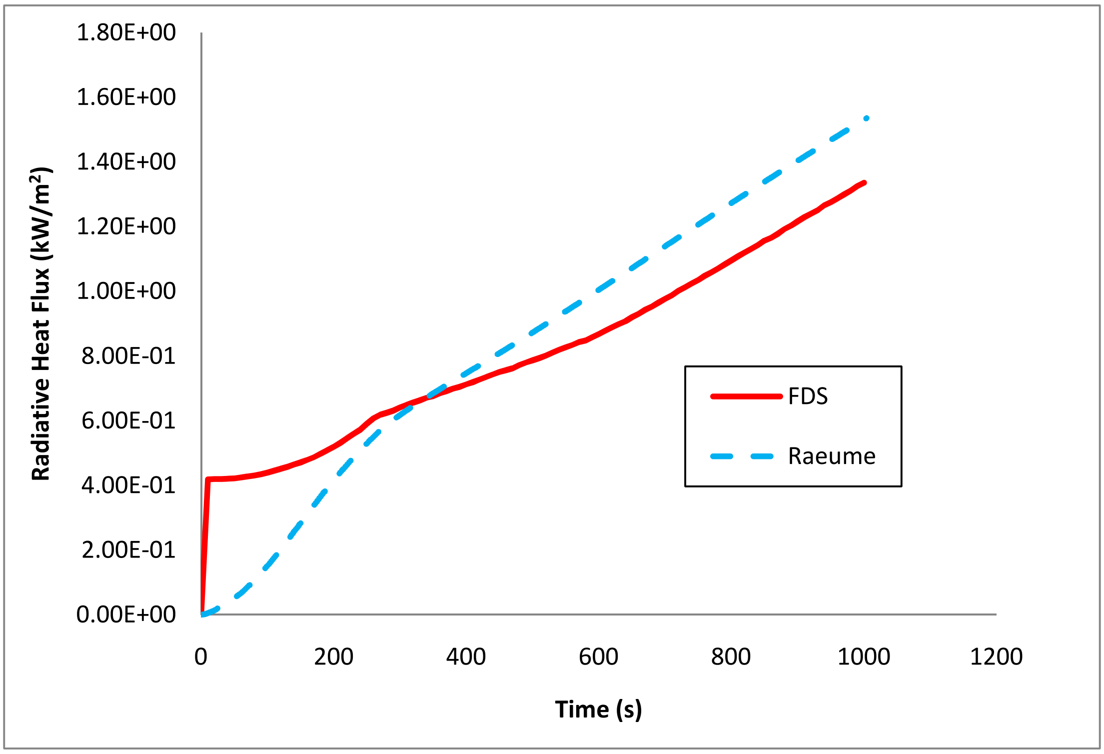

Figure B - 16: Radiative heat flux (kW/m^2) in the atrium as predicted by FDS and Raeume.

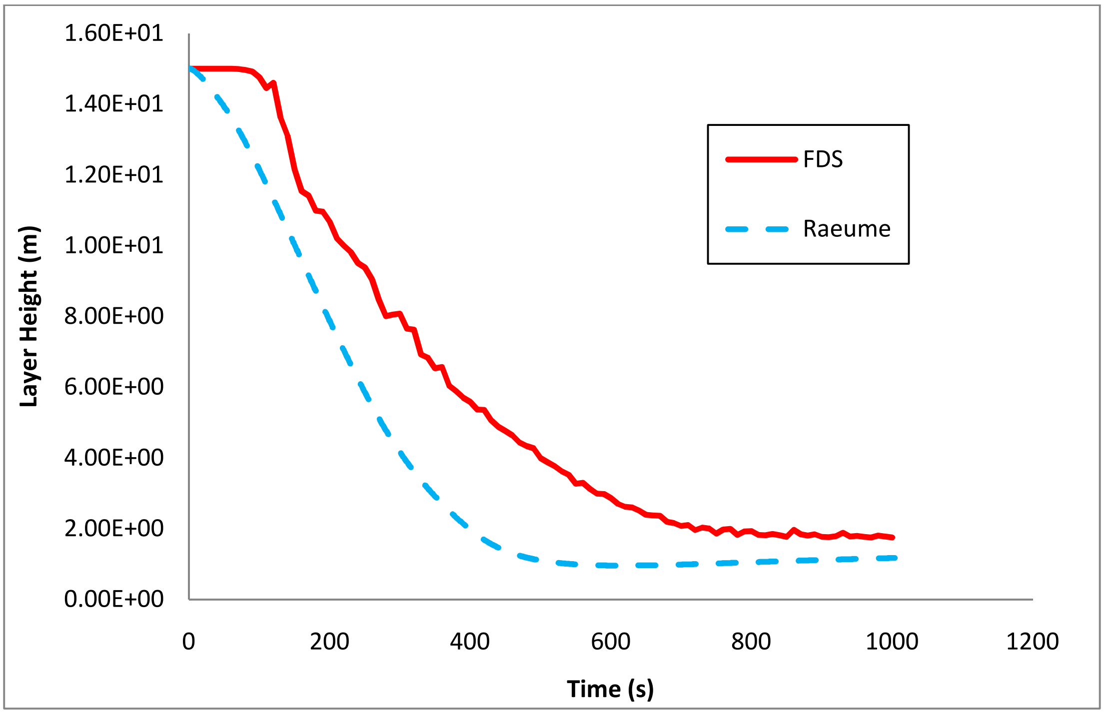

Figure B - 17: Smoke layer interface height (m) in the atrium as predicted by FDS and Raeume.

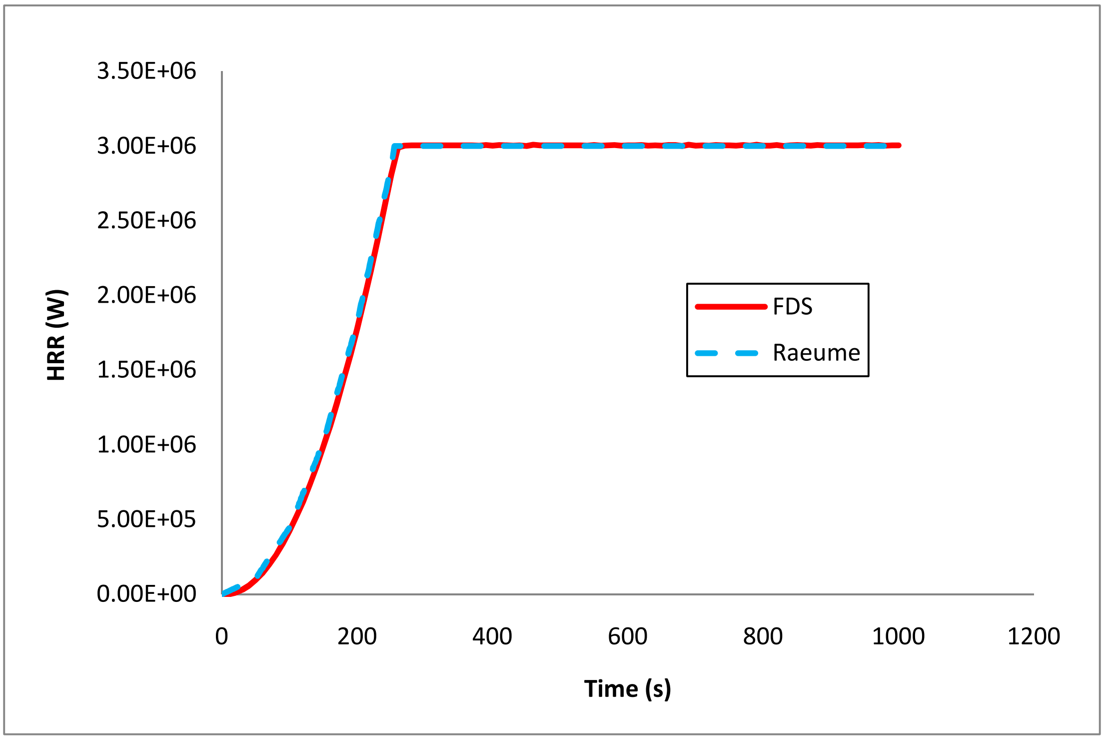

Figure B - 18: Output heat release rate (W) in the atrium as predicted by FDS and Raeume.

B.3 Corridor Fire

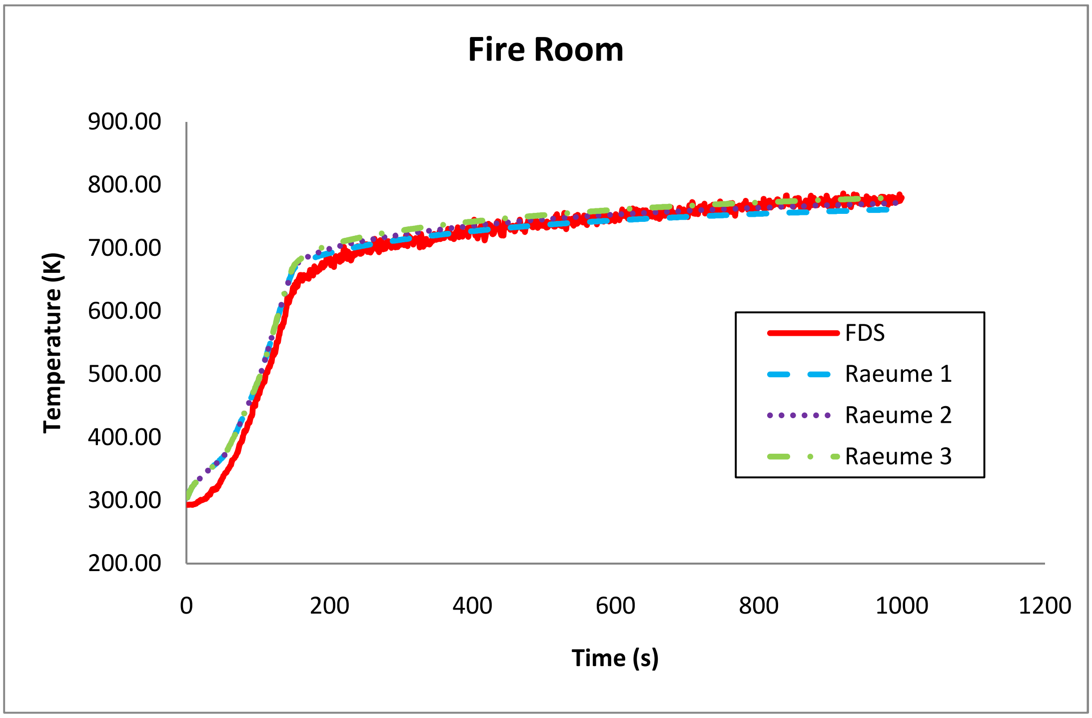

Figure B - 19: Temperature (K) in the fire room.

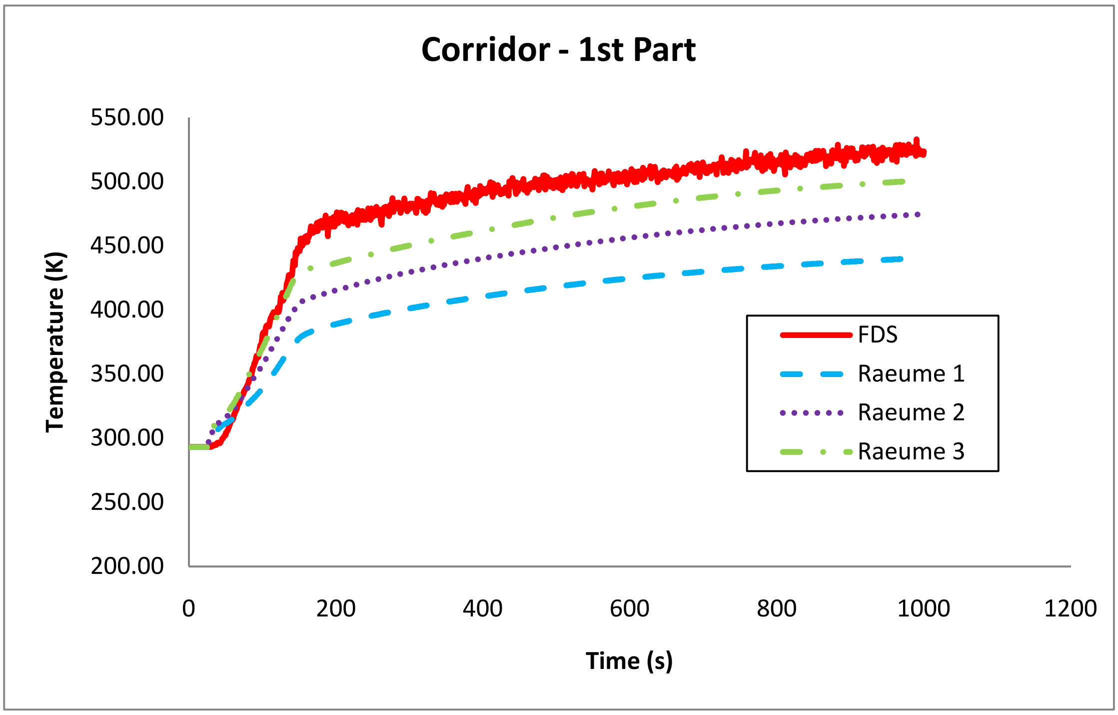

Figure B - 20: Temperature (K) in the first part of the corridor.

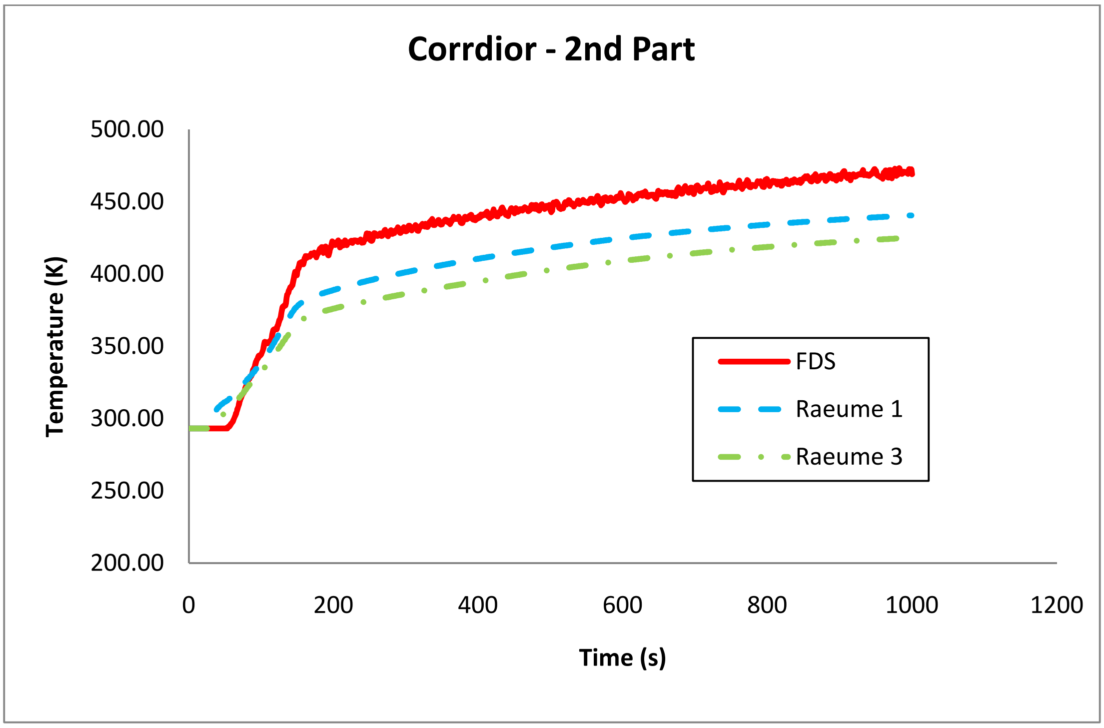

Figure B - 21: Temperature (K) in the second part of the corridor.

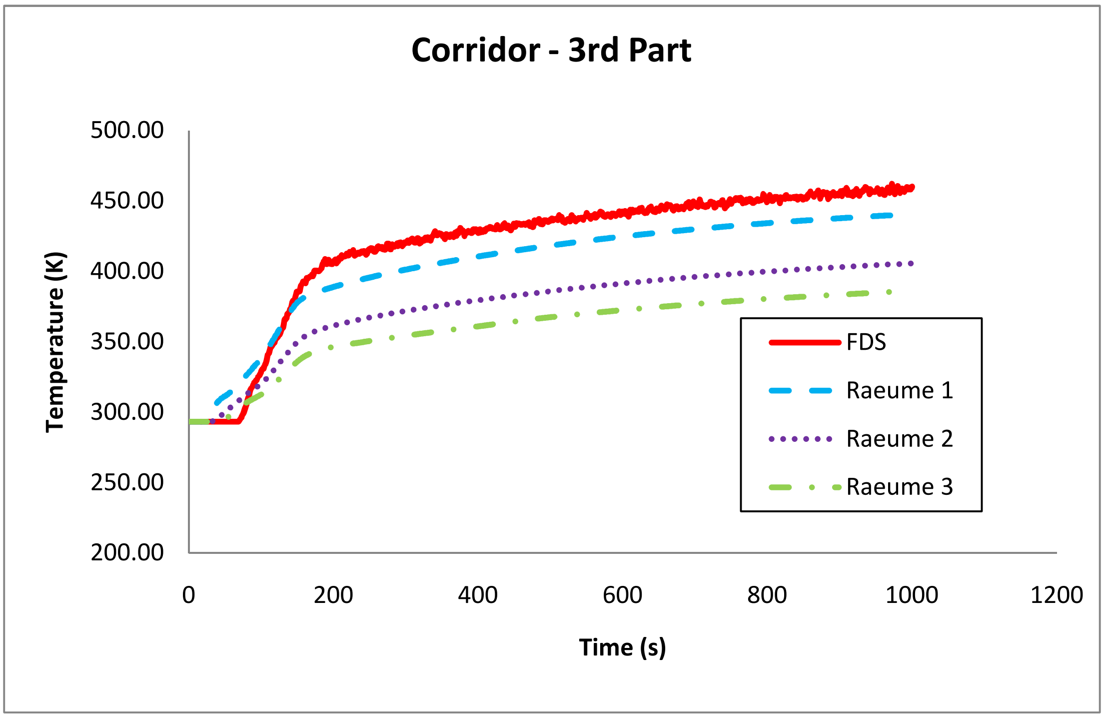

Figure B - 22: Temperature (K) in the third part of the corridor.

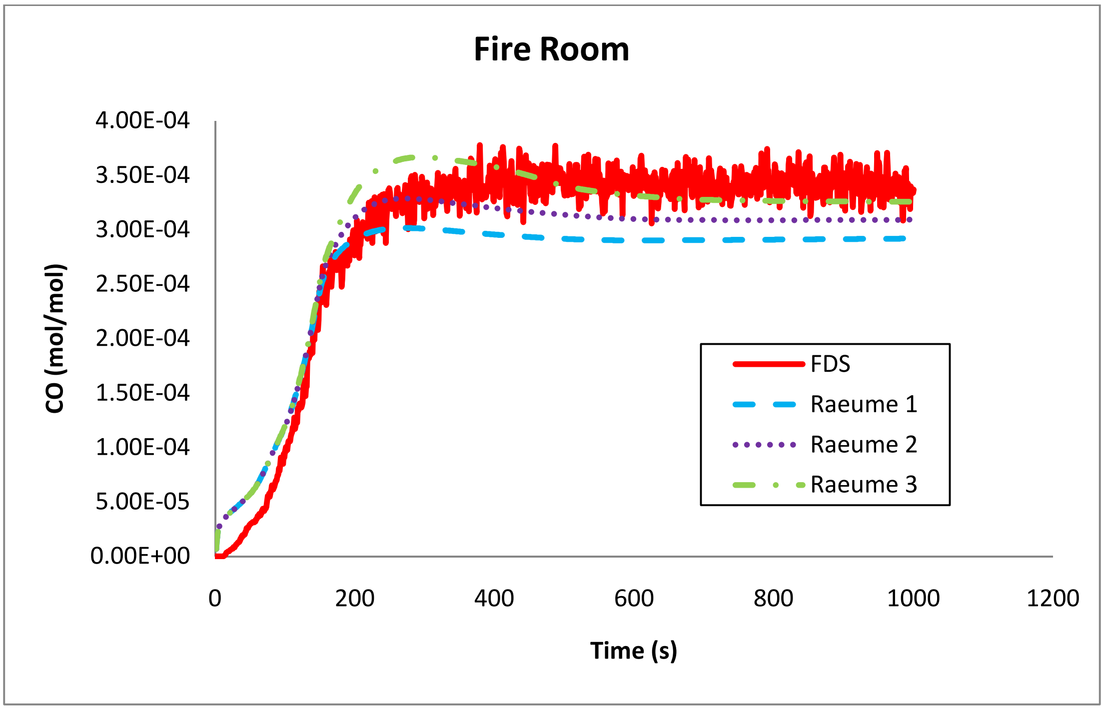

Figure B - 23: Carbon monoxide concentration (mol/mol) in the fire room.

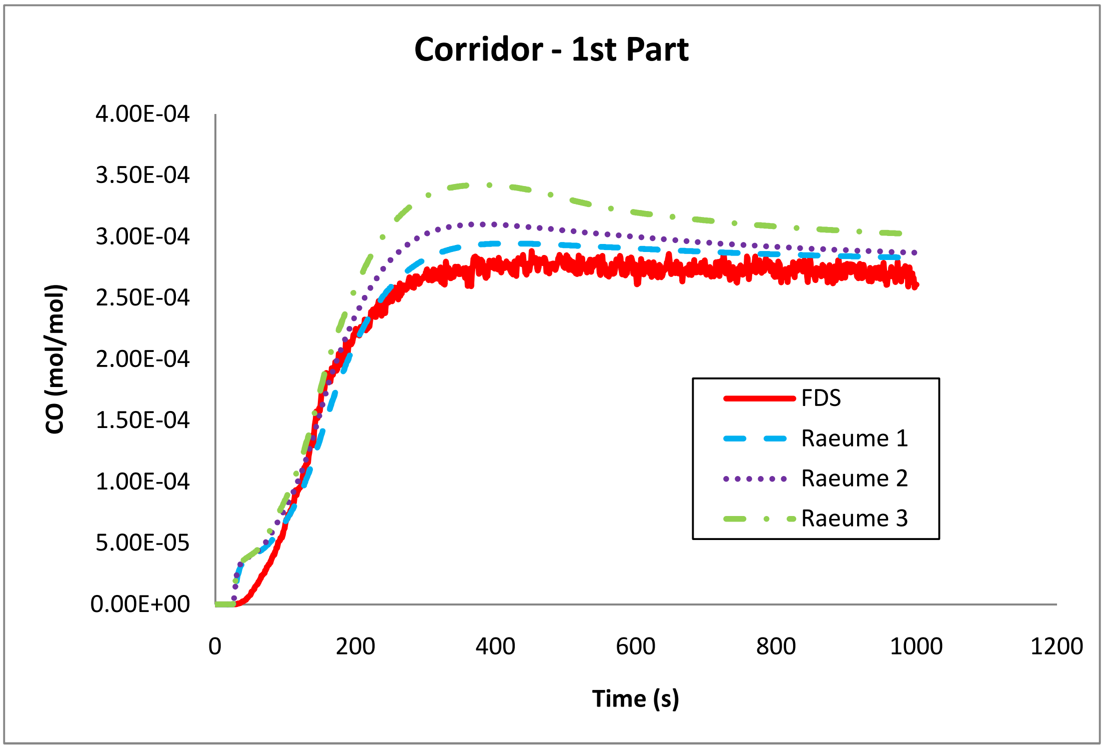

Figure B - 24: Carbon monoxide concentration (mol/mol) in the first part of the corridor.

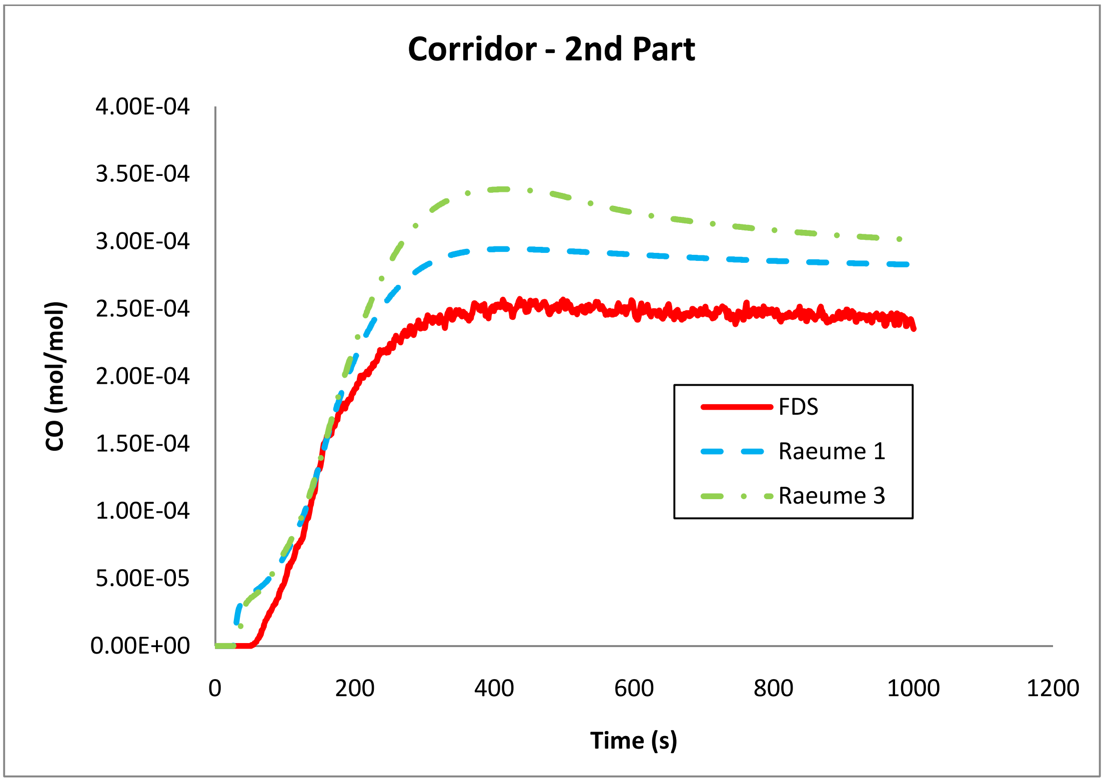

Figure B - 25: Carbon monoxide concentration (mol/mol) in the second part of the corridor.

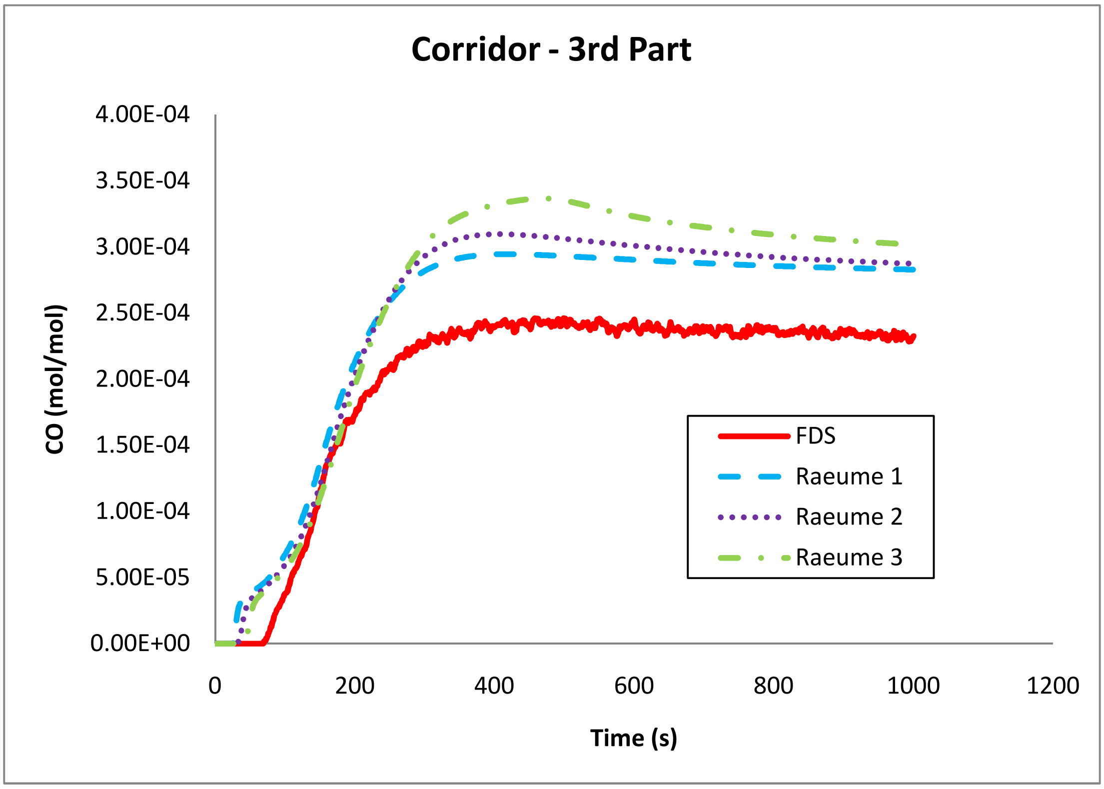

Figure B - 26: Carbon monoxide concentration (mol/mol) in the third part of the corridor.

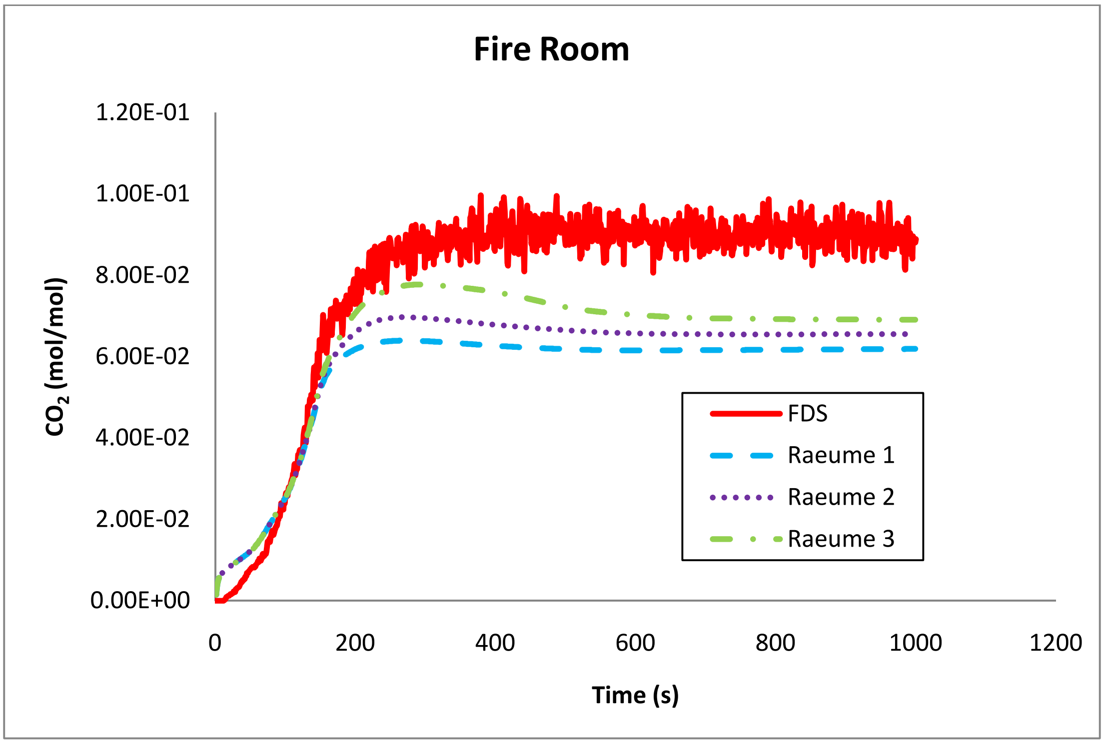

Figure B - 27: Carbon dioxide concentration (mol/mol) in the fire room.

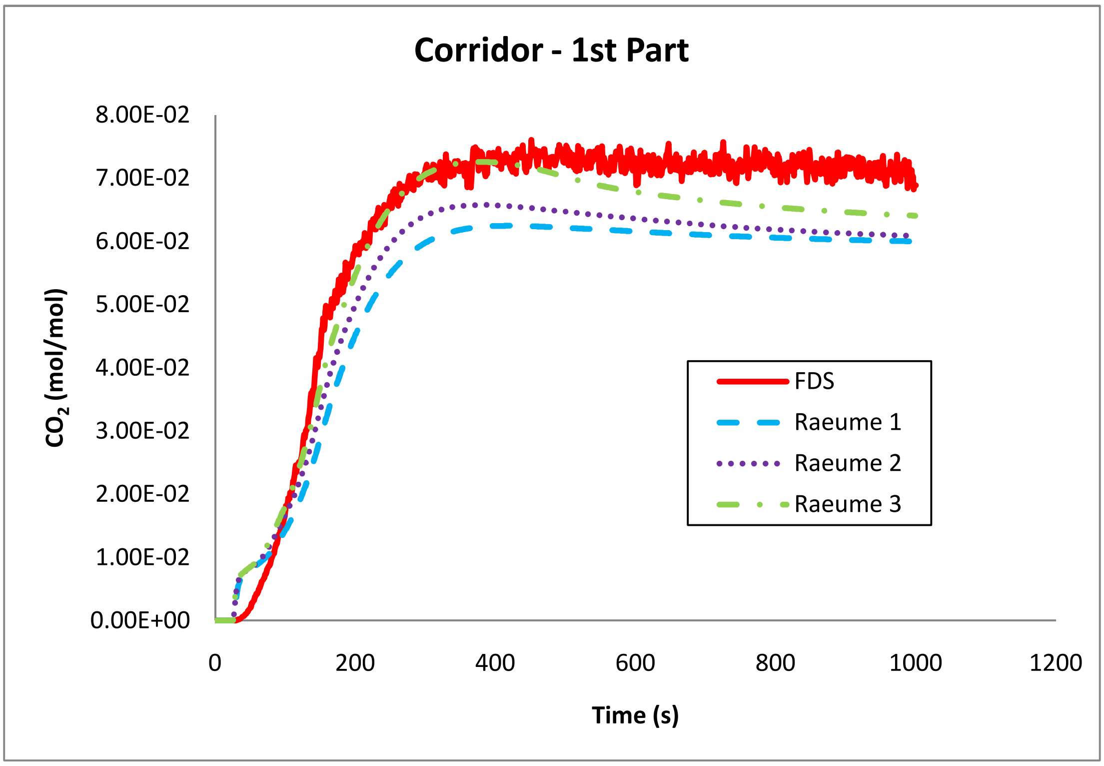

Figure B - 28: Carbon dioxide concentration (mol/mol) in the first part of the corridor.

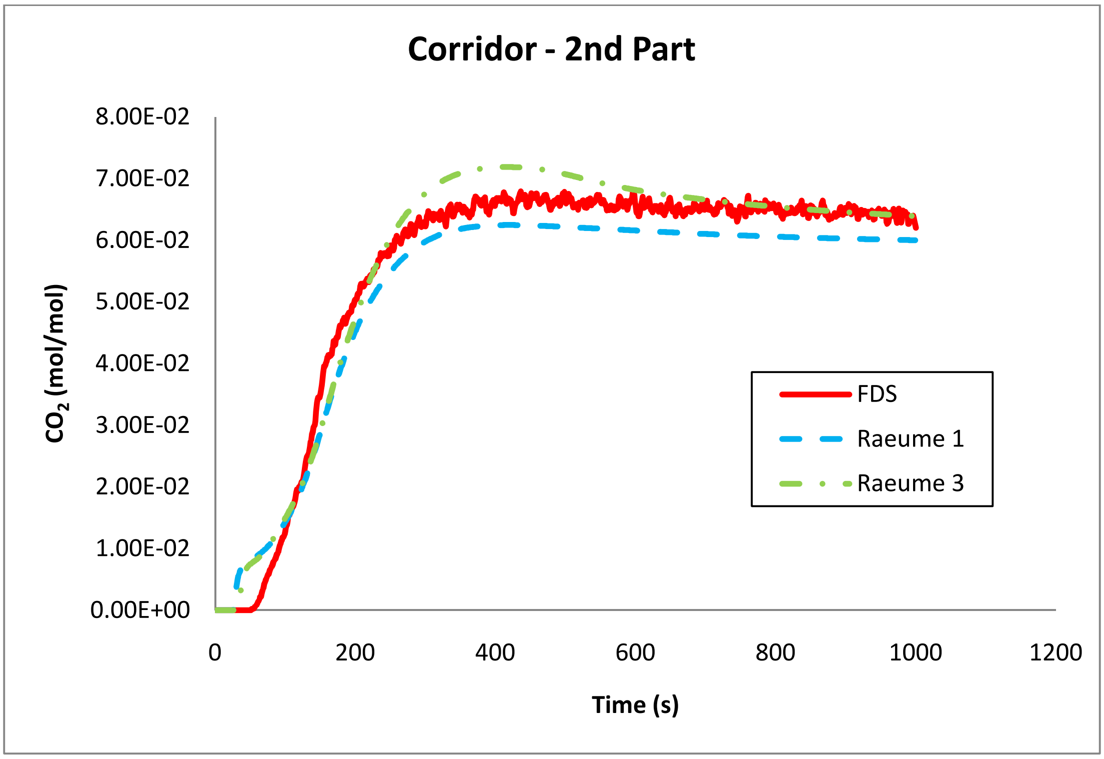

Figure B - 29: Carbon dioxide concentration (mol/mol) in the second part of the corridor.

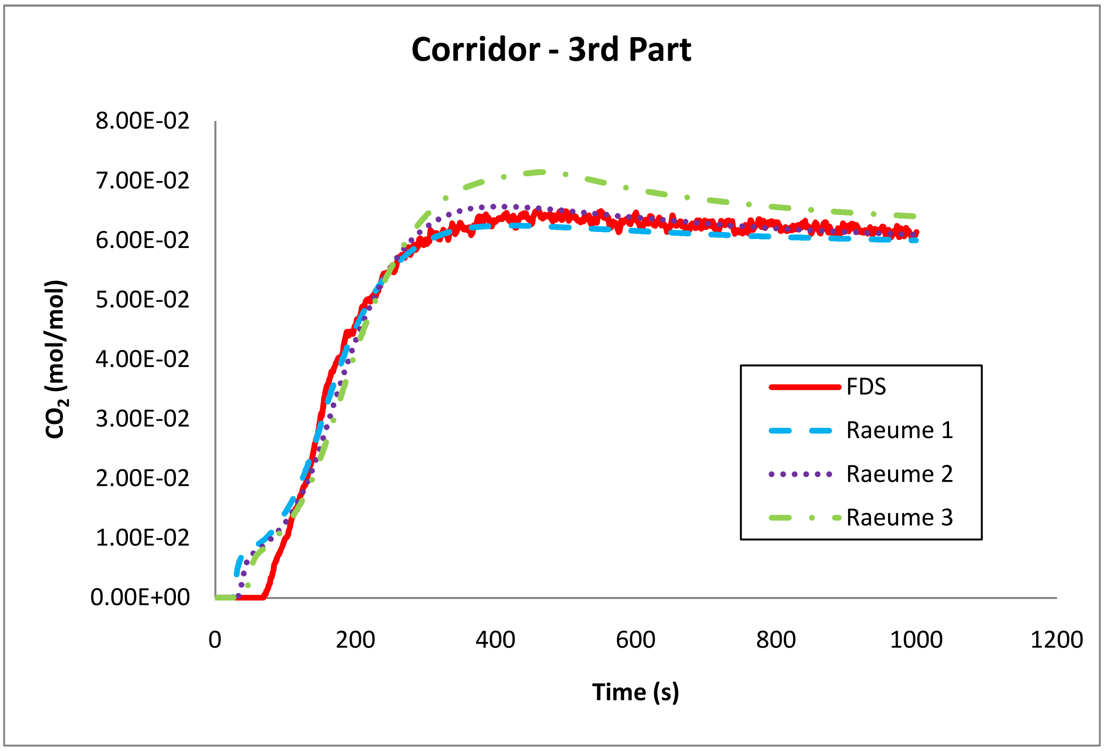

Figure B - 30: Carbon dioxide concentration (mol/mol) in the third part of the corridor.

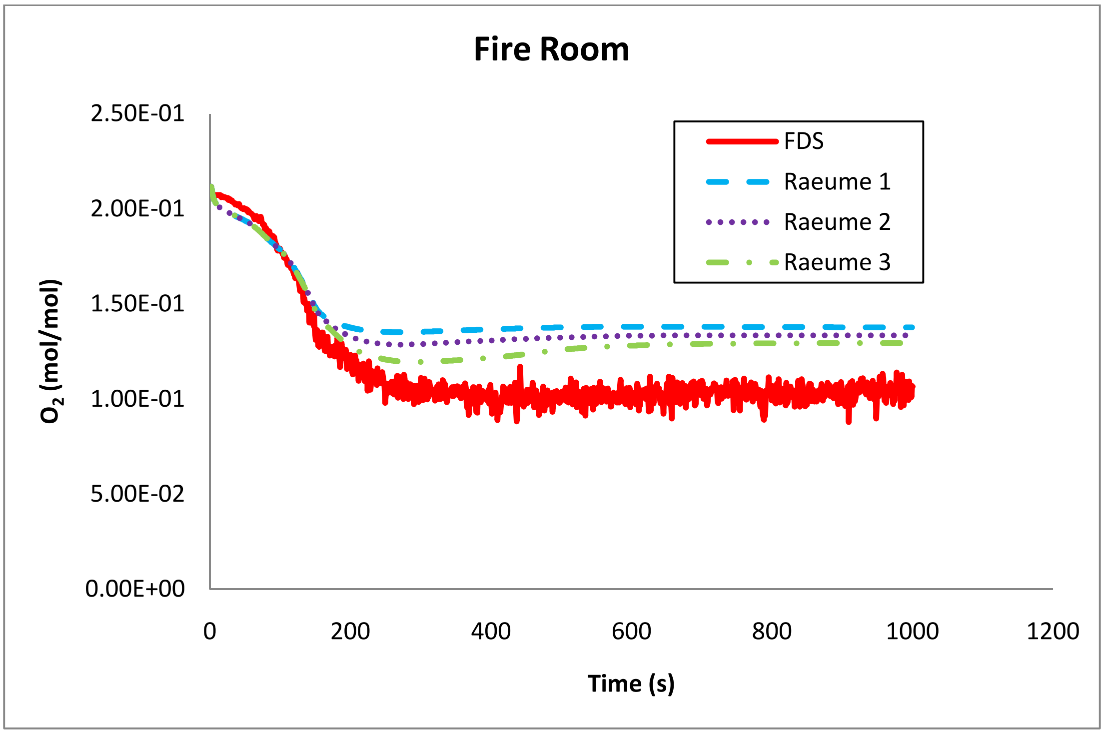

Figure B - 31: Oxygen concentration (mol/mol) in the fire room.

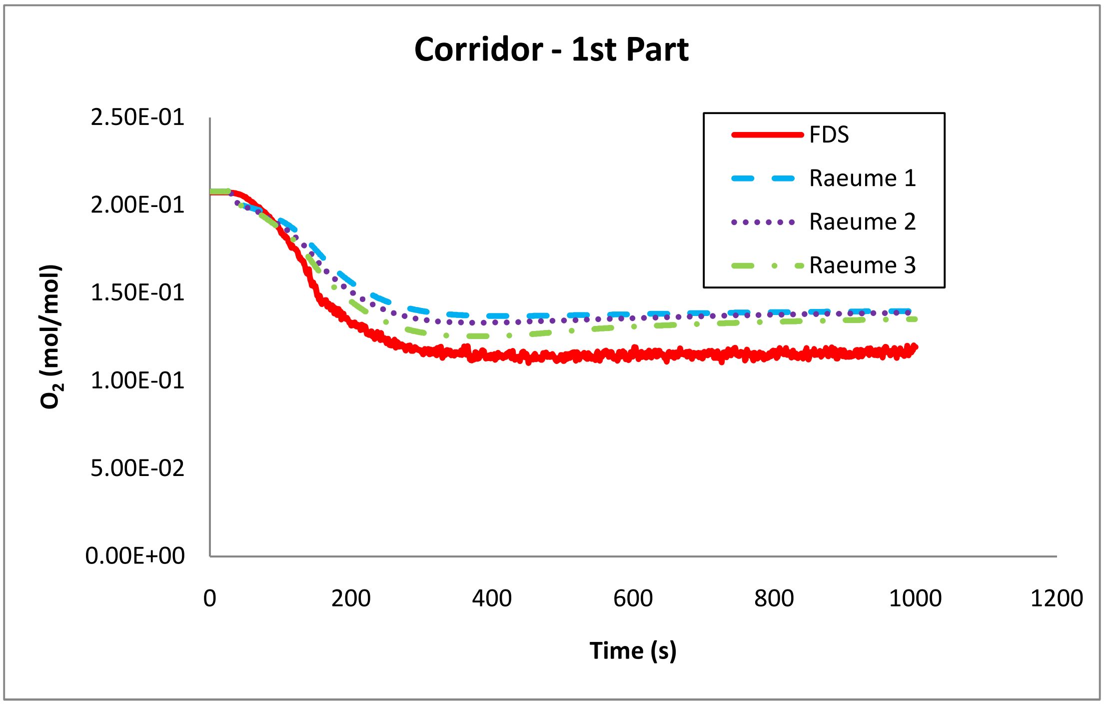

Figure B - 32: Oxygen concentration (mol/mol) in the first part of the corridor.

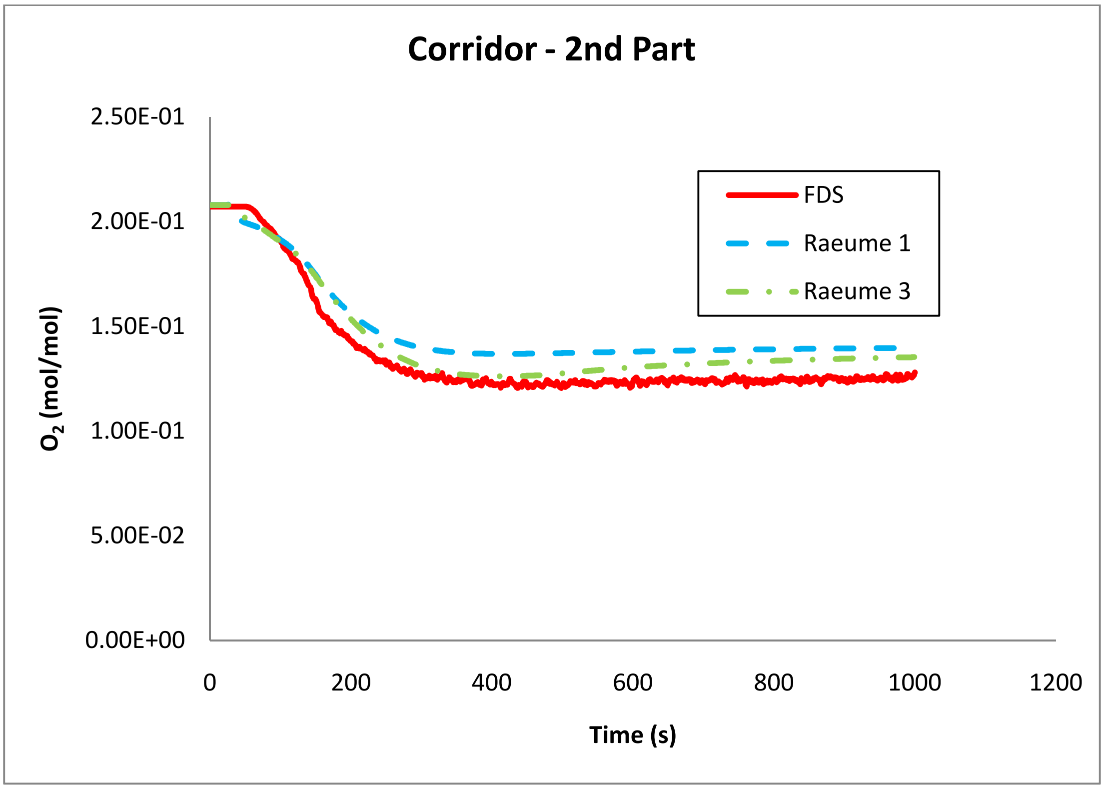

Figure B - 33: Oxygen concentration (mol/mol) in the second part of the corridor.

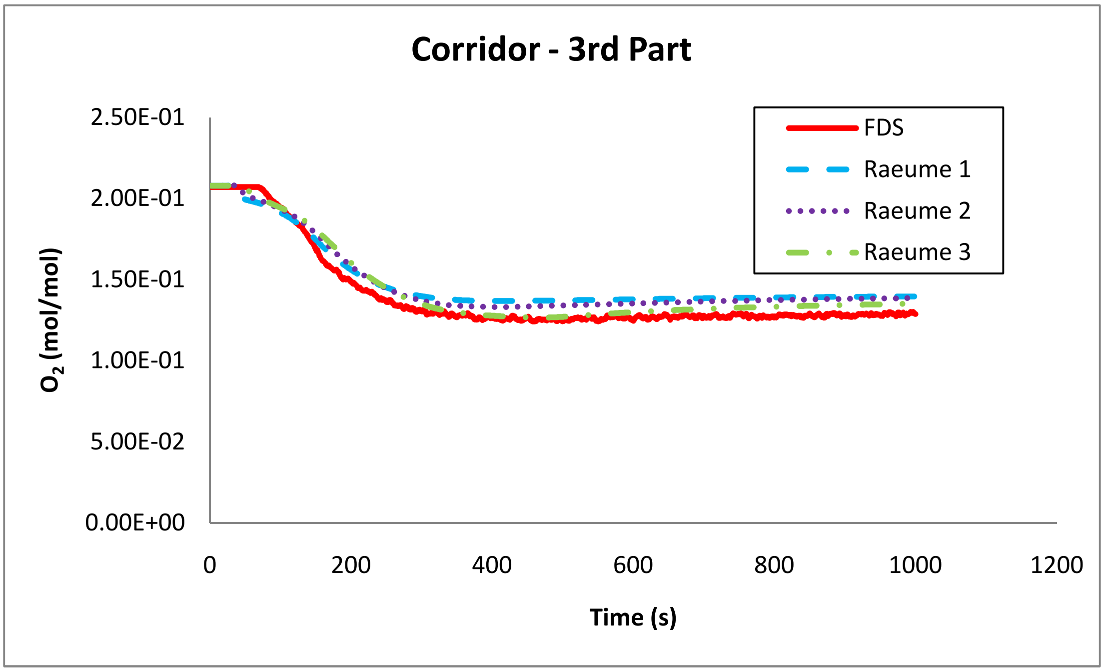

Figure B - 34: Oxygen concentration (mol/mol) in the third part of the corridor.

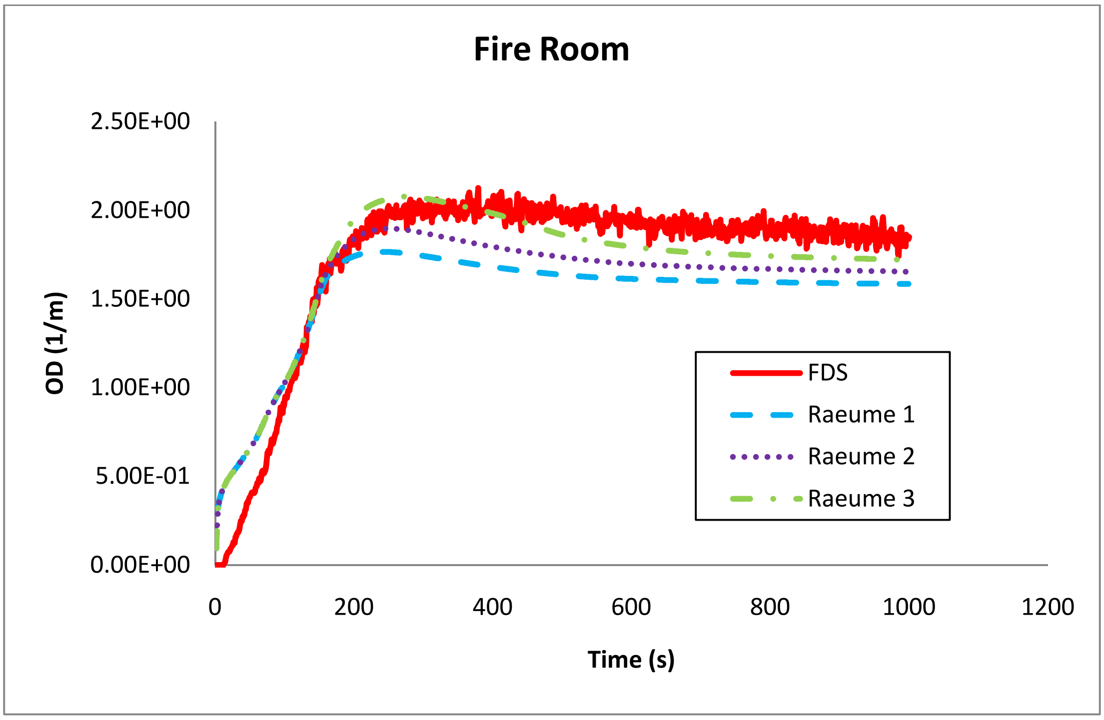

Figure B - 35: Optical density (1/m) in the fire room.

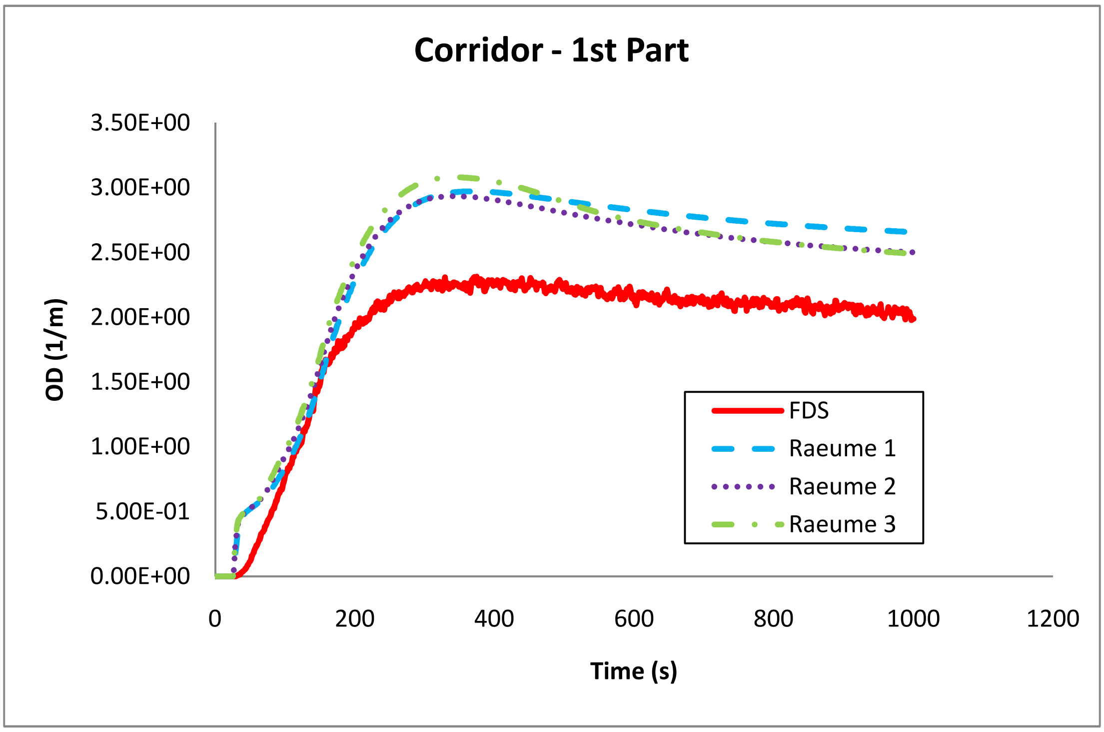

Figure B - 36: Optical density (1/m) in the first part of the corridor.

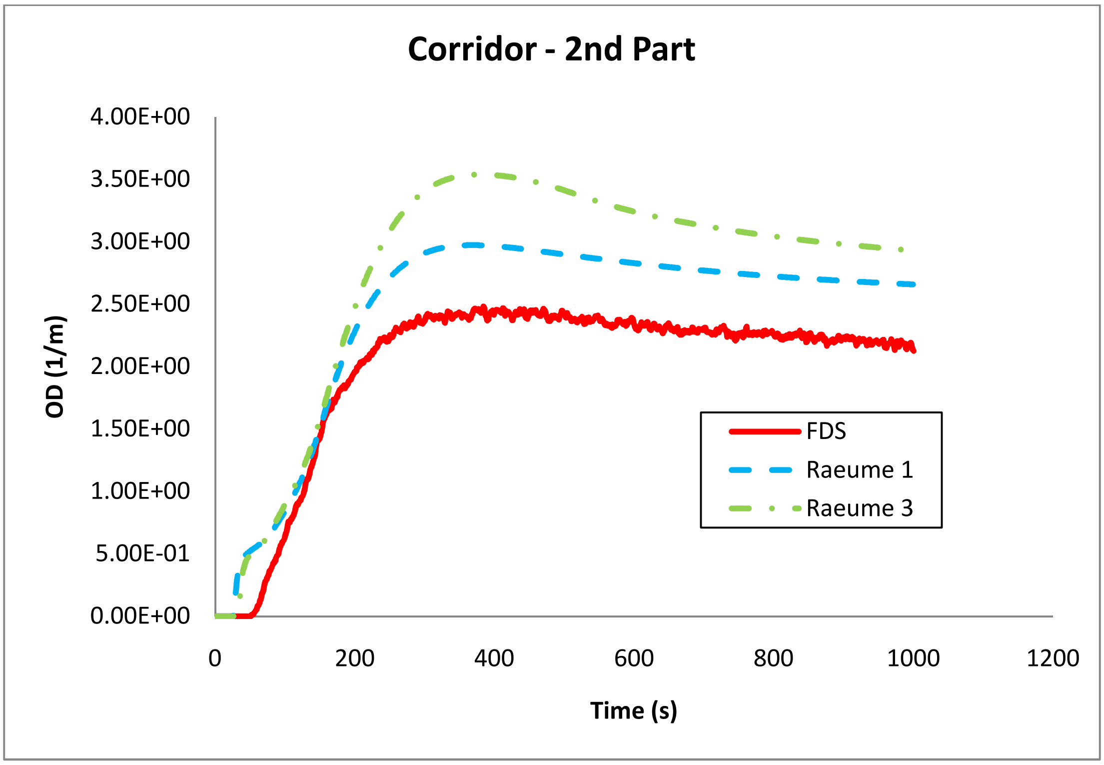

Figure B - 37: Optical density (1/m) in the second part of the corridor.

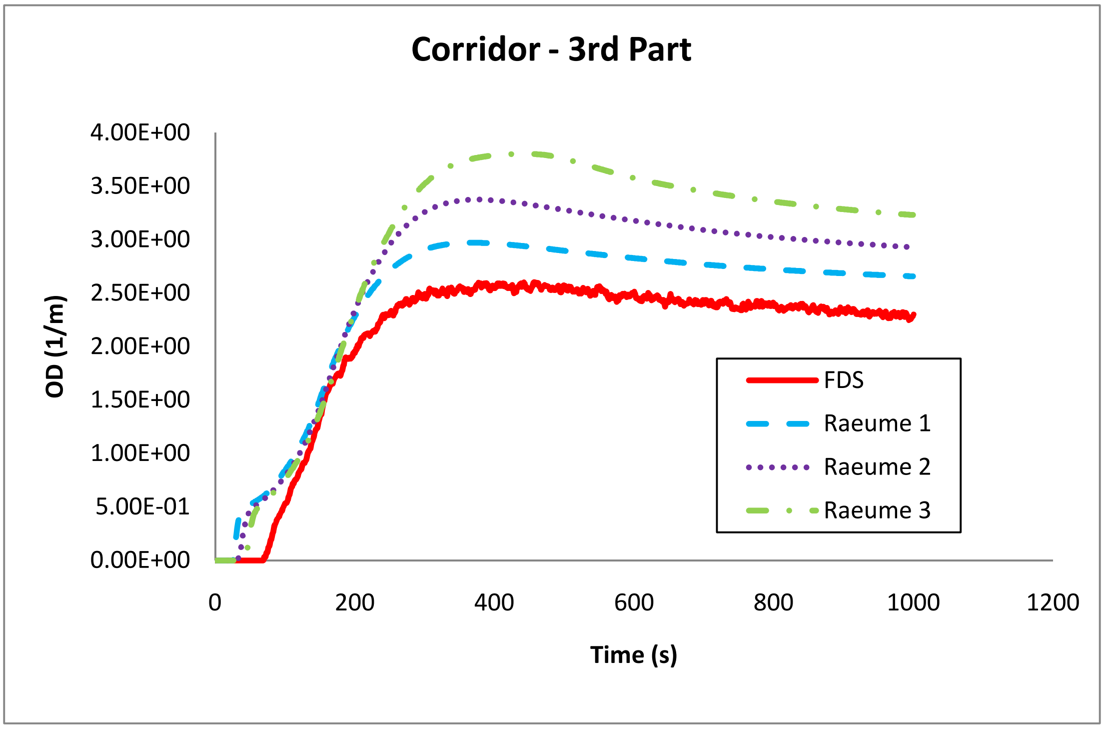

Figure B - 38: Optical density (1/m) in the third part of the corridor.

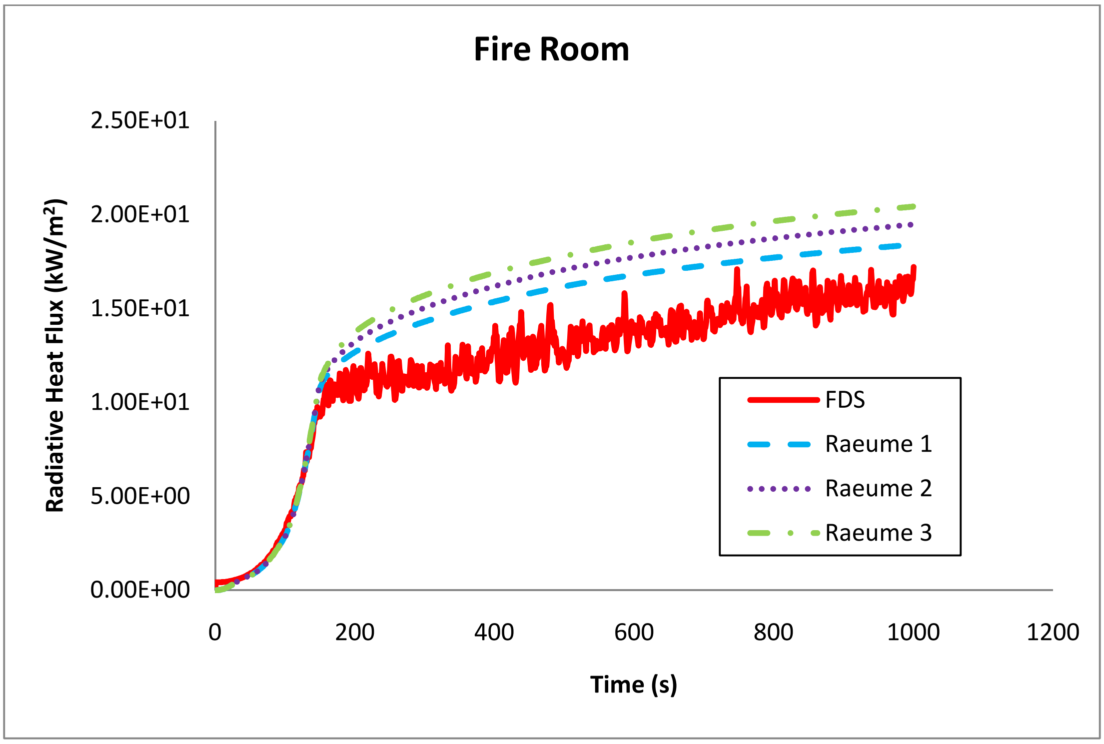

Figure B - 39: Radiative heat flux (kW/m^2) in the fire room.

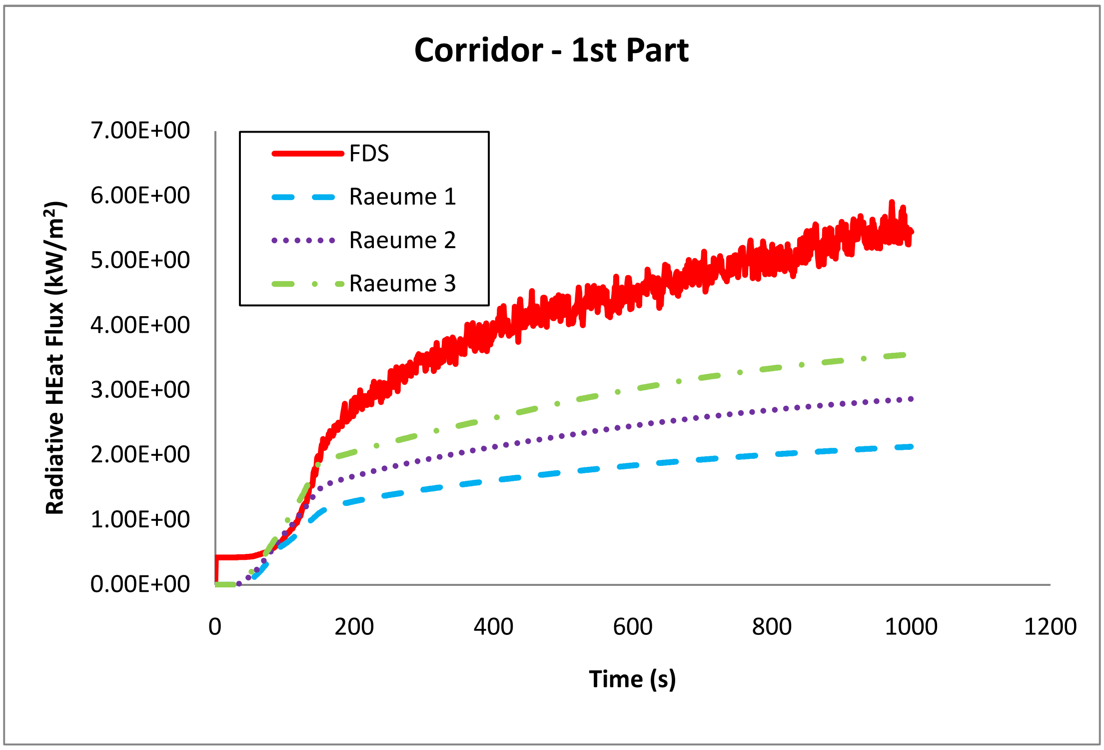

Figure B - 40: Radiative heat flux (kW/m^2) in the first part of the corridor.

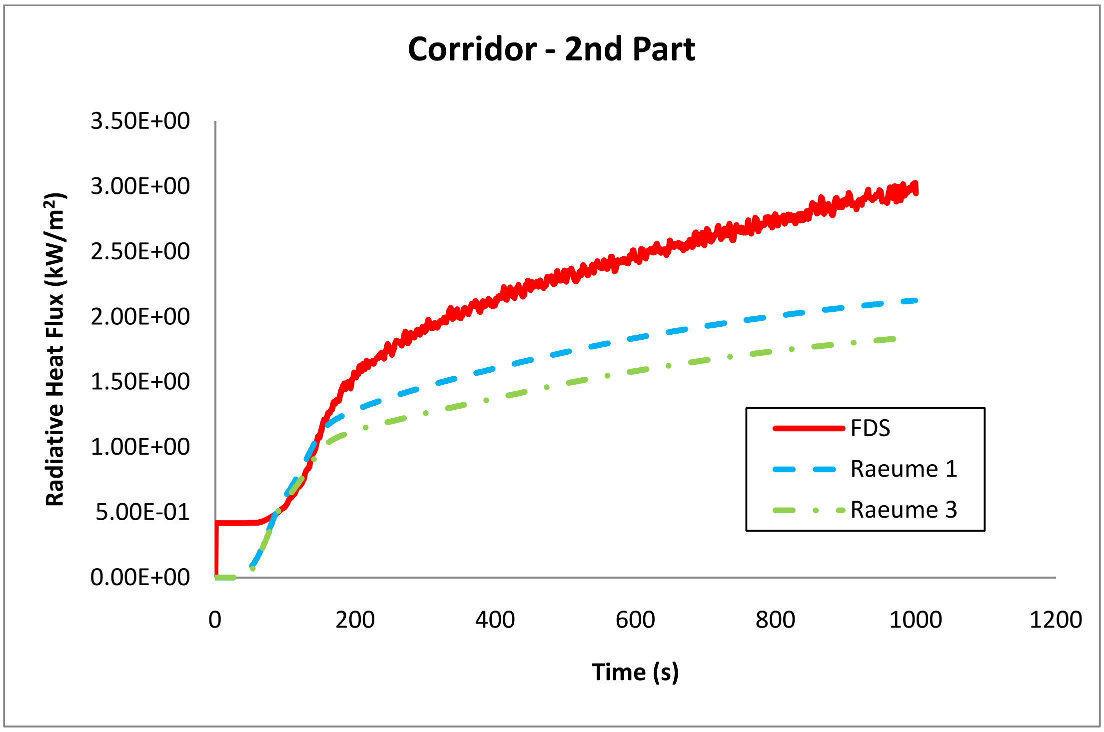

Figure B - 41: Radiative heat flux (kW/m^2) in the second part of the corridor.

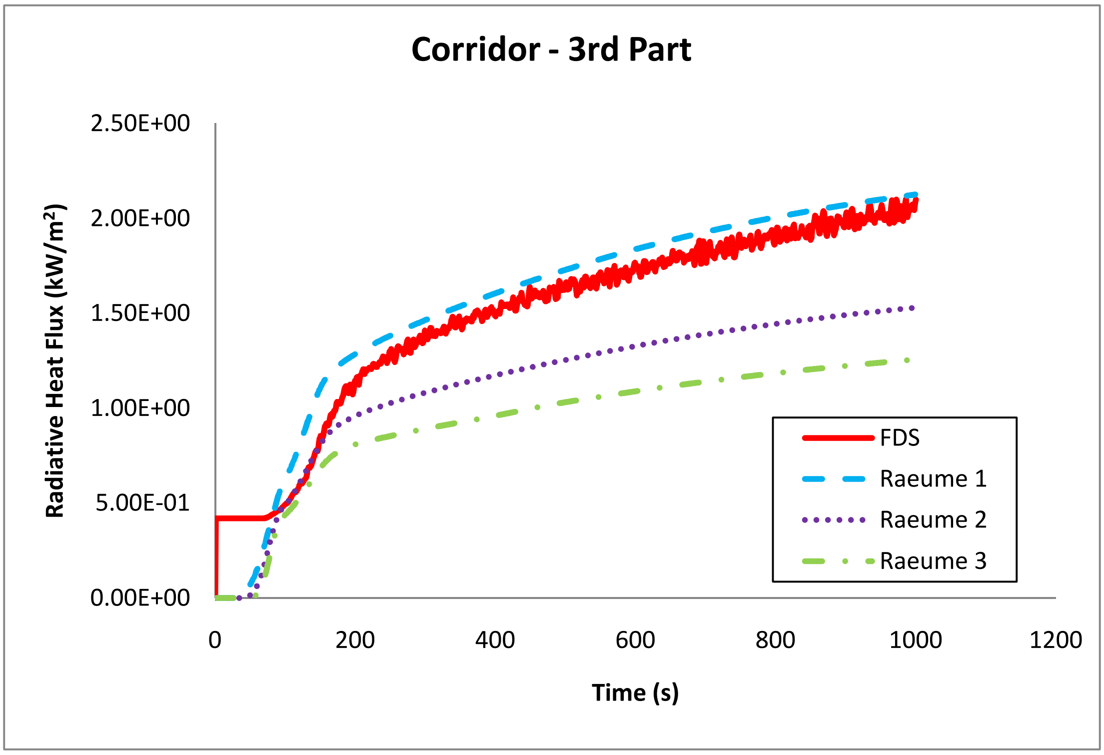

Figure B - 42: Radiative heat flux (kW/m^2) in the third part of the corridor.

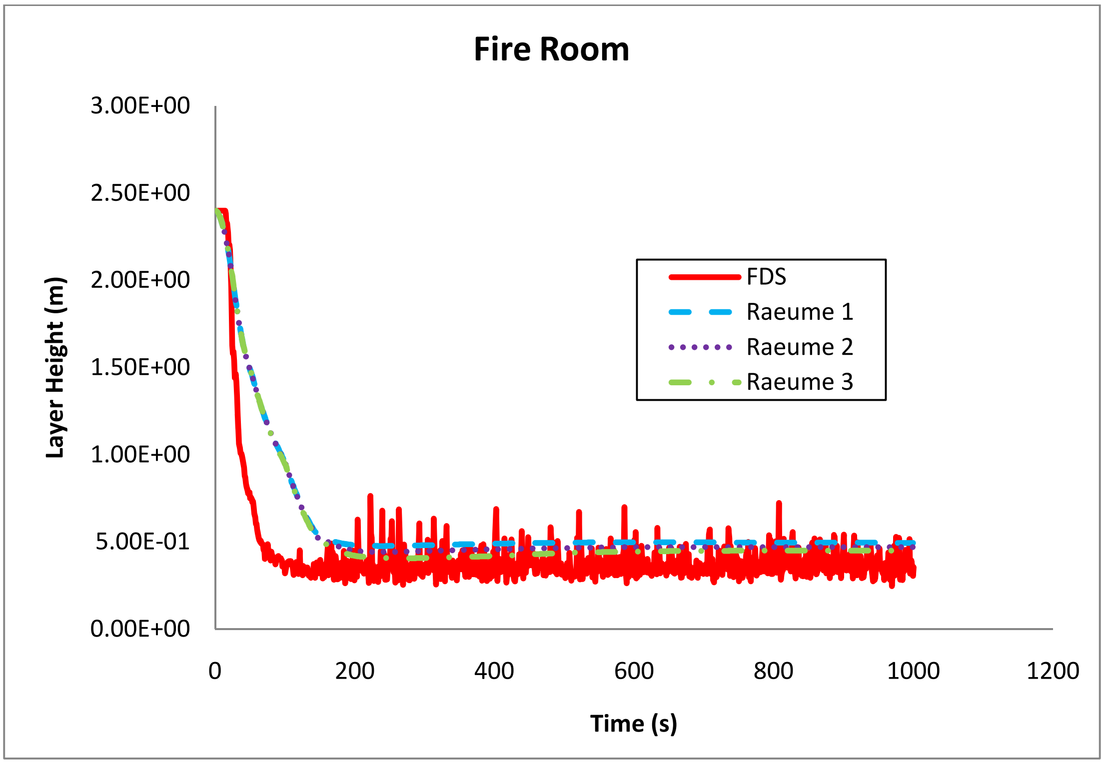

Figure B - 43: Smoke layer interface height (m) in the fire room.

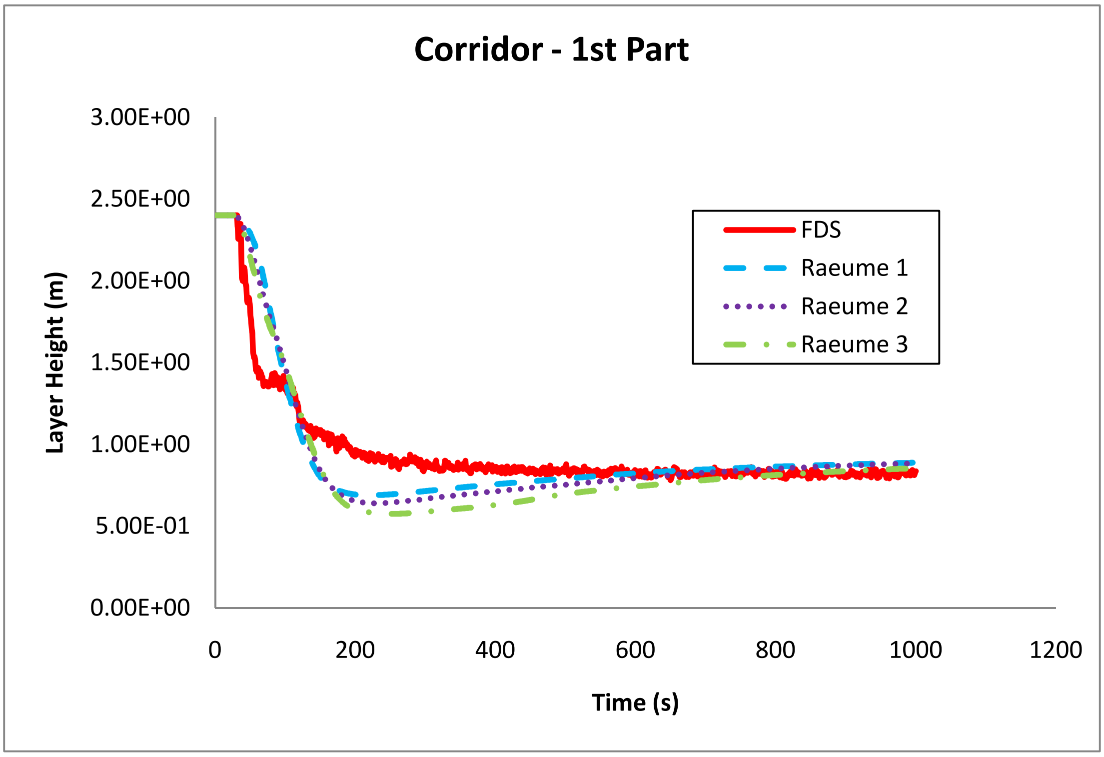

Figure B - 44: Smoke layer interface height (m) in the first part of the corridor.

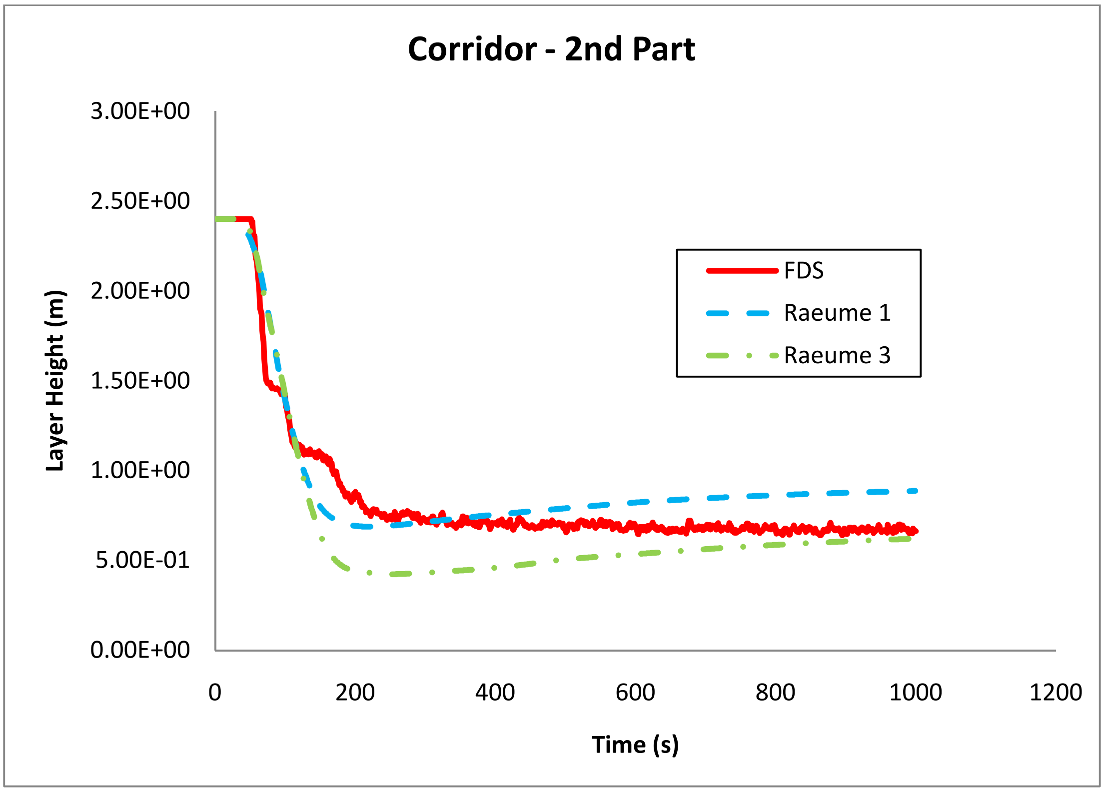

Figure B - 45: Smoke layer interface height (m) in the second part of the corridor.

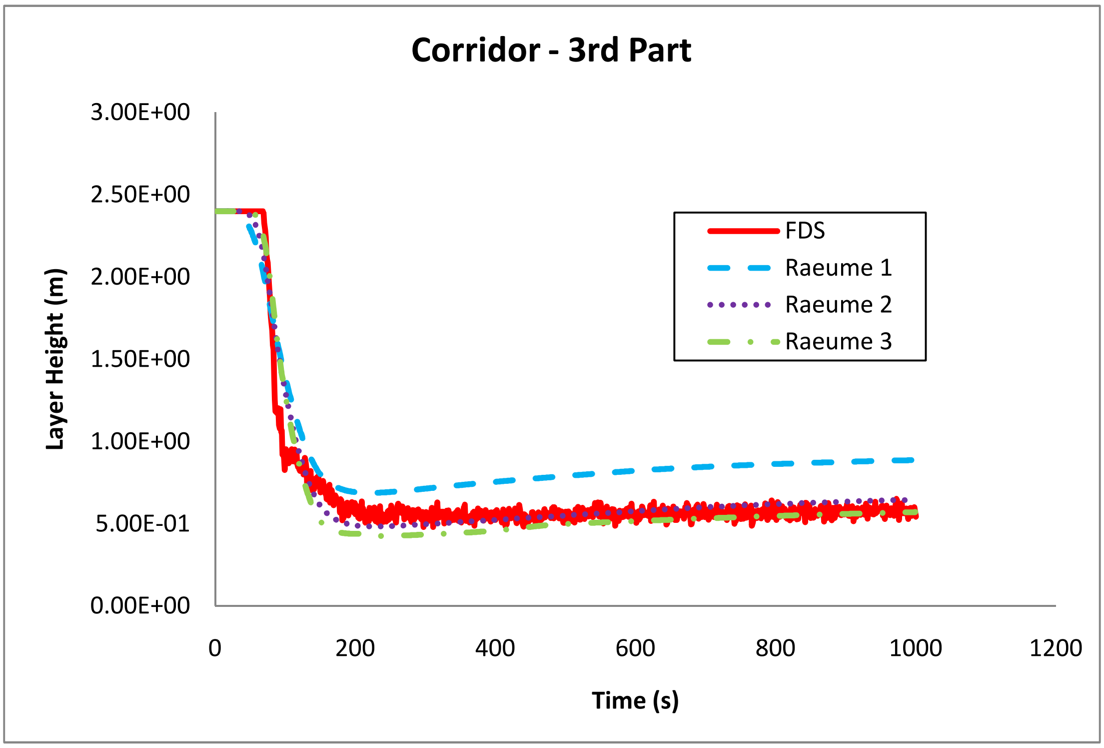

Figure B - 46: Smoke layer interface height (m) in the third part of the corridor.

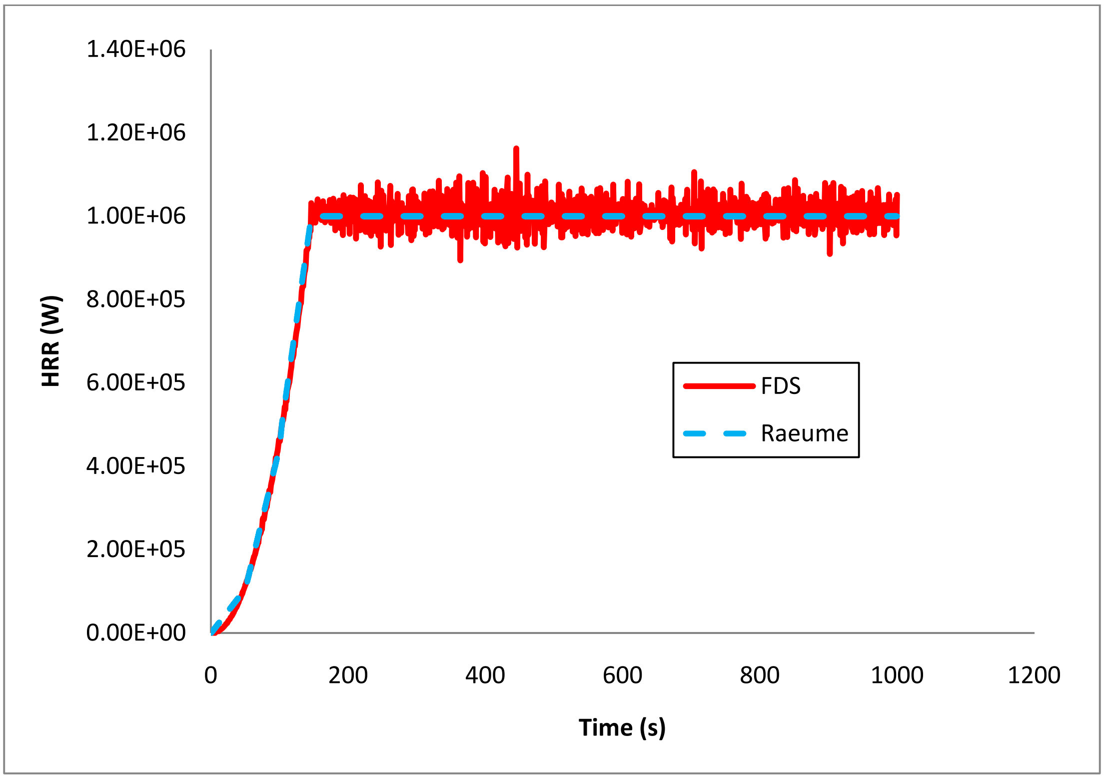

Figure B - 47: Output heat release rate (W) in the fire room.

Appendix C

Data for Fire Modelling

C.1 Boundaries Class Divisions

The different class divisions of the boundaries defined by SOLAS are presented below [SOLAS, 2004]:

"A" class divisions are those divisions formed by bulkheads and decks which comply with the following criteria:

1. they are constructed of steel or other equivalent material;

2. they are suitably stiffened;

3. they are insulated with approved non-combustible materials such that the average temperature of the unexposed side will not rise more than 140°C above the original temperature, nor will the temperature, at any one point, including any joint, rise more than 180°C above the original temperature, within the time listed below:

   - class "A-60" 60 min
   - class "A-30" 30 min
   - class "A-15" 15 min
   - class "A-0" 0 min

4. they are so constructed as to be capable of preventing the passage of smoke and flame to the end of the one-hour standard fire test; and

5. the Administration required a test of a prototype bulkhead or deck in accordance with the Fire Test Procedures Code to ensure that it meets the above requirements for integrity and temperature rise.

“B” class divisions are those divisions formed by bulkheads, decks, ceilings or linings which comply with the following criteria:

1. they are constructed of approved non-combustible materials and all materials used in the construction and erection of "B" class divisions are non-combustible, with the exception that combustible veneers may be permitted provided they meet other appropriate requirements of this chapter;

2. they have an insulation value such that the average temperature of the unexposed side will not rise more than 140°C above the original temperature, nor will the temperature at any one point, including any joint, rise more than 225°C above the original temperature, within the time listed below:

   - class “B-15” 15 min
   - class “B-0” 0 min

3. they are so constructed as to be capable of preventing the passage of flame to the end of the first half hour of the standard fire test; and

4. the Administration required a test of a prototype division in accordance with the Fire Test Procedure Code to ensure that it meets the above requirements for integrity and temperature rise.

C.2 Physical Properties of Materials

The table below presents the physical properties of boundary materials as used for fire modelling:

	Thermal conductivity (W/m.K)	**Specific heat capacity (J/kg.K)**	**Density (kg/m^3)**
Steel	51.9	483	7850
Rockwool	0.041	750	229
Fibre Glass	0.04	720	105

- Thermal conductivity: A physical property of the material presenting its ability to conduct heat (W/m.K).
- Specific heat capacity: The amount of energy required to raise a unit mass of the substance by unit temperature (J/kg.K).
- Density: The mass of material per unit volume (kg/m3).

C.3 Properties of Fuel

The table below presents the properties of fuel as used for fire modelling [SFPE, 2002]:

	Methane	**Wood**	**Upholstery (Polyurethane)**
Heat of combustion (kJ/kg)	50000	16400	24600
Soot yield (g/g)	0	0.015	0.194
CO yield (g/g)	0	0.004	0.028
CO_2 yield (g/g)	2.72	1.33	1.5

- Heat of combustion: The amount of energy released per unit mass of fuel consumption (kJ/kg).
- Soot yield: The fraction of fuel mass converted into smoke particulate (g/g).
- CO yield: The fraction of fuel mass converted into carbon monoxide (g/g).
- CO2 yield: The fraction of fuel mass converted into carbon dioxide (g/g).

C.4 Samples of the Input Files for Simulation Models

Samples of the input files used for the two main fire models used in this study (Raeume and FDS) and the evacuation model (Helios) are presented here. Raeume has its own graphical pre-processor to provide an easier way to generate the input files processed in the model. For Helios, some of the files can be generated by its Graphical User Interface like the geometry associations and passengers' locations files. The other files have to be partially or fully generated manually in form of written scripts. Finally, FDS input files can be generated with some Graphical User Interfaces provided by third parties, like PyroSym for instance [Thunderhead, 2008]. However, in this study, the scripts that constitute the input data were generated manually as described in the User's Guide of FDS. [McGrattan, 2008b].

The input files of the zone fire model **Raeume** are constituted of eight files which define the design fire scenario for numerical simulations. For simplicity the files presented here are those of a single room fire scenario.

"Vertices.dat" contains the vertices of the three dimensional grid representing the corners of each compartment in the domain.

```
8
1, 0.000000, 0.000000, 0.000000
2, 2.800000, 0.000000, 0.000000
3, 0.000000, 2.800000, 0.000000
4, 2.800000, 2.800000, 0.000000
5, 2.800000, 0.000000, 2.180000
6, 2.800000, 2.800000, 2.180000
7, 0.000000, 0.000000, 2.180000
8, 0.000000, 2.800000, 2.180000
-----------------------
nve
nve groups:
ive, xve,   yve,  zve
-----------------------
nve - total number of vertices
ive - vertex index
xve,yve,zve - vertex coordinates

File: Vertices.dat
```

"Direct.dat" is the file which contains all controlling data as initial conditions, constants and controlling parameters for numerical simulations.

```
9.810, 287.143, 30.000, 1005.000, 1.400, 100000.000, 0.000, 2000.000, 1.000
0.100, 0.100, 0.100, 0.100, 0.100, 0.100
1.000, 1.000, 1.000, 1.000, 100, 1.000
-----------------------------------------------------------------
g,    Ru,      Ta,    cp,     gamma, pref,   zref, tf,     dtime
esT0, eq0,     erT0,  ep0,    eV0,   eh0
req,  rep,     reV,   reT,    ntm,   dtp
-----------------------------------------------------------------
g     - gravity acceleration
Ru    - gas constant for air
Ta    - ambient temperature
tf    - final time
dtime - time step size
tolerances:
esT0  - surface temperature
eq0   - net heat flux from a surface
erT0  - gas layer temperature
ep0   - mean room pressure
eV0   - room volume
eh0   - interface height
req   - relxation for fluxes
req   - relxation for room pressure
reV   - relaxation for gas layer volume
reT   - relaxation for gas layer temperature
ntm   - maximum number of iterations
dtp   - time step for output

File: Direct.dat
```

"Walls.dat" is the main source of geometrical data and contains descriptions of all the walls, ceilings and floors in the domain.

```
6
1, 'WL1', 11, 1, 0, 1, 5, 1, 2, 7, 5
2, 'WL2', 11, 1, 0, 1, 5, 2, 4, 5, 6
3, 'WL3', 11, 1, 0, 1, 5, 4, 3, 6, 8
4, 'WL4', 11, 1, 0, 1, 5, 3, 1, 8, 7
5, 'BT_RM1', 11, 1, 0, 1, 1, 1, 2, 3, 4
6, 'CL_RM1', 11, 1, 0, 1, 1, 5, 7, 6, 8
------------------------------------------------------------------
nwg
nwg groups:
iwg, bw, lcw, nlw, nrw, n1s, n2s, iv00, iv01, iv10, iv11
------------------------------------------------------------------
nwg - total number of walls
for each wall:
iwg - number
bw  - text description
lcw - number of composite
nlw - left room
nrw - right room
n1s - discretisation in horisontal direction
n2s - discretisation in vertical direction
iv00 - lower left corner of the wall
iv01 - lower right corner of the wall
iv10 - upper left corner of the wall
iv11 - upper right corner of the wall

File: Walls.dat
```

"Vents.dat" describes the locations, dimensions and properties of all the vents in the domain like doors and windows.

```
1
1, 'VT1', 1, 0, 0.000000, 1.830000, 0.700000, 0.740000, 0.0, o
----------------------------------------------------------------------
nvg
nvg groups:
ivg, bv, nlv, nrv, h1,   h2,     coef,  breite,  laenge, lvo
----------------------------------------------------------------------
nvg    - total number of vents
for each vent:
ivg    - number
bv     - text description
nlv    - number of room to the left
nrv    - number of room to the right
h1     - height of commings
h2     - overall height
coef   - flow coefficient
breite - width
laenge - length of the horizontal projection
lvo    - switch: o for open, c for closed

File: Vents.dat
```

"*Fans.dat*" describes properties of all fans existing in the domain.

```
0
-----------------------------------------------------------------------------------
nb
Do i= 1, nb
ib,  bb,  nlb,  nrb,   dpb0, Vpb0,  Lbl,  Lbr,  Cbw,  Sb,     zb,    Db,    Cb,  lbo
End Do
-----------------------------------------------------------------------------------
nb   - number of fans
For each fan:
ib   - index of fan
bb   - text description
nlb  - number of room from where
nrb  - number of room to where
dpb0 - pressure head for zero volume rate
Vpb0 - volume flow rate for zero pressure difference
Lbl  - part of the length in the room from where
Lbr  - part of the length in the room to where
Cbw  - friction coefficient
Sb   - area of the cross-section
zb   - absolute height of the lower edge
Db   - height
Cb   - flow coefficient
lbo  - switch: o for open, c for closed

File: Fans.dat
```

"*Fires.dat*" provides the locations and properties of the fires in the domains.

```
1
1, 'FR1', 2, 1, 0.000000, 0.000000, 1.400000, 1.400000, 0.300000, 0.300000, p
-------------------------------------------------------
nfg
ifg, bf, lfu, nrf, Tig, Df,  xf,  yf,  zf,   hf,   lf
-------------------------------------------------------
nfg  - total number of fires, then for each fire:
ifg  - number of fire
bf   - text description of fire
lfu  - number of fuel from the database
nrf  - number of room
Tig  - ignition temperature
Df   - pool fire diameter
xf   - x-coordinate
yf   - y-coordinate
zf   - z-coordinate of the bottom of fire
hf   - height of the fire
lf   - fire type (p pool, w wall, v volume)

File: Fires.dat
```

"Qt.dat" describes the time histories of fire heat release rates.

```
1

0, 0.00
1, 62900.00
600, 62900.00
2000, 62900.00
2001, 0.00
99999
99999

File: Qt.dat
```

"Rooms.dat" describes the number of rooms their surfaces and heights.

```
1
1, 'RM1', 0.000000, 2.180000, 7.840000, 1
-----------------------------------------
nrg
0:nrg groups:
irg, br, z0r, hoer, Sbot
-----------------------------------------
nrg - total number of rooms
0:nrg groups (0 for ambient air outside):
irg  - number of room
br   - text description
z0r  - bottom level
hoer - height
Sbot - area of the floor

File: Rooms.dat
```

These input files are supplemented by a database library containing the required information about fuel characteristics and the boundary materials properties.

The input file of the field fire model **FDS** for a single room fire scenario is illustrated below. The script defines the domain, grid, boundaries, fire characteristics and all the measurements devices.

```
&HEAD CHID='Steckler', TITLE='Input file for Steckler room' /


&MESH IJK=50,27,24, XB=0.0,5.0,0.0,2.8,0.0,2.18 /

&TIME TWFIN=250.0 /

&MISC SURF_DEFAULT='INSULATION'
      TMPA=30                      /

&DUMP NFRAMES=25
      DT_RESTART = 50 /

&REAC ID                 ='METHANE'
      C                  =1.
      H                  =4.  /

&RADI RADIATIVE_FRACTION=0.15 /

&MATL ID                 ='FIBRECER'
      CONDUCTIVITY       = 0.04
      SPECIFIC_HEAT      = 0.7
      DENSITY            = 105.
      EMISSIVITY         = 0.9 /

&SURF ID                 = 'INSULATION'
      MATL_ID            = 'FIBRECER'
      COLOR              = 'KHAKI'
      THICKNESS          = 0.1 /

&SURF ID='BURNER',HRRPUA=698.888, COLOR='RED' /

&VENT XB= 3.45, 3.75, 1.25, 1.55, 0.0, 0.0, SURF_ID='BURNER' /

&OBST XB= 2.1, 2.2, 0.0, 1.03, 0.0, 2.18 /
&OBST XB= 2.1, 2.2, 1.77, 2.8, 0.0, 2.18 /
&OBST XB= 2.1, 2.2, 1.0, 1.8, 1.83, 2.18 /

&VENT XB= 0.0, 0.0, 0.0, 2.8, 0.0, 2.18, SURF_ID='OPEN' /
&VENT XB= 0.0, 2.2, 0.0, 0.0, 0.0, 2.18, SURF_ID='OPEN' /
&VENT XB= 0.0, 2.2, 2.8, 2.8, 0.0, 2.18, SURF_ID='OPEN' /
&VENT XB= 0.0, 2.2, 0.0, 2.8, 2.18, 2.18, SURF_ID='OPEN' /

** Thermocouples on the corner 0.305 by 0.305 **

&DEVC XYZ=2.505,0.305,0.0,QUANTITY='TEMPERATURE' /
&DEVC XYZ=2.505,0.305,0.1,QUANTITY='TEMPERATURE' /
&DEVC XYZ=2.505,0.305,0.2,QUANTITY='TEMPERATURE' /
&DEVC XYZ=2.505,0.305,0.3,QUANTITY='TEMPERATURE' /
&DEVC XYZ=2.505,0.305,0.4,QUANTITY='TEMPERATURE' /
&DEVC XYZ=2.505,0.305,0.5,QUANTITY='TEMPERATURE' /
&DEVC XYZ=2.505,0.305,0.6,QUANTITY='TEMPERATURE' /
&DEVC XYZ=2.505,0.305,0.7,QUANTITY='TEMPERATURE' /
&DEVC XYZ=2.505,0.305,0.8,QUANTITY='TEMPERATURE' /
&DEVC XYZ=2.505,0.305,0.9,QUANTITY='TEMPERATURE' /
&DEVC XYZ=2.505,0.305,1.0,QUANTITY='TEMPERATURE' /
```

FDS input file *(cont'd)*

```
&DEVC XYZ=2.505,0.305,1.1,QUANTITY='TEMPERATURE' /
&DEVC XYZ=2.505,0.305,1.2,QUANTITY='TEMPERATURE' /
&DEVC XYZ=2.505,0.305,1.3,QUANTITY='TEMPERATURE' /
&DEVC XYZ=2.505,0.305,1.4,QUANTITY='TEMPERATURE' /
&DEVC XYZ=2.505,0.305,1.5,QUANTITY='TEMPERATURE' /
&DEVC XYZ=2.505,0.305,1.6,QUANTITY='TEMPERATURE' /
&DEVC XYZ=2.505,0.305,1.7,QUANTITY='TEMPERATURE' /
&DEVC XYZ=2.505,0.305,1.8,QUANTITY='TEMPERATURE' /
&DEVC XYZ=2.505,0.305,1.9,QUANTITY='TEMPERATURE' /
&DEVC XYZ=2.505,0.305,2.0,QUANTITY='TEMPERATURE' /
&DEVC XYZ=2.505,0.305,2.1,QUANTITY='TEMPERATURE' /
&DEVC XYZ=2.505,0.305,2.18,QUANTITY='TEMPERATURE' /

** Thermocouples on the door way **

&DEVC XYZ=2.15,1.4,0.0,QUANTITY='TEMPERATURE' /
&DEVC XYZ=2.15,1.4,0.1,QUANTITY='TEMPERATURE' /
&DEVC XYZ=2.15,1.4,0.2,QUANTITY='TEMPERATURE' /
&DEVC XYZ=2.15,1.4,0.3,QUANTITY='TEMPERATURE' /
&DEVC XYZ=2.15,1.4,0.4,QUANTITY='TEMPERATURE' /
&DEVC XYZ=2.15,1.4,0.5,QUANTITY='TEMPERATURE' /
&DEVC XYZ=2.15,1.4,0.6,QUANTITY='TEMPERATURE' /
&DEVC XYZ=2.15,1.4,0.7,QUANTITY='TEMPERATURE' /
&DEVC XYZ=2.15,1.4,0.8,QUANTITY='TEMPERATURE' /
&DEVC XYZ=2.15,1.4,0.9,QUANTITY='TEMPERATURE' /
&DEVC XYZ=2.15,1.4,1.0,QUANTITY='TEMPERATURE' /
&DEVC XYZ=2.15,1.4,1.1,QUANTITY='TEMPERATURE' /
&DEVC XYZ=2.15,1.4,1.2,QUANTITY='TEMPERATURE' /
&DEVC XYZ=2.15,1.4,1.3,QUANTITY='TEMPERATURE' /
&DEVC XYZ=2.15,1.4,1.4,QUANTITY='TEMPERATURE' /
&DEVC XYZ=2.15,1.4,1.5,QUANTITY='TEMPERATURE' /
&DEVC XYZ=2.15,1.4,1.6,QUANTITY='TEMPERATURE' /
&DEVC XYZ=2.15,1.4,1.7,QUANTITY='TEMPERATURE' /
&DEVC XYZ=2.15,1.4,1.8,QUANTITY='TEMPERATURE' /

** Velocity Probes on door way **

&DEVC XYZ=2.15,1.4,0.0,QUANTITY='U-VELOCITY' /
&DEVC XYZ=2.15,1.4,0.1,QUANTITY='U-VELOCITY' /
&DEVC XYZ=2.15,1.4,0.2,QUANTITY='U-VELOCITY' /
&DEVC XYZ=2.15,1.4,0.3,QUANTITY='U-VELOCITY' /
&DEVC XYZ=2.15,1.4,0.4,QUANTITY='U-VELOCITY' /
&DEVC XYZ=2.15,1.4,0.5,QUANTITY='U-VELOCITY' /
&DEVC XYZ=2.15,1.4,0.6,QUANTITY='U-VELOCITY' /
&DEVC XYZ=2.15,1.4,0.7,QUANTITY='U-VELOCITY' /
&DEVC XYZ=2.15,1.4,0.8,QUANTITY='U-VELOCITY' /
&DEVC XYZ=2.15,1.4,0.9,QUANTITY='U-VELOCITY' /
&DEVC XYZ=2.15,1.4,1.0,QUANTITY='U-VELOCITY' /
&DEVC XYZ=2.15,1.4,1.1,QUANTITY='U-VELOCITY' /
&DEVC XYZ=2.15,1.4,1.2,QUANTITY='U-VELOCITY' /
&DEVC XYZ=2.15,1.4,1.3,QUANTITY='U-VELOCITY' /
&DEVC XYZ=2.15,1.4,1.4,QUANTITY='U-VELOCITY' /
&DEVC XYZ=2.15,1.4,1.5,QUANTITY='U-VELOCITY' /
&DEVC XYZ=2.15,1.4,1.6,QUANTITY='U-VELOCITY' /
&DEVC XYZ=2.15,1.4,1.65,QUANTITY='U-VELOCITY' /
&DEVC XYZ=2.15,1.4,1.7,QUANTITY='U-VELOCITY' /
&DEVC XYZ=2.15,1.4,1.75,QUANTITY='U-VELOCITY' /
&DEVC XYZ=2.15,1.4,1.8,QUANTITY='U-VELOCITY' /

&TAIL /
```

The input files processed in the evacuation model **Helios** to produce the final results are presented here. These include the geometrical arrangements and passengers' properties files.

The first script is the *main* file which loads the geometrical arrangements of the domain and calls the rest of the files by locating their folders.

```
loadModel C:/Evacuation/SOLAS/raeume.tri m1;

source C:/Evacuation/SOLAS/SOLAS.wall;

source C:/Evacuation/SOLAS/SOLAS.env;

source C:/Evacuation/SOLAS/raeume.ppl;

source C:/Evacuation/SOLAS/SOLAS.tsk;

source C:/Evacuation/SOLAS/SOLAS.obs;

source C:/Evacuation/SOLAS/SOLAS.speed;
```

The *wall* file describes the escape route where some exits are blocked or restricted.

```
addClickedPoint * 17.475906 5.946982 0.000000 0;
addClickedPoint * 18.166899 6.556299 0.000000 0;

addClickedPoint * 8.854338 6.557461 0.000000 0;
addClickedPoint * 9.570474 7.515189 0.000000 0;

selectWalls *;
  constrainSelectedWalls;
   forceCompileComponents;
   clearPoints *;
   deselectAllWalls;
```

The *speed* file specifies the initial walking speed for all the evacuees.

```
setSpeedOfThesePeople *  [new_NormalDistribution 1.1 0.1]
```

The *task* file assigns the subsequent tasks (waiting and walking) for all the passengers

```
beginAnnot goto1;
cellForCurrentAnnot 0.603023 15.755835 0.000000 0;
endAnnot;
taskGoto goto goto1 3;

taskWait wait1 [new_UniformDistribution 1020 1140];
assignTaskToAll wait1 20 0;
assignTaskToAll goto1 10 0;
```

The *observer* file defines all the devices that record the required final results.

```
proc C:/Evacuation/SOLAS/numFatalities {} {
    return [categorizedFatalities *];
}

proc C:/Evacuation/SOLAS/numInDeck0 {} {
  return [getNumberOfPeopleInDecks  *evel-0]
}

observer C:/Evacuation/SOLAS/numInDeck0 "Number of people in the fire deck"
0.0
observer C:/Evacuation/SOLAS/numFatalities "Number of deaths"  0.0
startRecordingFEDGroups "C:/Evacuation/SOLAS/fed_groups.csv"
```