# Computer Simulation of Residential Natural Ventilation Smoke Control System

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A thesis submitted in partial fulfilment of the requirement of the University of Greenwich for the Degree of Master of Philosophy

**December 2017**

# DECLARATION

I certify that the work contained in this thesis, or any part of it, has not been accepted in substance for any previous degree awarded to me, and is not concurrently being submitted for any degree other than that of Master of Philosophy (MPhil) being studied at the University of Greenwich. I also declare that this work is the result of my own investigations, except where otherwise identified by references and that the contents are not the outcome of any form of research misconduct.

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# ACKNOWLEDGEMENTS

I cordially thank my supervisor Dr Zhaozhi Wang, for his guidance, support, useful suggestions and strong motivation throughout in accomplishing my task and also for introducing me to new software's. I would also like to thank Professor Mayur Patel for his continuous support and guidance during research period. I would like to thank Professor Ed Galea for giving me the opportunity to show my research skills and allowing me to contribute my work in the research field.

# ABSTRACT

The main objective of the research is to explore the potential benefits of natural ventilation systems in domestic dwelling applications using SMARTFIRE CFD based fire simulation software and EXODUS evacuation simulation software. Based on the objective of natural ventilation system a detailed literature review has been performed and a new methodology has been proposed to understand the development of house fire with limited ventilation. The enhancement to fire modelling in terms of smoke removal using roof top vent through this study identifies the different vent sizes, positions and scenarios that can occur in a house. The proposed methodology uses the HRR curve method (simulation-correction method) which allows to design any fire realistic for any house structure. This study also proposes a solution to analyse the potential benefits or the risks involved using the roof top vent as the source of removal of smoke. And finally a survivability analysis will help to conclude the roof top vent application impact on survivability. Under an assumption that the fire is fixed with and without a top open, this study has demonstrated that a top vent is able to improve the dwelling survivability and the improvement in closed bedrooms just with leakages at the doorway is significant.

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# Glossary

CFD: Computational Fluid Dynamics

FDS: Fire Dynamic Simulator

FSEG: Fire Safety Engineering Group

HRR: Heat Release Rate

MLR: Mass Loss Rate

IVS: Impulse Ventilation System

CCVC: Corner Ceiling Vented Cabin

SMARTFIRE: CFD software used in the research

EXODUS: Evacuation Model Software

SOFIE: CFD software

NIST: National Institute of Standards and Technology

# Nomenclature

$\dot{Q}$= Heat Release Rate

α = Fire Growth Coefficient

$\Delta H_c$ = Heat of Combustion

$X_{O_2}$= Stoichiometric ratio

γ = Oxygen Mass Fraction

$m_a$ = Air Mass Flow Rate

$R$ = Equivalence Ratio

ρ = Fluid Density

ρU = the momentum flux density

$P$ = pressure

$v$ = specific volume

$Q$ = heat added to control volume

$W$ = work done by the control volume

$e$ = energy level

$pv$ = flow work

$\phi$ = dependent variable

$\Gamma_\phi$ = exchange coefficient and

$S_\phi$ = source term

$G_k$ = Shear production and

$G_B$ = Buoyancy production

$m_j$ = mass fraction of species

$S_j$ = mass rate of creation

$\Gamma_j$ = exchange coefficient of species

# Chapter 1

# Introduction and Research Background

## 1.1 Introduction

In modern society everyday safety is very essential but more or less it is taken for granted. Correct safety designs and the skills of the fire brigades are very vital in everyday safety. In today's era everyday fire procedures are becoming more complex, methods for fire safety and protection will have to develop continuously to improve everyday safety and living conditions. In order to understand, the kind of fire, firstly the cause of fire needs to be predicted. And to study the influence of fire on the environment different scientific methods are employed, including experimental studies and mathematical fire modelling. Full-scale experiments are expensive to perform and requires considerable amount of work. Since experiments are not used in ordinary building design but they have importance as a tool for the fire researchers and engineers. Usually small scale experiments are performed to understand the phenomenon of fire. In small scale experiments the geometry is scaled to more convenient proportions, for example to 1/3 of the true scale [Karlsson, *et al*., Chapter 1 and 10, 2000]. Thus using the results recorded from these small scale experiments mathematical models, hand calculation numerical methods and computer-based CFD models can be evaluated. It is not necessary that the experimental results are entirely accurate. There are errors present in experimental or numerical modelling, sometimes they are more significant and sometimes they are less significant but one can say that errors are present [Karlsson, *et al*., Chapter 10, 2000]. Mathematical models in fire science use different ways to explain fire phenomena based on analytical and numerical techniques. Due to growing increase in scientific models and understanding of fire and due to an easy access to powerful computers, progress has been made when predicting smoke phenomena, presence and concentration levels of combustible and toxic gases, calculation of temperature and pressure and flow of air through the enclosures due to fire, etc. [Karlsson, *et al*., Chapter 5, 6, and 7, 2000].

Computer modelling of fire has increased significantly during the last few decades. In computer modelling of fires in enclosures it is based on zone modelling and field modelling using CFD techniques [Karlsson, *et al*., Chapter 1 and 10, 2000].

## 1.2 Research Background and Motivation

Ventilations systems have been the basic means of removal of smoke in case of fire incidents, whether it is a domestic dwelling structure or complex structures which use natural or mechanical ventilation. They are widely used across the world for their potential use and how it provides help to the occupants in case of evacuation [The Building Regulations, GOV of UK, 2010, Domestic Ventilation Compliance Guide, 2010]. In case of fire the main cause of deaths is when people overcome to smoke and other toxic gases [Fire Statistics Great Britain, GOV of UK, 2012]. If the ventilation system enables to reduce the smoke and toxic gases level at the point that it helps the people to find the way to the emergency exits then their potential usage can be appreciated. They play an important role in finding the nearest exit. If the level of smoke near the emergency exit is high enough that occupants cannot see the exits door then it's difficult for the occupant to find another way and survive as well [Building Regulations, Fire Safety, GOV of UK, 2000].

The design and installation of ventilation systems are prescribed by the related regulations and standards depending on the type of ventilation (natural or mechanical ventilation) which describes the design, shape, size and the location of the ventilation system. However there is a lack of understanding about how the occupants will utilise the ventilation system when they need to. There is also a lack of methods to estimate the effectiveness of the ventilation systems. This has raised a lot of interest in the research and it has been suggested that a good number of physical aspects can influence the effectiveness of the ventilation system. Few of them are the position of the vents, presence of smoke, oxygen limits [Drysdale, 1985].

As we are considering the natural ventilation to be used so windows and doors opening fire scenarios are very relevant to study. Compartment fire scenario provides the basis to understand the impact of the fire in an enclosure which can relate to room fires in houses [Thomas 1974, Zukoski 1985, Karlsson *et al.*, 2000, Yii *et al.*, 2005, Mercia *et al.*, 2007, Mercia *et al.*, 2008, Man *et al.*, 2013., Bing *et al.*, 2013, Zhang *et al.*, 2013, Jian *et al.*, 2014, He *et al.*, 2014]. Compartment fires using door openings and roof openings were studied thoroughly and calculations based on the temperature and the flow of air through the openings and the pressure across the opening were mainly discussed [Yii *et al.*, 2005, Mercia *et al.*, 2007, Mercia *et al.*, 2008, Man *et al.*, 2013., Bing *et al.*, 2013, Jian *et al.*, 2014]. Experimental studies using compartment fire with door opening and roof opening showed that the mass loss rate (MLR) is influenced by the size of the roof vent. Since the door was opened along with the vent so there is enough air coming in the fire compartment through the two openings to allow it to burn for a longer time, which resulted in high temperatures. Numerous experiments have been conducted using only the door as the only ventilation in compartment fire scenarios.

Along with the compartment fires with vertical openings there are few studies that involve horizontal openings in a house fire [Stephen 2013, Lennon 2013, Yuen *et al.*, 2014]. But there is a lack in modelling the burning rate (fuel loss rate) considering the limited ventilation. Since most of the enclosure fires and house fires are ventilation controlled fires. Thus oxygen plays an important role to control the fire. Oxygen limiting values need to be studied to understand the factors that relate to oxygen limits [Drysdale, 1985].

The rapid development of the computer fire modelling techniques enables to study the occupant's survival chances in case of fire in the particular structure. Also it helps to improve the positioning and the modelling of the ventilation system which later can be used to study the real life scenario more closely in both with and without fire conditions. However most of the simulation models lack the capability to represent the interaction between the occupant and the smoke.

In terms of comparing the different measures present in the market which can be used for the purpose of removing smoke and toxic gases and improving atmospheric conditions during fire, a brief comparison is made here.

The fire doors may be cheaper to use in the dwelling structures than the cost for other methods and especially compared to roof top natural ventilation system. The fire door is able to stop the flaming fire to spread to the bedrooms with certain door burn-through time. However, the smoke can enter the rooms via the gap between the door and the frames even the door is closed. Therefore, the main aim of the research is to remove smoke and make the conditions better enough so that the occupant can stay inside for longer duration until the fire fighters rescue them. With fire doors it will not make the condition better because there are gaps and leakages around the door which can make the surrounding conditions worse. Whereas compared to other methods the natural ventilation system might be cost effective. With similar expense or more the fire door will not be able to fulfil the objective of removing smoke and toxic gases from the building whereas this method will be better for smoke removal.

Since an average cost for a single fire doors is £54-575 [https://wisetradesmen.com/list/how-much-do-fire-doors-cost] so based on the number of doors in the house the cost will vary. Similarly using a small sized ventilation fan will cost, £130-800 for a single fan [http://www.nfan.co.uk/store/category/types_extractor_fans].

Thus [http://www.ashfire.co.uk/] Ash Fire Management has potential customers and have installed this system. There is a potential usage of this design in the market. Since the cost of this system is not available but still depending on the demand of this system. From the Ash Fire Management it is concluded that there is a substantial market for its usage.

## 1.3 Research Question

A natural ventilation system as an evolutionary solution to toxic smoke control by removing the smoke from the building is now moving into the building market [http://ashfire.co.uk/naturvent.html]. This system is an attempt to improve the survivability chances of the occupants inside the structure by increasing the rescue time and to preserve the structural integrity. However, less studies have been conducted on the performance of such a system in terms of fire safety. The following research question has been raised to identify the research knowledge gap:

**Can a top natural ventilation system efficiently improve the survivability in domestic dwelling?**

Associated the above fundamental question, some sub-questions need to be considered

- How does the limited ventilation affect the heat release rate (HRR) of dwelling fires?
- What factors of a vent affect its function in smoke removal?

## 1.4 Research Objectives and Approach

To address the research question the following objectives are described:

- To develop a methodology to produce the HRR curve for dwelling fire considering the limited ventilations;
- To investigate the fire development inside the dwelling with prescribed fire sources under various top vent options;
- To examine the survivability of the investigated dwelling with the predicted atmospheric conditions;

Based on the research question and the objectives the approach will be applied in a way that different size of top vent, at different location with a modified T-square HRR curve for fire will be studied. This will help to analyse the vent size and location that can be beneficial for domestic structure in case of fire. Since the top vent will be used for the removal of smoke, the levels of toxic gases, smoke and temperature will be studied at critical locations to determine the effect of top vent on fire. All the data collected from fire modelling tool (SMARTFIRE) will be analysed by the evacuation modelling tool (buildingEXODUS) to study the impact of smoke, temperature and toxic gases on the survivability of the occupants presenting inside the building during fires.

## 1.5 Structure of Thesis

This report includes the progress of the study and the work towards the final MPhil. This report is consisted of eight chapters.

**Chapter 1 Introduction and Research Background**

The research question has been raised and the objectives have been proposed in this chapter.

**Chapter 2 Literature Review**

This chapter presents a literature review of existing studies and the knowledge gap based on the fire modelling and existing fire models for natural ventilation systems.

**Chapter 3 Fire and Evacuation Modelling**

This chapter describes the CFD fire modelling and evacuation modelling followed by a case study.

**Chapter 4 Derivation of Heat Release Rate (HRR) Curve for under-ventilated Fires**

This chapter proposes a methodology that can be used to derive the HRR for dwelling fires with various ventilations.

**Chapter 5 Fire Safety Assessment of Dwelling Top Vent—Fire Simulation**

This chapter presents the detailed research work with fire modelling the impact of top vent on fire development inside the dwelling.

**Chapter 6 Fire Safety Assessment of Dwelling Top Vent—Survivability Analysis**

This chapter includes the evacuation modelling research work. The fire hazards output from the fire modelling are used to examine the survivability in this chapter.

**Chapter 7 Conclusion**

This chapter includes the conclusions drawn from the results obtained from fire modelling and survivability analysis using top vent dwelling application.

**Chapter 8 Future Work**

This chapter describes the future work that can be done to improve the top vent application in dwelling fire scenarios based on the limits of the current study.

# Chapter 2

# Literature Review

## 2.1 Introduction

In this chapter the ventilation system in fires mainly the natural ventilation system is reviewed. There are usually two types of ventilation systems that are employed in the buildings or structures. These systems should follow the building regulations approved by the governments. Mostly the two types of ventilation system that are employed in the buildings [The building regulations 2000, Ventilation, GOV. UK] are:

1. Natural Ventilation System
2. Mechanical Ventilation System

A more detailed explanation of the types of ventilation system is described below.

### 1. Natural Ventilation System

Natural Ventilation enables fresh air to enter through the facade or roof windows. Natural Ventilation systems can be of different kind, doors, windows, roof top openings, air bricks are the main types of natural ventilation components used. The driving forces in natural ventilation are thermal buoyancy and wind pressure on buildings. The building design, form of the window opening and their location has significant impact on the occupants inside the house and also greatly influences the fire conditions inside the building. Natural ventilation system relies on the wind and the design of the house. In UK, doors and windows are placed according to the building regulations for ventilation [The building regulations 2000, Ventilation, GOV. UK] which contribute to the effect of these ventilation systems to the safety and the usage of the occupants inside the house. Also they are placed in accordance to the fire incidents. Especially the windows and doors of the kitchen greatly affect the structure of the house for fire incidents. Not much attention is paid to improve the safety of the occupants based on the natural ventilation systems. For the purpose of this many experimental and numerical investigations are available for house/dwelling fires. However there are not many specially designed natural ventilation systems for the purpose of fire safety in dwellings. Thus this factor needs to be highlighted and reviewed using natural ventilation system for residential houses.

### 2. Mechanical Ventilation System

Mechanical ventilation systems are used widely across the world. They can be found in complex enclosed structures like road tunnels, underground car parks and underground stations. Jet fans are the main source of mechanical ventilation. In both tunnels and car parks they are installed based on the building regulations and fire safety. They help to control indoor air quality. Excess humidity, odours, and contaminants can often be controlled via dilution or replacement with outside air using jet fans. Similarly in case of fire incident the jet fans acts as a source to remove the smoke that's been released from the burning fuel inside the structure [The building regulations 2000, Ventilation, GOV. UK].

## 2.2 Experimental Studies

This section focuses on the natural ventilation. Scenarios with roof top along with open doors or windows have been investigated thoroughly [Thomas 1974, Zukoski 1985, Karlsson *et al*., 2000, Yii *et al*., 2005, Mercia *et al*., 2007, Mercia *et al*., 2008, Man *et al*., 2013., Bing *et al*., 2013, Zhang *et al*., 2013, Jian *et al*., 2014, He *et al*., 2014]; the flow at the door way, the shape of the fire, the ventilation and the impact of the ventilation has been investigated as well. Numerous small and large scale tests have been carried out which showed the impact on the mass loss rate, and the oxygen concentration inside the compartment and how these factors are influenced by the ventilation [Zukoski 1985, Yii *et al*., 2005, Mercia *et al*., 2007, Mercia *et al*., 2008, Man *et al*., 2013., Bing *et al*., 2013, Zhang *et al*., 2013, Jian *et al*., 2014, He *et al*., 2014].

### 2.2.1 Experiments with Side Doors and Windows

There are many experiments that have been conducted at different levels to understand the behaviour of fire under limited ventilation.

Studies based on the door openings have been the focal point to study the compartment fire behaviour. Many experiments have been conducted at different levels to understand the compartment fire behaviour with door opening. Most of the compartment fire experiments include fixed fire i.e. pool fires. The series of compartment fires investigated by [Steckler *et al*., 1982] provides one of the more satisfactory test cases, although the particular place of fire source, where the changes are occurring are very noticeable. 55 full scale experiments were carried out to study the fire in the compartment with flow simulated by a fire. The air flow rate through the openings and the boundaries affecting the fire plume entrainment rate are described as a function of opening geometry which is the door, fire intensity and location of fire. And the opening flow rate also depends on the temperature distribution along the room. Since there was not much systematic studies available for the fire induced flows or fires involving air entrainment through the opening during that time. Thus this case gave the basis to introduce new methods and models to better understand the flow rates and other physical features related to fire closely.

Since the openings in the structure have to be evaluated to get the better picture, smallest openings are easy to evaluate and they have good ventilation limits, whereas the larger openings show drastic changes around in temperature and flow rate. The wind enhances the flow rate and the air entrainment rate. [Steckler *et al*., 1982] The rate of flow in this study is predicted for different openings but usually all the openings that were considered were smaller openings whereas in general it is not the case. The flow at the doorway was investigated thoroughly as well [Zukoski *et al*., 1985, and Nakaya *et al*., 1985].

Many experiments have focused on the door opening scenario to understand the impact of air on fire in a compartment [Cooke *et al*., 1998, Thomas *et al*., 1999, Walton *et al*., 2002, A.R. Parkes *et al*., 2005, Choel-Hong *et al*., 2010]. In under-ventilated fires the influence of the environmental variables on the heat release rate has been reported to be most important [Quintiere 2006, Tewarson *et al*., 1981, and Santo *et al*., 1981]. The influence on the heat release rate, and particularly on the fuel mass loss rate, has been investigated as well [Peatross *et al*., 1997, Pretrel *et al*., 2005, Santo *et al*., 1981, Tewarson *et al*., 1981, and Utiskul *et al*., 2005]. From more than 25 years, many investigators were interested in the influence of the confinement on the heat release rate. Using natural ventilation conditions, Takeda *et al* [Takeda *et al*., 1981] investigated the behaviour of liquid-fuel compartment fires in cubic rooms with a single rectangular opening. Later, Fleischman *et al* [Fleischman *et al*., 1997] recorded similar results for another liquid fuel (heptane) located in a compartment of 1 $m^3$ in volume equipped with small openings. Utiskul *et al* [Utiskul *et al*., 2005] investigated the fire behaviour of heptane pool fires in a small-scale cubic compartment with top and bottom wall vents. In a medium-scale room and using both natural and mechanical ventilation, Peatross *et al* [Peatross *et al*., 1997] investigated the effect of ventilation on the compartment fire environment. From the review of all these papers, it can be noted that the influence of the oxygen concentration on the mass loss rate (and consequently on the heat release rate) is significant in the fire duration.

During the analysis of 1-story and 2-story family house in case of fire with different door and window openings [Kerber, 2013], tenability in both the houses was limited for the occupants. But the possibility of saveable lives, especially behind closed doors, should be considered by the fire service in their risk analysis. The results showed similarity with other similar cases;

when a flaming furniture fire occurs in a home, occupants have a short time to evacuate safely. This furthers the need for smoke alarms and residential sprinkler systems to increase occupant safety. There are several variable changes that could be done to further validate and expand the conclusions from this kind of fire scenario. The first variable that could be altered is the fire location. They focused on living room or family room fires. Additionally with fires in the kitchen or bedrooms would allow for analysis of fire spread from these locations. Future experiments should also consider creating a ventilation opening after one already exists (from the fire creating one of its own by failing a window, or a door being left open by an escaping occupant, or a window left open on a warm day). Very little research has been conducted on these common fire service tactics used in a house [Kerber, 2013].

Another work presented by Tarek [Tarek, 2015] was a series of four multi-compartment fire tests carried out in an apartment located in a high rise building (the Rabot tower in the city of Belgium) in 2012. Two or three furniture items and the ignition location were designed to focus on the initial flame spread and then the possible occurrence of secondary ignition. In all four tests the fire was allowed to self-extinguish, i.e., there was no fire brigade intervention. Sofas and bookcases were used as the source of fire. The rooms were open during the fire experiments to the living room and into the corridor. The smoke and the heat flow was kept same in all the experiments. From the results it was concluded that the fire is faster in case of smaller fire room size. A major effect on the thermal boundary conditions on the insulation material was observed. This led to slower fire development. Many fire modelling aspects were measured like flame spread, external flaming, boundary conditions and heat and smoke spread were studied. In another study two series of full scale room fire tests comprising 16 experiments are used for a study of the onset of flashover [Annemarie *et al*., 2013]. The test program utilized an experimental setup comparable to the ISO Room Corner test where the door of the test room is open to a hood. The test results showed that by lowering the thermal inertia and thereby lowering the heat loss from the room and at the same time increasing the thermal feedback, a thermal runaway occurred before significant fire spread; but only for objects composed of a mixture of plastic/rubber/textiles and wood/celluloses. Hence it was showed that for these buildings the starting point of flashover may not always be found by the use of the temperature criteria for flashover.

In order to understand the effect of ventilation [Karlsson *et al*., Chapter 5, 2000], the openings present inside the building that evolves changes around the fire area can be termed as the ventilation effect. The effects of ventilation on combustion products are expressed in terms of relationship between concentration of products and equivalence ratio, R [Karlsson *et al*., Chapter 9, 2000]. For well ventilated fires, R< 1.0, where mostly heat and products of complete combustion (such as CO2 and water) are generated. For ventilation-controlled fires, R>1.0, where mostly products of incomplete combustion are generated with very high concentrations in a transition region for R between 1.0 and 3.5. The high concentrations of the products generated in the result of incomplete combustion are dangerous to life and property. For halogenated materials, this condition occurs for R < 1.0. The non-flaming region for fires is found to exist for R > 3.5. Correlations have been developed for the predictions of concentrations of products at various R values for the assessment of combustion toxicity and smoke damage hazards by zone fire models. The incomplete combustion depends on the chemical structures of the material. For the same R values, the CO concentrations are higher for materials with oxygen atoms in the structure, whereas smoke concentrations are higher for materials with carbon and hydrogen atoms in the structure [Karlsson *et al*., Chapter 9, 2000]. Thus depending on the level of these toxic gases present inside the building a better ventilation system is required to overcome these gases and allow the occupants to evacuate quickly and easily.

### 2.2.2 Experiments with Roof Top Vent

Numerous studies have been carried out using fire in a closed compartment with only horizontal openings as well [Kerber, 2013], in order to check the impact of the horizontal vent on the mass flow rate, oxygen concentration and the temperature inside the compartment. These studies show how the fire behaves when the size and shape of the ventilation are changed in accordance with the size of the fire. Also the level of oxygen inside the compartment is studied to understand the phenomenon of self-extinction. Mostly the ship cabins are with only ceiling vent without any other opening. Whereas, large ceiling vents are widely used in underground structures. And they possess special attention due to the presence of fire behaviours that differ from the fires in normal buildings and structures [Jojo *et al*., 2003, Sung-Wook *et al*., 2009, Ju-Seog *et al*., 2010]. These studies showed that the change in the vent size would make the fire phenomenon change as well. In ship cabins there is only one opening to prevent the fire from spreading to other rooms and to extinguish the fire.

In houses natural ventilation system is normally the only way to reduce the fire incidents. Ash Fire management have introduced a top vent application that could reduce the level of smoke during a fire accident in a residential dwelling [http://www.ashfire.co.uk/]. ASH Fire management under BRE [BRE report, 2013] have conducted an experiment to support this model in contribution with FSEG (Fire Safety Engineering Group) from University of Greenwich UK [Wang *et al*., 2013]. They have designed a one bedroom house and conducted a fire experiment to support the idea. They designed different fire scenarios that could possibly happen in house. The natural ventilation system apart from windows and doors they introduced is a roof top vent. This is the only detailed experimental investigation that has been done based on the roof top vent in house fires to the author's knowledge. They have done different experiments based on different fire scenarios, which enables to study the impact of fire inside the house. But due to the lack of the experimental evidence regarding the main fire scenarios inside the house this investigation sets back. Since not much literature is available about the kind of the fire inside the house and its physical interpretation. So there is a need to develop a methodology to obtain the fire structure that could be applied to any house in general.

A lot of experimental studies are available to study the impact of fire inside a compartment using the roof top vents. Mostly the experiments use an available and tested fire and study its affect inside the compartment and how the vent will affect the fire conditions inside the compartment. In addition to that there are many experiments that study the use of roof top vent for any available fire. Since the compartment fires are ventilation size and compartment size dependent. So the fire size inside the compartment needs to be correlated with the size of the vent and the compartment.

The experimental results [Yii *et al*., 2005] with fire source as a heptane pool fire (300mm diameter) near the wall furthest from the door vent showed that the mass flow rate of air into the compartment increases linearly as the size of roof vent opening increases. The results showed that with the additional centred roof vent (circular) along with the horizontal door opening, and the size of the ventilation during a fire is increased, this results in higher fire gas temperatures. The fuel mass loss rate also increases as a results of this, which affects the overall fire design. The vent flow modelling in this study also shows that the ventilation is not only dependant on the area of the roof vent opening, but also on the distance between the roof vent and the door. In case of sloped roof vent (with rectangular door opening) experiment [Jian *et al*., 2014], it was found that with the increase of the sloped roof vent area, the maximum mass burning rate decreases gradually and the total combustion duration increases. As the sloped roof vent area increases the heat loss through the roof vent increases and the gas temperature decreases consequently, leading to a reduction of the energy radiated from the hot gas to the unlit fuel (methyl alcohol fuel pan); as a result the mass burning rate decreases, even though more fresh air flows into the compartment. The influence of the inclination angle has not been explored due to the limited test equipment.

With a horizontal roof opening experiment [Mercia *et al*., 2007] along with an open door it was found that the hot layer average temperature increases linearly with HRR, decreases as the roof opening area increase, but decreases slightly as the fire area increases where the centred steady fire source is hexane pool lying on water. The hot layer thickness is unaffected by HRR, area of roof, but becomes thicker as the area of the fire increases. The total mass flow rate of smoke getting out of the compartment is unaffected by HRR and the area of the roof vent, but increases as area of fire source increase. Analysis of the studies reveals that the hot layer thickness was under-estimated, hot layer temperature was over-estimated and the total smoke mass flow rate is also under-predicted.

The concept of plume equivalence ratio (PER) [Karlsson *et al*., Chapter 9, 2000] is introduced to express the ventilation conditions for the flames in compartments with ceiling vents. The change in the opening size had limited impacts on the fuel mass loss rates, but significantly raised the oxygen concentrations in the compartment [Man *et al*., 2013]; however, the oxygen concentrations at the bottom layer began to decrease earlier.  During these experiments the impacts of ceiling vent sizes on the fuel mass loss rate and oxygen concentration at the fire base were studied. The fire source used was a heptane pool fire placed in the centre, whereas the square roof opening was set on the corner of the ceiling with no other opening in the compartment. The fuel mass loss rates were not affected and the oxygen concentration at the bottom didn't necessarily increase with the increasing opening size. However, the oxygen concentration at the bottom began to decrease earlier with larger opening size. The PER mainly declined with the increasing opening sizes. While for conditions with very small opening, the PER rarely changed because of the air inflows couldn't affect the bottom part of the compartment. The combustion efficiencies decreased with the burning procedures since the PER exceeded 1.0. Since in another experiment with almost same experimental description with no door opening and only roof opening on the corner of the ceiling and with n-heptane pool fire placed in the centre the mass loss rates showed same values when compared to free mass loss rate for small fires [Bing *et al*., 2013], even the fire was self-extinction. The fuel mass loss rate has only very weak correlation with the vent size in oxygen-controlled region. The mass loss rate of the investigated pool fire with a diameter of 0.1 m is practically unaffected by the vent size. However, for the larger fire, the mass loss rate is much lower than the free burning value. As the vent size increases, the oxygen concentration at the time of extinction becomes higher.

From the experimental results it was found that the size of the ventilation along with the size of the fire plays a vital role in order to study the impact of ventilation on fire. Usually the research is based on enclosure fires where the size of the compartment should correlate with the size of the ventilation and fire. Also the concept of self-extinction and oxygen-controlled region was focused in the experimental studies. Mostly the study is based on fixed fire/pool fire since the data from cone calorimeter enables the researchers to use those data values to study the fire under ventilation controlled conditions.

## 2.3 Numerical Studies

This section will focus on the simulations and the analysis based on the simulations of fire. Since many experiments have been conducted to study the impact of natural ventilation. Similarly these experiments have been simulated as well at different levels of fire research in order to understand the surrounding parameters and conditions more thoroughly through software's and fire simulations. Fire simulations give an insight to understand the parameters that can have an impact on the fire behaviour under certain conditions.

### 2.3.1 Simulations with Side Doors and Windows

In this section we have discussed about mostly the real life fire cases that have been simulated using fire modelling software's. These numerical studies enabled us to understand the fire parameters that are very vital for the fire simulations, and also how much these parameters and surrounding factors affect the fire simulations. In order to understand the real picture clearly through fire modelling these factors needs to be addressed carefully.

NIST performed a simulation case study for a fire incident happened in Riverdale Heights, Maryland, USA in 2012 using FDS simulation tool [Craig *et al*., NIST report 2015]. The structure involved in this fire incident was a single-story, single-family structure with a basement. The fire started in the basement and spread to the stairs. The door at the top of the stairs was open at the time of the fire. Based on the information the structure was unfurnished and the main source of fuel was wood. In the simulation two fire sources were used. One in the kitchen and one in the adjacent bathroom in the basement. The fire originated in the basement, and the interior stairwell acted as a chimney for hot gases in the basement to flow towards regions of lower pressure through the open front door of the structure. After the front door was opened by a fire fighter, a flow path was established between the basement and the front side of the structure (the front door). The opening of the front door resulted in a rapid change in the conditions within the flow path. In this fire incident, the initial failure of the basement windows with strong incident winds on the rear side of the structure coincided with a rapid change in the thermal conditions in the interior stairwell and first floor after the front door to the structure was opened. There have been many previous fire incidents in which changes in the flow paths are thought to have had an adverse impact on firefighter and occupant safety [T.A. Pettit *et al*., NIOSH 1999, Washenitz *et al*., NIOSH 1999, McFall *et al*., NIOSH 2001, Berardinelli *et al*., NIOSH 2006]. Hence there are many simulated cases by NIST and NIOSH until 2014 where we can see the impact of ventilation on fire. In another case simulated by NIST [Kristopher *et al*., NIST report 2014] in which the structure involved in fire incident was a four-story residential building with a flat roof. The fire originated in the basement living room and was initiated by a handheld electrical appliance that was located near the rear basement windows. Again FDS was used for the simulation. The basement contained upholstered furniture composed primarily of polyurethane foam, and the balcony was constructed of wood. The upholstered furniture items located in the middle of the basement living room were very large and flat, similar to the size and geometry of a mattress. Therefore for the initial fire the HRR of mattress was used in FDS. The secondary fires in the basement were divided among four additional upholstered furniture items (two couches, a lounge chair, and a chair). The third fire involved the wood on the rear basement balcony and exterior siding. The simulation in this study accounted for changes in ventilation due to a combination of fire department operations (opening doors) and fire acting on the structure (breaking windows). Again the air flow path was created by opening the front door by the fire fighters. Similar simulations with doors and windows opening in a fire incident have been simulated by NIST and NIOSH. Thus we can say that the fire modelling software has the ability to reproduce the same fire conditions in order to better understand the causes of fire injuries and deaths. Hence from the simulations one thing is clear that during a fire incident when a door or window is opened it creates a flow path for the fire. Thus due to rapidly developing or changing ventilation this may lead to flow paths that are a significant hazard to the fire service during a response. Hence a better way needs to be investigated in order to overcome the safety of the fire fighters.

Numerical simulations are carried out on a shelf fire in a storehouse to study the ignition manner, the fire spread and the combustion characteristics [Peizhong Yang *et al*., 2011]. FDS was used to simulate the fire. But in this case FDS was unable to deal with the phenomenon where the carton collapsed. Hence improved better numerical models need to be established.

### 2.3.2 Simulations with Roof Top Vents

Numerical simulations using FDS and some configurations computed using OZONE (zone model) [Mercia *et al*., 2008] showed that the total fire HRR value has the strongest influence on the hot smoke layer average temperature rise where the centred fire source used was a fixed fire with three different HRR values, and the compartment had opened door and opened roof vent. While the influence of the fire source area and the roof opening is smaller. The hot layer temperature rise increases linearly with the increase in HRR, decreases as the roof opening area and the fire source area increases. The hot layer thickness is unaffected by HRR, it is independent of area of roof, but increases as the area of fire increases. In another case where [Man Yuan et al., 2012] compared the predicted results with the experimental results. The case was simulated with a corner ceiling vented cabin. Pool fire was placed at the centre of the cabin. In this case the smoke reached the floor first before creating a ceiling jet and evacuating through the corner vent. In this study a simple two-stage heat loss model was developed. The comparisons showed that the model was able to provide reasonable predictions with simulations. In case of forced ventilation [Beyler, 1991] developed a model to predict temperatures in case with compartment having over-head forced ventilation. The extinction of flames is predicted using the limiting oxygen index concept. While the fire environment in compartments with overhead forced ventilation is quite different than naturally-ventilated fires or fires ventilated from floor level. Hence from all these simulated cases it was concluded that the fire modelling software's have the ability to recreate the fire scenario.

Thus the conclusion based on the numerical studies is that the fire in a compartment/house depends on the size and position of the ventilation, size of the fire and the HRR. The compartment fire scenarios were mostly studied with open door along with opened roof vent. The mass loss rate of the fuel increases with the increase in the size of the roof vent. The ventilation is dependent on the distance between the roof vent and the door vent as well. Whereas, the mass loss rate of the fuel is unaffected for the fire of size around 0.1 m i.e. for small fires the vent size does not affects. But it increases as the size of the fire becomes bigger as the entrainment increases as well. Also the average temperature rise decreases with the increase in the size of the fire area and roof vent. The hot layer thickness is affected by only the size of the fire, it becomes thicker as the size of the fire increases and vice versa but it is unaffected by the HRR and area of roof vent. As discussed about the equivalence ratio before as well.  The equivalence ratio declined with the increase in the roof vent opening, but for smaller openings it was almost unaffected because the air inflow didn't affect the bottom part of the compartment. Thus it is assumed that the equivalence ratio can exceed 1.0, and also the combustion efficiencies will raise with the increase in the size of the roof vent openings.

Thus better modelling approach can enable the researchers to develop better designs that can improve the survival chances. Since based on the NIST simulations again no method or design for the house was proposed that can improve the response time for the fire fighters and also the life efficiency. Mostly due to the fires after the occupants it's the fire fighters lives that are at risk. Therefore based on the gaps found after reviewing the experimental and numerical ventilation scenarios. A better methodology and design is required in order to remove smoke in case of fire and improve the survival chances of the occupants and fire fighters.

## 2.4 British Building Standards

The ventilations systems are usually use to supply fresh air continuously. Also ventilation is used to maintain the temperature and the humidity at comfortable level. But the main purpose of ventilation in fire incidents is to reduce the potential fire or explosion hazards and remove smoke that is contaminated inside the structure. Doors and windows can be opened to remove the smoke which can allow the people to evacuate quickly. Thus if a better way to improve the fire safety in dwellings is proposed, a more efficient way to remove smoke other than the doors and windows needs to be provided. The method should work solely for the fire incidents and it should be correlated with the smoke level inside the dwelling to improve the survivability of the occupants inside the structure.

The placement of the doors, windows, roof top vents should be in accordance to the building standards. The house cannot be designed without keeping in accordance the building regulations since they are implied based on the safety of the occupants and how to overcome any incident such as fire. The British building standards have a section mentioning the fire safety information and the information regarding the ventilation, use of fuel and power [The building regulations 2000, Ventilation GOV. UK, Building Regulations 2010 GOV. UK]. The owner should have the fire safety information before the completion of the construction work. The owner has to maintain the equipment with reasonable safety, and also he should be given sufficient information regarding the ventilation system and its maintenance requirements as well. So the ventilation system can be operated in a manner to avoid any incidents. Also using jet fans in car parks and underground stations/road tunnels have to be placed according to the regulations [The building regulations 2000, Ventilation GOV. UK, Building Regulations 2010 GOV. UK], keeping in account the air pressure created by the fans and the safety.

The position of the ventilation system in dwellings is also based on the approved UK Government document. There should be reasonable access for maintenance for the vents and the performance which can be achieved by providing the airflow rates set out in the document [The building regulations 2000, Ventilation, GOV. UK]. How many windows and doors are required in kitchen, bedroom and bathroom and they should follow the specified lower and higher air flow rate settings.

## 2.5 The Natural Top Vent Tactic

In this section we will discuss the fact that based on the review from the literature from both experimental studies and numerical studies we have been able to make a conclusion. The experimental studies along with the numerical research provided us the opportunity to find the knowledge gap that we found in the research. There has been a lot of research on fire in dwellings and enclosures and using different kinds of ventilation systems under fire scenarios. There has been research using especially designed roof top ventilation as well to study the impact of top vent on fire. Usually the study focuses on the impact of air on fire using ventilations. Not much research is based on how can ventilation be the factor to improve the survivability chances of the occupants inside the structure.

Ash Fire Management under the BRE project were able to design a certain kind of roof top natural ventilation system and studied the effect of this ventilation on fire [http://www.ashfire.co.uk/, BRE report, 2013]. This roof top natural ventilation design from Ash Fire Management follows the UK Gov. approved building regulations [The building regulations 2000, Ventilation, GOV. UK]. This designed house has a ventilation system installed in the loft of the dwelling structure and it was studied that how the vent can affect the fire and how smoke can be removed from the top vent. But again this study is limited to certain factors. In this study they considered fixed fire and spreading fire. Using both the fires they did not clearly make the conclusion that if this top vent is useful in removing smoke and improving the survivability chances inside the dwelling. The study was limited to only computing the temperatures, smoke and other toxic gases level at certain locations and the uncertainties of complex of the test with the spread fires.

Hence this study enabled us to highlight this knowledge gap. In case of fire in dwelling if roof top vent system is active, will it be useful or not in removing smoke along with that will it improve the survivability chances of the occupants inside the dwelling structure? Since most of the research focuses on the fact that how smoke can be removed using top vent and how fire will behave under ventilation. But not much attention is paid on how survival chances can be improved if a certain design of ventilation system is installed in the building solely for this purpose. Thus the focus is mainly on the top vent as the main object for removal of smoke and how it will improve the survivability. The top vent needs to be positioned according to the building regulations [The building regulations 2000, Ventilation GOV. UK] as mentioned earlier.

## 2.6 Conclusion

From the literature review we were able to understand the impact of ventilation system on fire. Also if air and other factors like size of the ventilation, size of the fire can make a difference on the behaviour of fire? Different locations and sizes were studied, different openings like doors and windows were studied as well. Mainly the idea in all the studies was to understand the behaviour of fire under ventilation condition and how the position, size along with other openings like doors and windows will affect the fire.

Also we concluded that there is no much research available regarding the house fire and using roof top ventilation as a source for removal of smoke in case of fire. Mostly the research is based on the behaviour of fire under top vent application. Not much research has focused on how the top vent application can improve the survivability chances of the occupants inside the residential structure under fire scenario. Also how different openings can affect the survival and where and why the top vent application should be placed? What size of vent can be beneficial for the removal of smoke and will it improve the survivability of the occupants in case of fire? Thus a specially designed ventilation system can be used to study the impact of air on fire and especially on smoke and whether it will improve the chances for survivability in the remainder chapters.

# Chapter 3

# Fire and Evacuation Modelling

## 3.1 Introduction

In modern society, the everyday safety is mostly taken for granted. Computer modelling of fire has significantly become more popular and increased during the last decades. Computer modelling of fire is usually based on zone modelling and field modelling using CFD techniques.

Zone models are extensively employed in building fire safety design. The zone models are not very accurate and reliable, and mostly two-zone models are used for better approximations. Thus, the fire researchers really does require a more accurate method to use in studying fire scenarios. There is a possibility that in future the zone models will be replaced by the field models because of their uncertainty [Karlsson, *et al*., Chapter 1 and 10, 2000]. When this will happen it is not predictable. However, the two-zone model will surely last until any new development. Whereas the field modelling is concerned, the compartment fires using field modelling accounts for increasingly complex representations of the physical and chemical processes which may occur. The field models require detailed evaluation. The detailed explanation of the two modelling approaches is described below.

Since the filed modelling is widely used now a days the fire modelling becomes an essential part in the fire research. And based on the calculation from the fire modelling better designs can be made to improve fire situations. Similarly evacuation is the main factor involved when there is a fire. Hence evacuation modelling enables to understand the possible human reactions and behaviours in case of a fire situation.

The objective of this chapter is to describe the basic methods and models used in fire simulations and to get familiar with the fire and evacuation software SMARTFIRE and EXODUS. As an example, the simulation results to a complex cabin fire using SMARTFIRE are briefly summarised.

## 3.2 Modelling Approach

### 3.2.1 Zone Models

In zone modelling the influence of fire is studied in an enclosed room where the room is divided into limited number of zones or control volumes. The most common zone model is called two-zone model, in which the room is divided into two distinct control volumes; one upper control volume near the ceiling called upper layer, consisting of burnt and entrained hot gases and one cold lower layer which contains fresh air [Karlsson, *et al*., Chapter 1, 2000]. The empirical equations for mass, energy which are mainly used and chemical species are solved separately for both the layers respectively and transition of mass and energy between the zones is accounted by the use of a plume model [Karlsson, *et al*., Chapter 1, 2000]. In some zone models, the plume appears to be a third "layer" though in other models the influence of the plume is ignored. Considering the transient plume effects, in which for example the temporal build-up of the plume and the time taken by the hot gases to move from the base of the fire in the lower layer to the upper layer, are left without consideration. Both hot and cold layers, and control volumes, are assumed to be homogenous and temperature, density, pressure etc. are used to represent average values over the zones [Karlsson, *et al*., Chapter 1, 2000].

A large number of experiments have been performed in order to verify and evaluate the validity of zone models and to identify the uncertainties [Karlsson, *et al*., Chapter 1, 2000]. The main usage of zone-models is to present approximate values of the location of the smoke interface and gas layer temperature. In large spaces, for example in high rise buildings and atriums, and other complex structures the zone model should be used with extra care.

### 3.2.2 Field Models

In field modelling, firstly a domain in space is defined. The simulation is carried out through the whole domain, and the proportions are determined by the size of the object that has to be simulated. For field modelling the whole domain is divided into a large number of small control volumes, which in addition can be defined as some kind of obstacles or walls, or simply it can consist of air or fluid space. In such a way, the actual geometry that is to be simulated is built up inside the computational domain, relevant boundary conditions need to be defined as well. Computational Fluid Dynamics (CFD) technique, is then applied in order to solve a set of non-linear partial differential equations (PDEs). Since most of the air flows encountered in real life are very complex to be simulated. This means that one has to consider various models in order to make simulations possible and close to the reality. In the case of fire, a combustion model is used to simulate the different aspects of combustion; a turbulence model is included to predict the buoyancy driven turbulent flow as well as a radiation model is used to simulate the thermal radiations across the fire area. There are many additional sub-models that can be included such as smoke model, toxicity model, sprinkler model etc. [Karlsson, *et al*., Chapter 1, 2000].

In CFD, there is a talk about the use of a pre-processor, a solver and a postprocessor to evaluate the solution to the problem. The pre-processor is used to define the actual problem and it includes mesh generation, all the boundary conditions, selection of appropriate models that are to be used and what output is required for analysis etc. Since from the name solver one can judge, the solver uses the input data to find a solution to the problem. Now, as the conservation equations i.e. for energy, mass and momentum are concerned they are non-linear partial differential equations and their analytical solutions are not simple to evaluate. Instead, field models use different kinds of numerical techniques to find the solution to these equations. The solutions obtained are then examined, analysed and presented using some post processor software.

Looking at the rapid progress in computer technology and the availability of powerful computers in less cost, field models are not only a tool for the fire engineers and researchers but they are also applicable in fire safety to optimise the safety in buildings in relation to fire etc. The accuracy of a simulation depends mainly on two factors which are the grid resolution and the specific models that is being used [Karlsson, *et al*., Chapter 1 and 10, 2000]. Indeed field modelling can be a powerful tool but again the engineers and the researchers need to learn and to be aware of limitations and uncertainties in the respective software they use.

## 3.3 Computational Field Fire Models

Thus, the fire safety community really does require more accurate methods to make use of in their work. Usually zone models and field models [Karlsson, *et al*., Chapter 1 and 10, 2000] are used in the computer modelling which will enhance the CFD calculations. Since the field models have been more useful than zone models in most of the aspects in order to achieve accurate results with better precision. The user should have knowledge about specific models that are going to be considered in CFD modelling of fire, numerical techniques employed and knowing the cause of uncertainties in calculations will always be necessary for a successful use of CFD modelling techniques in fire safety calculations. It is no doubt that field models offer a powerful tool in fire safety engineering. Field models can have a breakthrough in no time, using the growing knowledge and computer programming power. But before CFD modelling is fully accepted in the fire safety community it has to prove its worth and superiority depending on the output it provides to the researchers and the engineers. The fire safety largely depends on correct designs and the professional skills for fire safety. With the need of better fire safety procedures there is a need of better methods to understand the influence of fire on the structure and the occupants. In order to understand, analyse, and predict the effects of fire on the structure and the occupants different scientific methods have been employed in the recent years, including practical experiments and mathematical modelling.

Since as said earlier full scale experimental studies are costly, and the experiments are not performed in the original structure but they are often performed in small scale structures sometimes which are more or less accurate proportion of the regular structure. But it should be kept in mind that the experimental results are not necessarily and entirely accurate but they give more of an approximate idea. Errors are present but sometimes they are less significant and sometimes more. A large number of experiments have been performed in order to evaluate the validity and reliability of field models and also to identify the uncertainties present in the model.

The CFD codes that are used for simulation of the fluid flow, transfer of heat and other chemical reactions are e.g. PHOENICS [developed by CHAM-2008], FLUENT [Ansys Inc.], and ANSYS CFX [Ansys Inc.]. Whereas when it comes to the fire filed modelling under CFD code then we have FDS [developed by NIST], SOFIE [developed by Cranfield/FRS], JASMINE [developed by FRS], KAMELEON [developed by SINTEF/NTH], and SMARTFIRE [Developed by UOG].

### 3.3.1 Basic Conservation Equations

Classical fluid dynamics is concerned with the mathematical description of the behaviour of the fluid. The fluid dynamics has developed some equations which are known for more than 150 years now. Navier Stokes Equations which includes 3- dimensional, time dependent and nonlinear partial differential equations (PDEs). These equations in their general form cannot be solved analytically. Then comes the CFD code which through computer simulation solves the Navier Stokes equations using fire modelling techniques [Karlsson, *et al*., Chapter 1 and

10, 2000, Batchler, *et al*., 1967, Chacón *et al*., 2014]. The conservation equations are based on mass, momentum and energy.

$$\int_v \frac{\partial \rho}{\partial t} dV + \int_S (\rho)U.n\, dS = 0 \tag{3.1}$$

Equation (3.1) is the conservation equation of mass, where:

$\rho$ = Fluid Density

$v$ = volume

$S$ = surface

U = fluid velocity

$n$ = unit normal

V = control volume

$dS$ = control volume surface area

$$\int_v \frac{\partial U}{\partial t} dV + \int_S (\rho U)U.n\, dS = F \tag{3.2}$$

Equation (3.2) is the conservation equation of momentum, where:

$F$ = sum of the external forces

$\rho$U = the momentum flux density

$$\int_v \frac{\partial (\rho e)}{\partial t} dV + \int_S (\rho(e + pv))U.n\, dS = \frac{dQ}{dt} - \frac{dW}{dt} \tag{3.3}$$

Equation (3.3) is the conservation of energy, where:

$P$ = pressure

$v$ = specific volume

$Q$ = heat added to control volume

$W$ = work done by the control volume

$e$ = energy level

$pv$ = flow work (if pressure difference exists)

Thus the Navier Stokes equations are based on the above mentioned equations of mass, momentum and energy. The Navier Stokes Equation can be derived using the corresponding conservation laws of mass, momentum and energy.

The equation below is called the convection-diffusion equation. Using the Navier Stokes equation and applying the vector notation the following general equation is derived [Karlsson *et al*., Chapter 1 and 4, 2000, Batchler *et al*., 1967]:

$$\underbrace{\frac{\partial(\rho\phi)}{\partial t}}_{\substack{\text{accumulation}\\ \text{rate}}} + \underbrace{div(\rho \mathrm{u} \phi)}_{\text{convection}} - \underbrace{div(\Gamma_\phi \Delta\phi)}_{\text{diffusion}} = \underbrace{S_\phi}_{\text{Source}} \qquad \text{efflux per unit volume} \tag{3.4}$$

Where;

$\phi =$ dependent variable,

$\Gamma_\phi =$ exchange coefficient and

$S_\phi =$ source term

CFD software uses the above mentioned form of equation (3.4). Different source terms can be used, and necessary equations can be constructed. All the necessary equations can be constructed using the source terms from the Table 4.1; Pressure does not appear independently as the subject of a conservation equation; it is however used in an iterative correction scheme; Smoke is one of the concentration variables.

Table 3.1: Conservation Equations Subject to different Source Terms

| **Equation** | $\phi$ | $\Gamma_\phi$ | $S_\phi$ |
|---|---|---|---|
| Continuity | 1 | 0 | 0 |
| U-momentum | U | $\mu_e$ | $-\frac{\partial p}{\partial x}+\frac{\partial}{\partial x}\left(\mu_{eff}\frac{\partial U}{\partial x}\right)+\frac{\partial}{\partial y}\left(\mu_{eff}\frac{\partial V}{\partial x}\right)+\frac{\partial}{\partial z}\left(\mu_{eff}\frac{\partial W}{\partial x}\right)-\frac{2}{3}\frac{\partial}{\partial x}(\rho k)$ |
| V-momentum | V | $\mu_e$ | $-\frac{\partial p}{\partial y}+\frac{\partial}{\partial x}\left(\mu_{eff}\frac{\partial U}{\partial y}\right)+\frac{\partial}{\partial y}\left(\mu_{eff}\frac{\partial V}{\partial y}\right)+\frac{\partial}{\partial z}\left(\mu_{eff}\frac{\partial W}{\partial y}\right)-\frac{2}{3}\frac{\partial}{\partial y}(\rho k)+g(\rho-\rho_o)$ |
| W-momentum | W | $\mu_e$ | $-\frac{\partial p}{\partial z}+\frac{\partial}{\partial x}\left(\mu_{eff}\frac{\partial U}{\partial z}\right)+\frac{\partial}{\partial y}\left(\mu_{eff}\frac{\partial V}{\partial z}\right)+\frac{\partial}{\partial z}\left(\mu_{eff}\frac{\partial W}{\partial z}\right)-\frac{2}{3}\frac{\partial}{\partial z}(\rho k)$ |
| Temperature | T | $\Gamma_e$ | $q/C_p$ |
| Concentration | C | $\Gamma_c$ | $S_c$ |
| Kinetic Energy | k | $\Gamma_k$ | $G_k - C_D\rho\varepsilon + G_B$ |
| Dissipation | $\varepsilon$ | $\Gamma_\varepsilon$ | $C_1\frac{\varepsilon}{k}(G_k+G_B)(1+C_3R_f)+C_2\rho\frac{\varepsilon^2}{k}$ |

## 3.3.2 Turbulence Models

Turbulence means unsteady and irregular. The turbulence flow of fluid has been defined as the flow which is irregular and unsteady in space and time, it is rotational as well. The Reynolds numbers are very high. There is rapid mixing of the fluid and there is a range of eddy sizes. Small eddies have high frequency fluctuation which relates to viscous forces and larges eddies have low frequency fluctuations which relates to momentum transfer.  The classical turbulence model is the Reynolds Stress and Eddy Viscosity [Karlsson, *et al.*, Chapter 4, 2000, Batchler *et al.*, 1967].

In CFD turbulence models enables to solve system of mean-flow equations. Also it enables to determine the model constants that are "Universal", which increases the scope of the model applicability. It simulates the effects of turbulence on the mean-flow quantities but it leaves the detailed turbulence structure within the flow unsolved [Karlsson, *et al*., Chapter 4, 2000, Batchler *et al*., 1967, Baldwin, *et al*., 1978]. It reduces the mesh for very large industrial problems. In order to address this chaotic and random flow a very fine mesh is used based on the turbulent eddy length scale. In order to overcome the large mesh size sensible approximation based on the engineering simulation tools needs to be utilised. The turbulence models are classified as [Wilcox, 1993]:

- Simple Turbulence Model
- Zero-Equation Models (Prandtl's mixing length model)
- One-Equation Models (k-L model)
- Two-Equation Models (k-e Model)
- Reynolds Stress Models
- Algebraic Stress Models

In CFD code the most widely used turbulence model is the k-e model. In k-e model the Reynolds stress and the viscous stress are similar which means the turbulent transport of momentum is proportional to the mean gradients of velocity [Wilcox, 1993]. It is one of the simplest turbulence models. Since in this model only the boundary conditions needs to be specified. It includes thin shear flows, recirculating flows, confined flows, fire modelling and pollutant dispersion. It is a well-established and validated model. This model has some limitations as well but CFD can tackle the problem of modelling turbulent flows without thinking about the computational effort required to achieve the solution. The k-e turbulence model with added sources is [Wilcox, 1993]:

$$S_k = G_k - C_D \rho \varepsilon + G_B \tag{3.5}$$

$$S_\varepsilon = C_1 \frac{\varepsilon}{k}(G_k + G_B)\left(1 + C_3 R_f\right) + C_2 \rho \frac{\varepsilon^2}{k} \tag{3.6}$$

The above set of two-equations (3.5 and 3.6) represent the source terms of the two governing equations of the k-e model as seen in Table 4.1, where;

$G_k$ = Shear production and

$G_B$ = Buoyancy production

One of the advantages of k-e model is that it is the simplest turbulence model, where only the boundary conditions need to be specified. Whereas the disadvantages include that it requires further two differential equations to be solved. It also produces inaccuracies when the flow is rotating/swirling. But still it is the best model that CFD can use to tackle the problem of modelling turbulent flows [Celik, 1999].

### 3.3.3 Fire Models

Fire modelling not only involves heat transfer and fluid flow but it comprises of other factors like combustion, reaction and phase transport.

#### 3.3.3.1 Combustion Model

Combustion can be called as a process in which a fuel reacts with oxidant usually atmospheric oxygen to form combustion products. The products are not formed in a single step in fact they follow a series of reactions to produce the final products. For example even simple fuels like methane take 50+ steps of reaction before it finally produces the products. Since it is assumed that the convention-diffusion equation can be used for the combustion calculations. Thus the transport equation for reaction species of any variable can be represented by the mass fraction of fuel, oxidant or product [Magnussen, *et al.*, 1977]. The transport equation for combustion is:

$$\frac{\partial(\rho m_j)}{\partial t} + div\ (\rho u m_j) - div\Gamma_{\emptyset}\Delta m_j = S_{\emptyset} \tag{3.7}$$

Where; $m_j$ = mass fraction of species,

$S_j$ = mass rate of creation,

$\Gamma_j$ = exchange coefficient of species.

For combustion model the stoichiometric ratio is the very key for modelling. Based on the mixture fraction the conservation equation for mixture is defined as:

$$\frac{\partial(\rho m_{mix})}{\partial t} + div\ (\rho u m_{mix}) - div\Gamma_{\emptyset}\Delta m_{mix} = 0 \tag{3.8}$$

Thus based on the reaction rate, reaction can be of two types:

- Diffusion Controlled

- Kinetically Controlled (Eddy-Breakup Model)

The model that has been widely used for the combustion reaction is the kinetically controlled Eddy-Breakup model. The source term for fuel for the Eddy-breakup model is given by [Brain Spalding, 1971]:

$$S_{fu} = -\min\left[\rho \frac{\varepsilon}{k} C_R m_{fu}, \rho \frac{\varepsilon}{k} C_R \frac{m_{ox}}{s}, \rho \frac{\varepsilon}{k} C_R \frac{m_{pr}}{(1+s)}\right] \tag{3.9}$$

Since the reaction rate is influenced by the slow chemical reaction, above source term (Equation 3.9) is solved with two equations ($M_{fu}$ and $M_{mix}$). Thus the overall reaction rate of the fuel is:

$$S_{fu} = -\min\left[\rho \frac{\varepsilon}{k} C_R m_{fu}, \rho \frac{\varepsilon}{k} C_R \frac{m_{ox}}{s}, \rho \frac{\varepsilon}{k} C_R \frac{m_{pr}}{(1+s)}, R_{fu,kinetic}\right] \tag{3.10}$$

Where $R_{fu,kinetic}$ is the Arrhenius kinetic rate.

This model has some limitations when the turbulence predictions are not accurate [Brain Spalding, 1971].

### 3.3.3.2 Radiation Model

Radiation is related to heat transfer. Therefore radiation model is also called Radiative Heat Transfer Model as well. Radiation is very essential and dominant in cases where the heat flux changes or varies greatly. It is always essential to represent the characteristics of heat and mass transfer in mathematical modelling of fires where radiation is of great importance. In regions of high temperatures where there is chemical reacting fluid flow significant amount of radiations are emitted [Karlsson, *et al*., Chapter 10, 2000, Batchler *et al*., 1967]. Generally low temperature regions absorb radiations such as walls or other surfaces of interest and hence in turn they contribute to the heat transfer. In clear cold air limited radiation is absorbed also in thermally reflective surfaces limited radiation is absorbed. The radiation model must have the ability to predict the heat flux distribution which takes part in the simulation and also the temperature distribution which takes part in the transport medium. In order to achieve the accuracy in the predictions of reaction rates and species concentrations the temperature distributions should be accurate [Karlsson, *et al*., Chapter 10, 2000, Batchler *et al*., 1967].

In CFD there is a need of a simple and accurate model. Also the computational effort should be minimum to achieve reasonable accuracy. In CFD, radiation models should consider flux methods for gaseous mixtures and estimate radiant flux that has been transmitted. And the whole computational domain should be able to evaluate the fluxes. There is an Ideal Radiation model used in CFD. It radiates in all directions. But in reality the radiation is distributed through 4pi radians angle. The best known methods are [Karlsson, *et al.,* Chapter 10, 2000, Batchler *et al*., 1967]:

- Six-Flux Model
  In six-flux model the radiations are considered only in the six coordinate directions.
- Discrete Flux Model
  Whereas in discrete-flux radiation model a number of rays are used that are projected at various angles from a point. The larger the number of rays considered the better the model gets to reality.

Both these models have some advantages as well as limitations. Six-flux model uses diffusion type equations for calculations, also it is compatible to flow equations. Whereas discrete-flux model has similar method of calculation when only six-rays are used in the coordinate direction. Six-flux model has a high degree of computational economy whereas the discrete model can be costly but will provide accurate results if number of rays are increased. Since the limitations in both the models are also very vital to be understood. The six-flux model has low accuracy, difficult to work for complex geometries and models only single-phase flows. Whereas, the discrete-flux model is expensive in terms of computational effort when number of rays are increased, and same like six-flux model it is also restricted to single-phase flows [Batchler *et al*., 1967].

### 3.3.3.3 Toxic Model

The correlations between the yields of species and the equivalence ratios are utilised by the toxic model. These yields are derived from the small scale experiments to predict the generation and transportation of toxic gases within fire enclosure. As discussed about the equivalence ratio in previous chapters, the equivalence ratio is calculated with the mixture and stoichiometric mixture fraction for a control volume [Purser, 1989].

Of species like CO, $CO_2$, and $O_2$ their mass fraction is calculated with the following equations [Wang, *et al*., 2007]:

$$Y_i = y_i(\varphi, T)\xi \tag{3.11}$$

$$Y_{o2} = \mu_{air,o}(1-\xi) - y_o(\varphi, T)\xi \tag{3.12}$$

Where $y_i(\varphi, T)$ represent the yields of species $i$ and $y_o(\varphi, T)$ the consumption of oxygen per kilogram in equation (3.11 and 3.12) respectively.

### 3.3.3.4 Smoke Model

While using the combustion model or heat release model it is then prescribed to check the smoke production as well. In combustion model usually the heat release rate is predicted along with that in order to predict the smoke production another relationship needs to be defined. This relationship is the function of the conditions prevailing locally close to the fuel. The easiest way to represent fire is to use the volumetric heat or smoke source. A Multi-Particle Size smoke model has been developed by considering the settling velocity of smoke particles [Hu, *et al.*, 2011]:

The smoke and toxicity convention-diffusion equation is defined as:

$$\frac{\partial(\rho\emptyset)}{\partial t} + div\ (\rho u\emptyset) + div(\rho u_{th}\emptyset) - div(\Gamma_{\emptyset}\Delta\emptyset_j) = S_{\emptyset} \tag{3.13}$$

The recently developed model of smoke using Multi-Particle size concept use almost three different smoke or soot particle size ranges. In addition to the derived three groups of particles concentrations, an algebraic slip model is also used to allow gravitational settling. This gravitational settling has a strong effect on the heavy smoke particles. This effect can be noticed greatly in large geometries.

### 3.3.3.5 Boundary Conditions

The Navier Stokes equations before they are solved require boundary conditions. These boundary conditions define the flow of the fluid or heat-flow. Usually these boundary conditions provide the necessary information that is required about the fluid, like how it entered the computational domain, from where it will leave. Also if the temperatures are involved so what will be the temperature when the fluid enters the domain, and what will it be when it leaves the domain.  Other boundary conditions are the walls, obstacles, materials etc. [Karlsson, *et al.*, Chapter 1, 2000, Batchler *et al.*, 1967]

There are a number of boundary conditions that are available to the CFD users when they use modelling tools. Some of them like:

- Walls: where the walls have been assigned fixed values
- Inlets
- Outlets
- Open boundaries

Thus these boundaries can be linear or non-linear as well. Other type of boundaries are the time dependent boundaries which have an impact on the requirement of the CPU and memory [Galea, *et al.*, 2014].

#### 3.3.3.6 Numerical Solution Procedure

There a number of numerical solution procedures and different transport equations require different solution procedures. Some of the solution procedures are:

- Point-by-Point
- Line-by-Line
- Plane-by-Plane
- Whole Field

All these have different requirements and different solutions. For example for pressure the best procedure is to consider the Whole-Field procedure [Karlsson, *et al*., Chapter 10, 2000].

## 3.4 SMARTFIRE

The development of the CFD codes has made possible to bring the CFD fire models from the laboratories to the design desk. Since fire field models use techniques to solve the Navier Stokes equations that describes the fluid-flow and transfer of heat, momentum and mass with in a fire environment. In order to achieve good predictions a good CFD code is required. A better fire model and a user which has skills to use the CFD codes. Many CFD codes are difficult to use and these factors can make the users move away from the fire modelling.

### 3.4.1 Software Description

SMARTFIRE is CFD based fire field modelling software [Galea *et al*, 2007]. It is developed by FSEG at the University of Greenwich. The aim of SMARTFIRE is to improve the current CFD codes and bring efficiency in the CFD solutions; to try and make it simpler to attract the users which are fire engineers, architects, etc., to add research based tools for the advanced

CFD users; and finally to provide teaching and learning aid for the non-expert users. SMARTFIRE is based on the latest and modern tools and techniques [Galea, *et al.*, 2007]:

- Consists of latest CFD codes for fire modelling techniques.
- Provides knowledge-based CFD control and User assistance
- Easy and friendly Graphical user interface
- It has versions designed especially to run on parallel standard PCs
- CAD interface is developed to make building modelling easy
- It is integrated with Evacuation modelling as well

The uses of SMARTFIRE [Galea, *et al.*, 2007] can be elaborated as well. Thus the software has the ability to solve bigger computational domains and also complex structures. Some of the capabilities of SMARTFIRE are:

- Can be used for large environments such as multi-story buildings
- Can be used to simulate complex environments like aircrafts
- Be useful for small domestic fires as well
- Complex structures like car parks can be simulated as well in SMARTFIRE

SMARTFIRE [Galea, *et al.*, 2007] can be divided in to three sections which can highlight the functionality of the software, CFD modelling tools and fire modelling features.

### 3.4.2 Software Features

The SMARTFIRE features are:

- It is written in C++ using object oriented techniques
- GUI has been driven with application-specific user-friendly interface
- Run time user interface is very dynamic
- CAD tool allows to import complex geometry very easily
- Parallel versions on standard PCs can run
- Intelligent menus
- And finally Pre, during and Post simulation visualisation tool

All SMARTFIRE tools and features are user friendly and easy to understand and learn for a non-expert user.

### 3.4.3 CFD Tools

The CFD tools and techniques that have been employed in SMARTFIRE are [Galea, *et al.*, 2007]:

- Transient or steady state mode
- For laminar or turbulent flows modified k-e model is employed and LES for the research version exists
- Porosity face or volume patches
- Group Solvers
- 3D unstructured mesh ability
- Geometry automatic structured mesh
- Experiment engine for the research version

These CFD tools will enable the user to understand the basic CFD techniques and concepts.

### 3.4.4 Fire Modelling Features

The fire modelling tools are based on the fact that the better the fire model the better to understand the real fire environment. The features that are used in SMARTFIRE are [Galea, *et al.*, 2007]:

- Combustion Model (eddy break-up model)
- Toxicity Model
- Smoke Model
- HCL and HCN Model
- Fan Models and Force Ventilation Models
- Several Radiation Models (6 flux model, multi ray model which includes up to 48 rays model)
- Water and sprinkler models
- Suppression model (Only in research version)
- Flame Spread Model (Developed in version 4.1)

All these models will allow the user to see the fire environment closer to the reality.

## 3.5 Simulations using SMARTFIRE

The simulations run in SMARTFIRE gave an understanding about the tools and the models that are employed in SMARTFIRE. Before the research it is vital to understand all the tools and models in order to achieve better results with greater accuracy. It is also vital to familiarise oneself with all the latest CFD codes and fire modelling tools that can help to get better picture of the fire environment.

Hence in order to understand all the available tools and fire models some simulations were performed. Case study based on the fire in a Cargo plane was studied using SMARTFIRE.

### 3.5.1 Cargo Fire B-707 Baseline Case

The fire scenario discussed here is from a series of baseline fire experiments in which the fire was placed at the centre of a forward cargo compartment [Blake, 2000]. Currently there is a need of a better smoke detection system, which can help to detect the smoke within the cargo compartment and provide an indication to the flight crew within 1 minute of the start of the fire. This time for detection is based on a scenario when the fire is very small and it is in a state where the temperature is not significantly high, and the structural integrity of the plane is not in danger [Smoke alarms edition, 1997]. The experimental test fixture was equipped with diagnostics to measure the temperature (40 thermocouples), smoke obscuration (six smoke meters), heat flux (two sensors), and gas species concentrations. Figure 3.1 below shows the test fixture instrumentation for B-707 cargo. A ventilation duct is also shown in the figure, but typical ventilation rates were too low to impact the results; therefore, all B-707 cases were ran without ventilation in the experimental fixture. The smoke detectors were placed at three locations in this particular compartment. The detectors were placed in the recessed area and were then covered with a screen to prevent baggage from damaging the detectors [Blake, 2000].

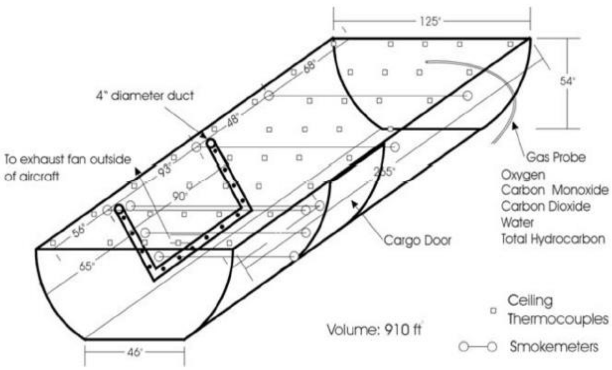


Fig. 3.1 B-707 cargo compartment geometry layout

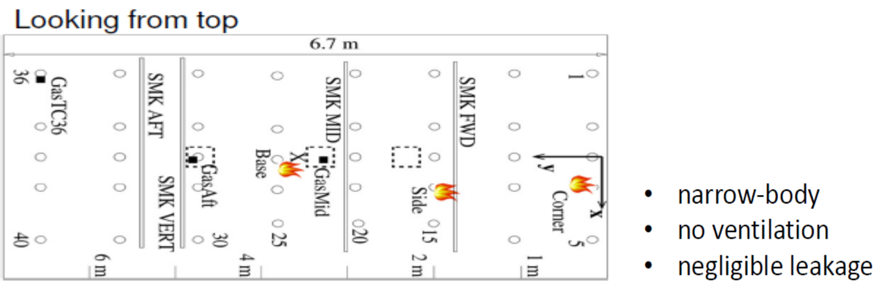


Fig. 3.2 Top view of B-707 cargo compartment with all the sources placed

Same experimental conditions were used for the simulation as well. Two different wall approaches, curve and staircase, were used to simulate the case.

### 3.5.2 Simulation Case 1: Base Line Case1 (CURVED)

In this case, the cabin wall was created with curved shape as in the real cabin using FEMGV [FEMGV]. The mesh was created by FSEG at University of Greenwich. The simulations were performed with quite few modifications. Firstly only radiation model was used for the analysis. Later it was analysed that combustion model along with radiation model will provide better approximations. Thus combustion model along with radiation model was used for the final simulations. The time step size was 5 seconds and the total simulation time was 200 seconds. The results obtained by the case were studied. Through mesh sensitivity analysis. It is concluded that a mesh consisting of 67×27×135 computational cells (Figure. 3.3) is able to produce reliable solution to the investigated scenario. Analysis on the difference in temperature, smoke and gas species concentrations for 60, 120 and 180 seconds was performed. To perform the comparison the data from each TC and SM was analysed. The initial temperature domain was set at 293K.

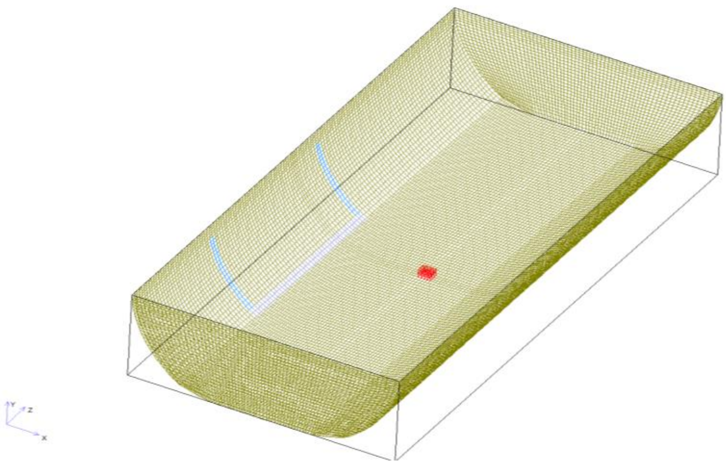

Fig. 3.3 Curved geometry and the mesh for the baseline case.

Figure 3.4 compares the temperatures at 40 positions at 120 seconds between the experimental results, the prediction in the work in [Öztekin, *et al*., 2012] and the current simulation. From this figure, both the predictions show similar temperature distributions as well as found in the experiment.

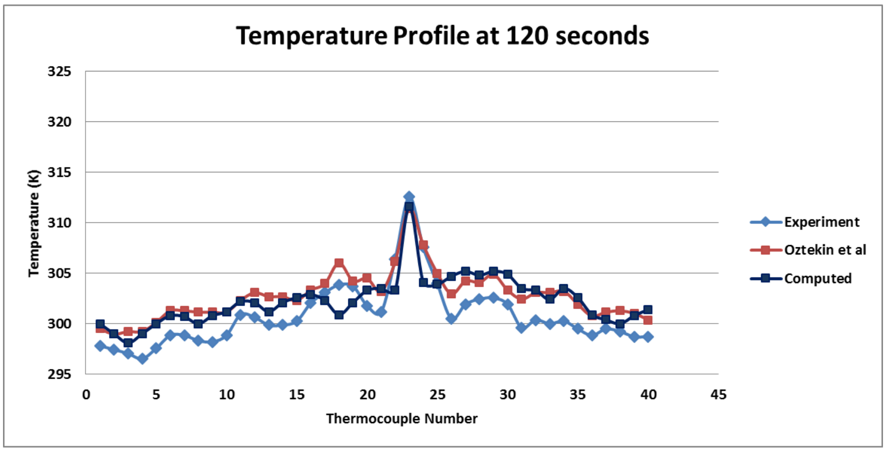


Fig. 3.4 The figure shows the comparison profiles for all the 3 possible outcomes at 120 seconds.

The temperature at 60, 120 and 180 seconds were collected for the selected validation. At 60 seconds the computational temperatures at the TC locations are plotted with the experimentally acquired temperatures. It is noted that the distribution of predicted temperatures in the compartment have similar trend to the experimental data. The magnitude of the computational temperatures is slightly higher for the simulations with no heat loss to the walls. Since the CFD simulator has the ability to transfer heat to the walls while the walls remain at a constant temperature. A comparison at 120 and 180 seconds was also performed. The simulated temperatures continue to increase with time. Between 120 and 180 seconds there was not much increase in the temperature values.

### 3.5.3 Simulation Case 2: Base Line Case 2 (STAIR CASE)

In this case the curved walls was approached with staircases with a cell budget of 42×38×44 computational cells (Figure. 3.5) while the other set up are the same as those in Case 1.

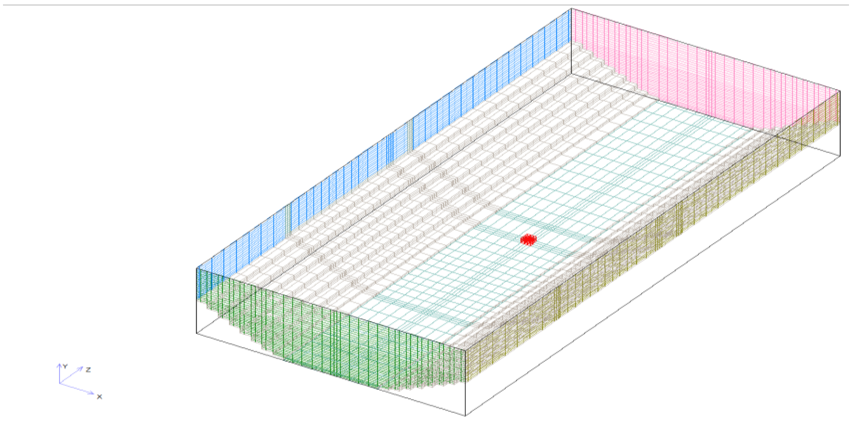


Fig. 3.5 shows the stair case geometry of the cargo compartment.

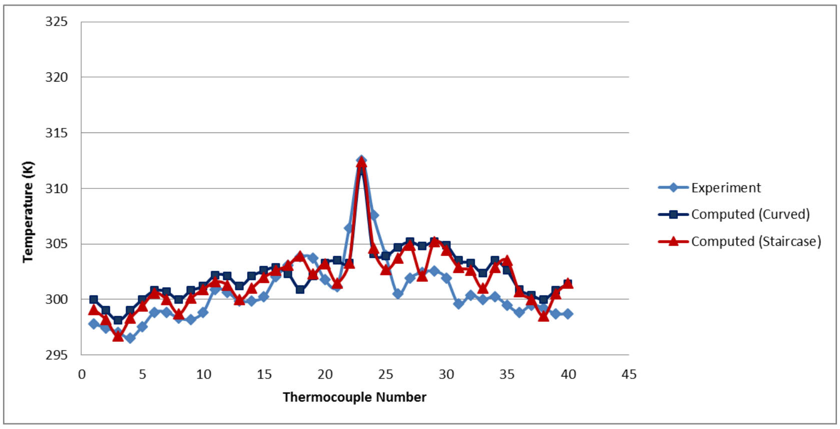


Fig. 3.6 Measured and predicted temperatures at 120 seconds.

Based on the results from Figure. (3.6) we can see that staircase geometry results have a lot of fluctuations. This could be due to the fact that the geometry has used obstacles to create the staircase geometry. Also the mesh plays and important role here. Because of the staircase geometry the mesh was not very fine at places. Whereas the smooth curved geometry has not much fluctuations in the temperature because of the smooth and fine mesh at the edges of the compartment. Generally, the different approaches of cabin walls have insignificant impact on the predicted temperatures under the cabin ceiling for the given fire size.

### 3.5.4 Conclusion

Results of these simulation comparisons indicate that more computations using various models need to be conducted to produce good results. A number of improvements with modifications to the computational model were performed like using radiation model along with the combustion model later in the simulation. For the investigated fire scenario, the approaches to cabin walls, curve shape or staircase approach, have insignificant impact on the predicted temperatures under the ceiling of the cabin.

Hence this case study allowed the author to familiarise oneself with SMARTFIRE. Also the tools and models that can help to improve the results for future simulations. Hence many factors and parameters are often ignored when modelling fire. Thus this case gave an insight into the fact that ignoring these factors will not provide a real fire scenario picture. So attention needs to be paid on the surrounding parameters and right fire model needs to be used.

## 3.6 EXODUS

After fire modelling the need to understand the fire scenario better is to look at the possible evacuation procedures and survivability as well. Based on the results from fire modelling if evacuation modelling can be analysed as well then it will make the job of the researcher, engineer and architects easier. It will allow the user to understand all the evacuation possibilities, reasons and causes of deaths of the occupants of the building and finally how to improve the building structures in terms of fire safety.

Evacuation modelling is defined as the development and application of tools that can predict and describe the behaviour and movement of a population with in a defined region of space. In this space the population is subject to emergency and hazard conditions. Evacuation modelling includes:

- Building code regulations related to evacuation
- Simple hand calculation of egress time
- Computer based evacuation simulation models

Evacuation modelling is essential in designing features for emergencies. It can help to evacuate the populated areas quickly and efficiently. Including human behaviour can help to produce high accuracy and can precise the incident reconstruction. Thus FSEG in the University of Greenwich has designed an evacuation environment called EXODUS that can help to model the above mentioned possibilities [Manual EXODUS, 2012].

### 3.6.1 Software Description

For evacuation purpose 4 versions are available:

- buildingEXODUS
- airEXODUS
- maritimeEXODUS

- vrEXODUS

All these are used for different environments and scenarios. Our main focus is on the buildingEXODUS. In this we can design any complex building and run the simulations to test the human behaviour and evacuation process. EXODUS is based on the five interactive core sub-models [Manual EXODUS, 2012].

- **Occupant**
  In this agent's description like age, gender, height etc. are defined.
- **Movement**
  This model controls the physical movement of the agents from current position to the next possible position.
- **Hazard**
  It has the ability to control the hazard options like heat, smoke and other narcotic gases.
- **Behaviour**
  This model determines the agent's response to the current situations and functions locally and globally both.
- **Toxicity**
  This models determines the effects of fire hazards on agent's using the toxic models like (Purser, Speitel).

### 3.6.2 Software Features

The features of EXODUS include [Manual EXODUS, 2012]:

- **Geometry Mode**
  This allows the user to construct the geometry that needs to be modelled
- **Population Mode**
  This is used to generate the population or group of agents that will reside in the building
- **Scenario Mode**
  It controls the scenario parameters like exit possibilities, exit potential, fire hazard zones, signage visibility etc.
- **Simulation Mode**
  In this mode the simulation is executed. And in this mode the user can specify the range of scenario output data. 3D view after the complete simulation can be viewed as well.

After complete simulations the results can be analysed and based on the results conclusions can be drawn about the building structures and human behaviour in particular situation.

## 3.7 Coupled Fire and Evacuation Simulation Technique

Usually, the fire safety of an enclosure is assessed by employing the concepts of available safe egress time (ASET) and required safe egress Time (RSET). In this approach, the fire simulation and evacuation simulation are carried out separately. The fire simulation provides the value of ASET and the evacuation simulation provides the value of RSET. If the ASET is not greater than the RSET by a prescribed value, the enclosure is deemed not safe in terms of fire safety. However, in this approach, the evacuation simulation is performed without any influence of the fire hazards.

Instead of the use of the ASET/RSET concept, the direct evaluation of the number of casualties (predicted incapacitations and severe injuries) resulting from the evacuation subjected to the impact of the developing fire has been developed to aid in fire investigation and safety assessment [Galea, *et al*., 2008, Korhonen 2009]. In the coupled fire and evacuation analysis technique, fire hazards in an enclosure are predicted by a CFD or zone fire model, then the predicted fire hazards are loaded into an evacuation simulation tool to predict the outcome of the evacuation inside the fire enclosure. This technique can employ any fire and evacuation simulation tools that are capable of achieving the objectives respectively of each simulation.

In the SMARTFIRE-buildingEXODUS coupling, the computational domain used in the fire simulations is divided into a set of zones. The fire hazard data predicted by SMARTFIRE is averaged over these zones to produce two values: a hazard value at an arbitrary nominal head height, and a value at an arbitrary nominal knee height at each time step. The zone based hazard data produced by SMARTFIRE is then imported into the buildingEXODUS model into corresponding spatial zones. Within the buildingEXODUS model, when agents are considered to be standing, they are exposed to the hazards at head height; when the occupants elect to crawl, they are exposed to the hazards at knee height. An agent is considered incapacitated when the FED (fractional effective dose) (either FIN or FIH) is equal to one. Here

- FIH – fractional incapacitating dose of heat, both radiative and convective (based on the Purser model described in [Purser 2002]). It consists of the contributions from radiative heat and convective heat, represented with FIHr and FIHc respectively.
- FIN – fractional incapacitating dose of narcotic agents, which include CO, $CO_2$, HCN,

$O_2$ and irritants based on the Purser model described in [Purser 2002]. The contributions from CO and HCN are represented with FICO and FICN respectively.

The coupled fire and evacuation analysis technique using SMARTFIRE and buildingEXODUS has been used in a number of applications including incident reconstruction, investigation, and engineering design. These include the reconstruction of the Station nightclub fire involving 100 fatalities [Galea, *et al*., 2008]; Manchester Airport B737 cabin fire with 53 deaths [Galea, *et al*., 2017]; the design of wide cabin aircraft with 1000 passengers [Galea, *et al*., 2010] and the shooting range fire killing 15 people [Wang, *et al*., 2017].

The coupled fire and evacuation analysis technique using SMARTFIRE and buildingEXODUS will be used in this study.

## 3.8 Conclusion

Hence in this chapter CFD modelling and specifically fire modelling has been discussed. Different kinds of modelling approaches exist. Thus based on the current requirements field fire models have certain advantage for fire safety design purpose over zone models. CFD fire field modelling plays a vital role in everyday fire safety. Based on the studies better building structures can be designed which can improve the safety of the occupants residing inside the buildings. Fire scenarios can be studied closer to the reality which will allow the future research to focus on the possible fire conditions and situations that can occur. Different and improved fire models have been discussed which gives an insight to understand the models better and select the best possible models for fire scenarios. The structure and models of the fire simulation tool SMARTFIRE has been familiar by simulating a complex cabin fire.

Evacuation modelling is essential in designing features for emergencies. Better understanding of the fire will enable to create possible evacuation methods which can be studied through evacuation modelling. Human behaviour in all the possible fire situations can help to understand the possible ways the people can evacuate the building in case of an emergency or fire. Also it will help the engineers and architects to design structures based on the results of the human behaviour which will improve the evacuation process in case of fire. The structure and functions of the evacuation tool EXODUS has been familiar.

Only when coupling the fire and the evacuation analysis can a true understanding of the implications of a fire scenario be fully appreciated. The coupled fire and evacuation analysis technique is widely used in fire reconstruction, accident analysis and building design. In the remainder of this thesis, this coupling technique is applied in the optimal design of the top vent for removing smoke and increasing survivability in house fires.

# Chapter 4

# Derivation of Heat Release Rate (HRR) Curve for under-ventilated Fires

## 4.1 Introduction

This Chapter is attempt to derive a burning rate (HRR) for dwelling fire with limited ventilations.

According to the research development the fire has been said to follow the T-square HRR curve model [Hyeong-Jin *et al*., 2000, Bukowski *et al*., 2008]. However, there are no limitations available in the literature for the oxygen concentration described under which the fire will extinct or continue to burn in house fire when applying such a T-square fire. Or simply the defined T-square HRR curve is not dependent on the limits of oxygen entering the fire plume. Since the size of the house varies so a methodology is required that can be applied to achieve a HRR curve using T-square model for a house fire in general. As explained earlier about the limitations in the available experimental and numerical data related to house fire, an approach is followed that allows to define a designed fire for a house and later that designed fire depends on the available oxygen.

## 4.2 T-Square Fire Model

For the T-square HRR curve there are many criteria depending on the value of α (fire growth coefficient, kW/s$^2$). What is a T-square fire model?

The T-square fire model is defined as:

$$\dot{Q} = \alpha t^2 \tag{4.1}$$

Where $\dot{Q}$ is the required HRR (kW), α is the fire growth coefficient (kW/s$^2$) and $t$ is the incubation period (sec). The fire growth coefficient has already been defined to lie in a range starting from $10^{-3}$ kW/s$^2$ for a very slow fire to 1 kW/s$^2$ for very fast fire. The time $t$ depends on the location and source of fire but data related to most of the burning items has been available depending on the location and the source of fire [Babrauskas *et al*., 1992] where fire growth rates of some furniture items have been quantified.

According to the research the house fire is usually medium in nature. The fire in a house is ventilation controlled, there could be leakages around the house but still the fire is ventilation controlled. In order to achieve the objective of developing a T-squared heat release curve for house fire, firstly we need to understand the impact of HRR curve in an enclosure.

For HRR curve in an enclosure there are two ways to understand the significance of air on fire or in other words impact of Oxygen on fire. How fire will develop under different scenarios in an enclosure. The best way to understand this phenomenon is to firstly study the two extreme scenarios. One with an open door and one with closed door of the enclosure or compartment. The two cases will allow us to develop an understanding that how the fire will develop and how it will extinct or will develop a flashover scenario during the study of both the cases. We will use the same objective of T-squared HRR curve for the initial fire growth and after fire growth we will understand how open door and closed door scenario will affect the fire with limited or unlimited oxygen.

## 4.3 Modification of T-Square Fire Model

In order to apply the T-Square fire model in building fire safety, it should be modified by considering the ventilation of the investigated geometry.

### 4.3.1 Case 1: HRR curve with closed door

The first case is without any ventilation. In this case, all doors/window are completely closed. The HRR curve in this case is derived in such a way that firstly the peak HRR and the peak time for any given fuel are determined.

The initial fire is considered to follow a T-square fire growth model. Since the initial stage of the fire depends on the T-square model so the curve for the initial stage is evaluated first. Thus the T-square fire growth model depends on the fire growth coefficient and the time. As defined in equation (4.1):

$$\dot{Q} = \alpha t^2$$

Where $\alpha$ = fire growth coefficient (kW/s$^2$)

$t$ = time (sec)

$\dot{Q}$= heat release rate (kW)

Hence the HRR at the initial stage will be somewhat similar to Fig 4.1:

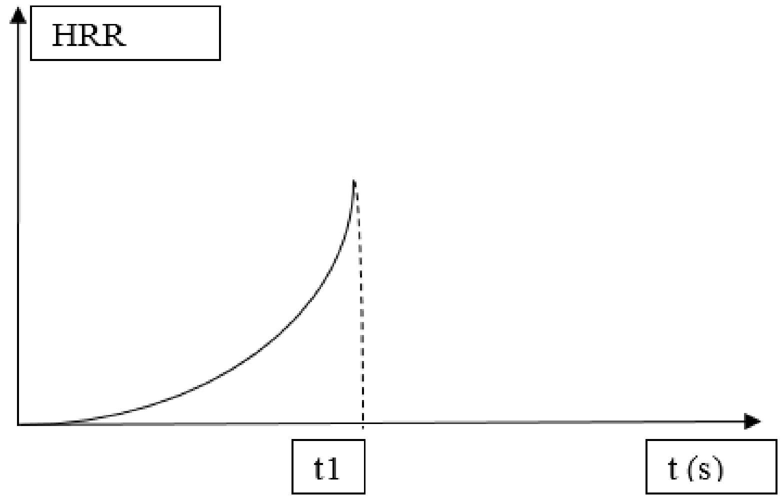


Fig. 4.1 HRR curve using T-square model

At a particular time interval $t_1$ it will reach a particular level of HRR.

Using the total heat released as a function of time equation (4.1) is integrated to find the area under the curve.

Thus the area under the curve will be expressed as:

$$\int_0^t \alpha t^2 dt = \frac{\alpha t^3}{3} \tag{4.2}$$

Now using the above expression and defining it as a function of the total fuel burnt.

$$\frac{\alpha t^3}{3} \times \frac{1}{\Delta H_c} \tag{4.3}$$

Where $\Delta H_c$ = Heat of combustion

Now expressing the total fuel burnt as a function of the amount of oxygen needed for complete combustion. This amount of oxygen will depend on the fuel source since it varies with the type of fuel.

Thus,

$$\frac{\alpha t^3}{3} \times \frac{1}{\Delta H_c} \times X_{O_2} \tag{4.4}$$

Where $X_{O_2}$ = stoichiometric $O_2$ to fuel ratio.

Finally the amount of oxygen consumed can be defined as equal to the original amount of oxygen in the fire room by a fraction.

$$\frac{\alpha t^3}{3} \times \frac{1}{\Delta H_c} \times X_{O_2} = \gamma_1 \times Mass\ of\ O_2 \tag{4.5}$$

Where $\gamma_1$ = oxygen mass fraction for the decay time;

Mass of $O_2$ = kg;

and

$$Mass\ of\ O_2 = Density\ \times Volume\ \times Percentage\ of\ O_2 \tag{4.6}$$

Density here refers to the air density: percentage of $O_2$ usually takes 23%.

Thus a defined fraction $\gamma_1$ in the above equation represents the ratio of oxygen consumed to the original amount of $O_2$ inside the room. Usually in most of the literature they say when between 10-13% of oxygen in air is left; the fire will start to decay [Drysdale, D. 1985]. So assuming based on the oxygen limits defined for the fuels it is assumed that when half of the oxygen inside the fire room is accumulated than the fire will extinct.

Thus equation (4.5) is the final equation to find the decay time with an assumed $O_2$ decay fraction of $\gamma_1$ .

Since the peak HRR at a particular time is mentioned, now the time at which the fire will start to extinct will be evaluated.

If the decay is linear it can be shown as:

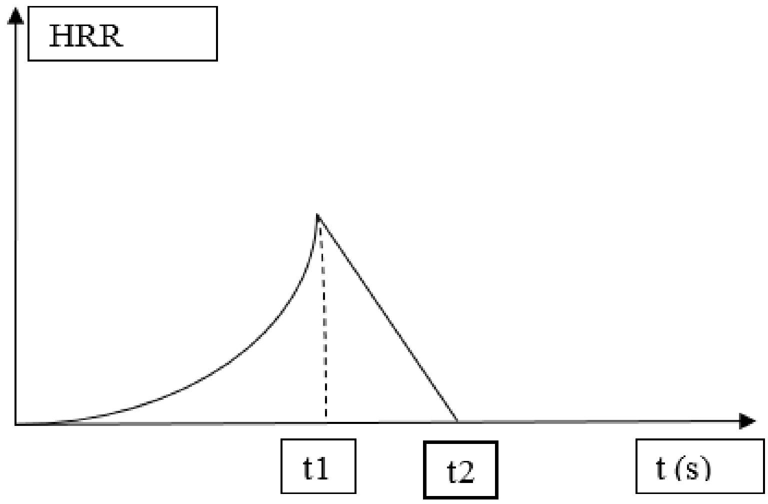


Fig. 4.2 HRR curve with linear decay phase

Hence for a given time $t_1$ it reaches its peak then for a particular time interval it will start to decay and the HRR will become almost zero during the extinction.

For linear decay time it is assumed that the fire to reach peak HRR and then start decreasing linearly depends on the linear function.

The linear function for the decay stage is derived as:

$$\dot{Q} = \beta t + C \tag{4.7}$$

This equation will help to evaluate the decay time depending on the decay fire coefficient and the peak HRR at time $t_1$.

Similarly the area under the curve for the decay phase is computed. But as considered the fire to decrease linearly, so the area under the curve will be equal to the area of a right angled triangle.

Thus the area will be defined as:

$$Area = \frac{(t_2 - t_1) \times \dot{Q}_{max}}{2} \tag{4.8}$$

Thus in the above equation the HRR is the peak HRR at time $t_1$. Hence than the above expression is defined as a function of the total fuel burnt.

$$\frac{(t_2 - t_1) \times \dot{Q}_{max}}{2} \times \frac{1}{\Delta H_c} \tag{4.9}$$

Where $\Delta H_c$ = Heat of combustion

Similarly the total fuel burnt is defined as a function of the amount of oxygen needed for complete combustion.

$$\frac{(t_2 - t_1)\ \times \dot{Q}_{max}}{2} \times \frac{1}{\Delta H_c} \times X_{O_2} \tag{4.10}$$

Where $X_{O_2}$ = stoichiometric ratio

Finally the amount of oxygen consumed can be defined as equal to the amount of oxygen left in the fire room by a fraction.

$$\frac{(t_2 - t_1)\ \times \dot{Q}_{max}}{2} \times \frac{1}{\Delta H_c} \times X_{O_2} = \ \gamma_2 \times Mass\ of\ O_2 \tag{4.11}$$

Here $\gamma_2$ = oxygen mass fraction from the decay of HRR to the complete extinction of the fire.

Thus equation (4.11) is the final equation to find the time of extinction.

Hence the function for the HRR with a linear decay phase can be defined as:

$$\dot{Q} = \begin{Bmatrix} \alpha t^2 & t \in [0, t_1] \\ \beta t + C & t \in [t_1, t_2] \end{Bmatrix} \tag{4.12}$$

Where $\beta = -\frac{\dot{Q}_{max}}{(t_2 - t_1)}$

$C = \ -\beta t_2$

$t_1 = \sqrt[3]{\frac{3\ \times \gamma_1 \times Mass\ of\ O_2\ \times \Delta H_c}{\alpha \times\ X_{O_2}}}$

And $t_2 = \frac{2\ \times \gamma_2 \times Mass\ of\ O_2\ \times \Delta H_c}{\alpha \times\ X_{O_2}} + t_1$

To simplify the calculation, we can assume that $\gamma_2$ =1- $\gamma_1$. Hence (4.12) represents the set of equations for the growth phase and the linear decay phase of fire.

Similarly a quadratic function is used to define the decay phase of the fire as well. Thus using the quadratic curve the function will be given as:

$$\dot{Q} = \beta t^2 + \delta t + c \tag{4.13}$$

It can be shown as:

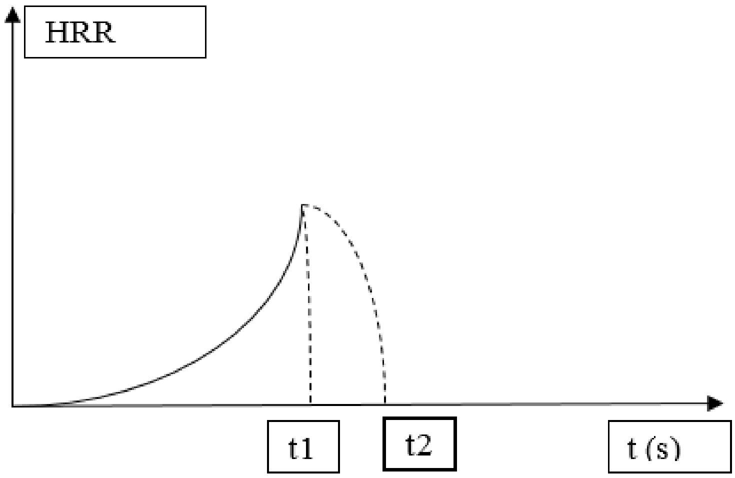


Fig. 4.3 HRR curve with curved decay phase

Since the growth phase will be evaluated similarly, but for the decay phase now instead of a linear function there is a quadratic function. The time $t_1$ is the time to reach the peak HRR, whereas the time $t_2$ will be the time required by the fire to extinct.

For the quadratic curve the information that will be available is:

At time $t = t_1$ the HRR $\dot{Q}$ = Maximum HRR at that time. This is already computed using the T-square fire growth model. It is assumed here that the peak HRR is also the peak value of the function (4.13). At time $t = t_1$ the change in the HRR is given by:

$$\left.\frac{d\dot{Q}}{dt}\right|_{t_1} = 0 \tag{4.14}$$

And at time $t = t_2$ it is assumed the HRR $\dot{Q} = 0$

And finally the area under the curve for the decay phase will be defined as:

$$\int_{t_1}^{t_2} \dot{Q}dt \times \frac{1}{\Delta H_c} \times X_{O_2} = \gamma_2 \times Mass\ of\ O_2 \tag{4.15}$$

In this way 4 equations are achieved to solve the 4 unknowns i.e. β, δ, c, and $t_2$. Thus the unknowns and the time for extinction can be evaluated based on these unknowns.

And $\gamma_2$ is a percentage of oxygen needed under which the fire to extinct.

Hence the HRR function depending on the quadratic curve will be defined as:

$$\dot{Q} = \begin{Bmatrix} \alpha t^2 & t \in [0, t_1] \\ \beta t^2 + \delta t + c & t \in [t_1, t_2] \end{Bmatrix} \tag{4.16}$$

Where $\beta = -\frac{\dot{Q}_{max}}{(t_2 - t_1)^2}$

$\delta = -2\beta t_1$

$C = \dot{Q}_{max} + \beta {t_1}^2$

$t_1 = \sqrt[3]{\frac{3 \times \gamma_1 \times Mass\ of\ O_2 \times \Delta H_c}{\alpha \times X_{O_2}}}$

And $t_2 = \frac{3 \times \gamma_2 \times Mass\ of\ O_2 \times \Delta H_c}{2 \times \dot{Q}_{max} \times X_{O_2}} + t_1$

Thus (4.16) represents the set of equations for the growth phase and the quadratic decay phase of the fire.

Hence after studying the case with closed door we have concluded that using the modified T-square HRR curve, from equation (4.12 or 4.16), the fire will develop based on the amount of oxygen available in the compartment/enclosure. Also based on the information available which is the HRR and the time of fire growth we can calculate the time the fire will start to decay and finally the time of extinction can be computed as well using the above mentioned set of equations. We have developed two different sets of equations depending on two different approaches that can be used to evaluate the unknown coefficients and the time for the fire to decay and finally the time of extinction. If the unknown coefficients are computed then it will be easier to find the time of decay and fire extinction. Thus, this case helped us to understand the impact of limited air on fire and how fire will grow, reach a maximum stage and start to decay and then finally extinct.

The set of equations (4.12 and 4.16) represents the two methods to achieve the time of decay of fire and the time of fire extinction. Using these two sets we can calculate the time for the fire will take to decay under no ventilation and also the time the fire will extinct based on the oxygen consumption as the main factor for fire extinction.

### 4.3.2 Case 2: HRR curve with open door

The second case is with a fully opened doorway. The HRR curve in this case is derived in such a way that firstly the peak HRR and the peak time for any given fuel are evaluated. Assuming the fire will follow a T-square curve for the initial stage and for the later stage after flashover has occurred in case with open door and a free space outside the fire room, the fire will reach a steady state.

Since the case with a fire room with open door and a free space has already been computed thus for the initial stage the fire will follow the T-square curve and for the steady state it will follow the curve already derived [Drysdale, 1985]. Thus in case with open door the fire depends on the ventilation factor which depends on the area and the height of the ventilation. The ventilation is the main factor in order to change from the point of fuel controlled fire to ventilation controlled fire. The air mass flow rate is defined [Drysdale, 1985] as:

$$m_a \cong 0.5\, A\, \sqrt{h} \qquad (4.17)$$

Where $A$ = area of the ventilation (m$^2$)

$h$ = height of the ventilation (m)

According to [Babrauskas *et al*., 1992] the heat release rate using the above mentioned air mass flow rate can be computed. The heat release rate will be stoichiometric heat release rate, given by;

$$\dot{Q}_{stoich} = 1520\, A\sqrt{h}\; (kW) \qquad (4.18)$$

But since this is the stoichiometric heat release rate now, for the heat release rate after the flashover has been developed is:

$$\dot{Q}_{fo} = 750A\sqrt{h}\; (kW) \qquad (4.19)$$

Thus the above equation gives the minimum heat release rate for flashover. Thus the initial fire growth depends on the T-square model until the HRR reaches $\dot{Q}_{fo}$. And after reaching this maximum or peak HRR the fire will reach steady state with a constant HRR.

Hence the graph for this particular case or the HRR graph for this case will be defined as:

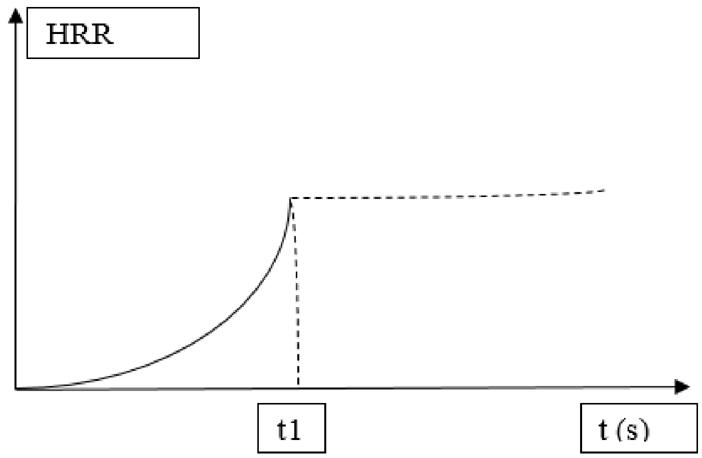


Fig. 4.4 HRR graph with steady fire

Now based on the information collected from the two extreme cases we will try and develop a method to derive a HRR curve for dwelling fire with limited ventilation. There can be some openings, some leakages but the fire will be ventilation controlled to study the impact of oxygen consumption on fire. Also the method will allow us to have an understanding about the top vent application in dwelling fires. Thus based on the two extreme cases we can say that after applying the designed methodology the derived HRR curve should lie between the two extreme cases.

## 4.4 HRR curve with limited ventilation

The third case is with limited ventilations, between no ventilation and a fully opened doorway. The previous derived HRRs under two extreme conditions are helpful to understand the development of house fire with limited ventilation. A methodology to represent the development of the fire needs to be developed for simulating fire under various ventilation conditions. And in order to demonstrate the methodology a fire scenario and a dwelling structure needs to be designed to test the methodology.

### 4.4.1 The Methodology

In order to develop the methodology we made some assumptions at the start. These assumptions helped us to develop the methodology. The assumptions we made before we developed the method are the parameters and variables:

- Known Heat of Combustion.
- Stoichiometric $O_2$ to fuel ratio is available.
- Fire is ventilation controlled.

These assumptions enabled us to develop the method that can be used to compute the HRR for a fire with limited ventilation. The method works on the existing T-square MLR curve, where the curve is modified using the **Simulation-Correction** method. We run the simulations and stop and we correct the MLR at that time:

- Initially define a fire volume which represents the fire plume of the investigated fire and select the coefficient for T-square type MLR;
- **Step 1** we run the fire scenario with the original T-square type MLR;
- **Step 2** Calculate the oxygen rate entering the prescribed-fire volume;
- **Step 3** Then we find the time $t_m$ at which the oxygen rate, $\dot{O}_{t_m}$, is equivalent to the MLR, $\dot{F}_{t_m}$.
- **Step 4**. Modify the MLR curve such that the mass loss rate keeps a constant of $\dot{F}_{t_m}$ after time $t_m$.
- **Step 5** Continue to simulate the scenario with the modified MLR curve and go to Step 3 until the oxygen rate reaches the level for the point of extinction.

Since the MLR is always checked and modified during the simulation, this process is called **Simulation-Correction** method.

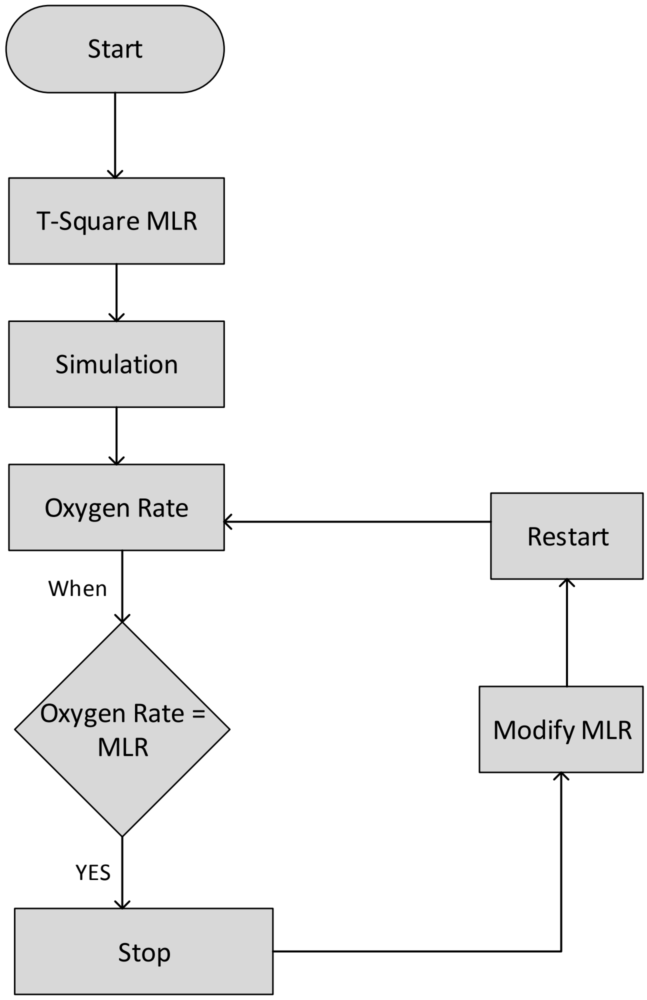


Fig. 4.5 Methodology to obtain HRR curve

### 4.4.2 Method Application

In order to apply the methodology based on the assumptions we need to design a dwelling structure and fire scenario. The designed structure should follow the UK Gov. Building regulations. The designed house has extended front and back area as well to understand the impact of air outside the house, also some extended region on the side of the house has been designed as well to make it a more realistic situation in which the side extension can be accounted as the other house. The SMARTFIRE case specification tool allows to design the structure, also the materials used can be assigned the specific material properties. The location and the source of fire has been set up in this tool. The opening and the closing of the doors and windows is based on the fire scenario that has been designed to run.

The location of the fire is living room since most of the fires in houses are accounted to happen in living room, other than kitchen [Fire Statistics, 2016]. The source of fire can be any furniture material. Here sofa has been decided as the fire source, to get more realistic picture of house fire and also sofa is the material which takes a lot of time to burn and in turn it extracts a lot of smoke which is the main objective of our study. The doors of the fire room is open in this particular scenario study. The roof top vent is active, which means depending on the oxygen level inside the structure the vent will become active. How the vent activation time is calculated, it's been discussed later. This case study was designed to test the **Simulation-Correction** method.

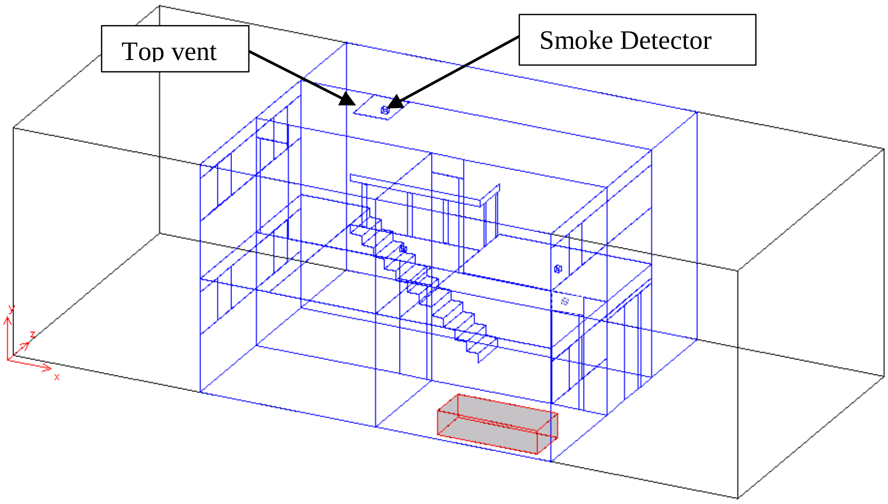


Fig. 4.6 Geometry setup of dwelling fire

The geometry of the dwelling is shown in Fig. 4.6. It can be seen from this figure the location of the fire source; the location of doors and windows. Also the roof top vent located at the ceiling of the first floor can be seen. The geometry refers to an experimental study in [BRE report, 2013].

### 4.4.2.1 Geometry specifications

- Region of the house with extension: 15.53 m × 4.8 m × 6.44 m
- Size of the house: 7.53 m × 4.8 m × 4.4 m
- Rooms: Total 4 rooms (2 rooms on each floor)
- Doors: Total 5 doors (1 in each room, 1 front door)
- Fire Source: Sofa (polyurethane foam) (SFPE Handbook, Chapter 3, 2002)
- Windows: Total 6 windows (Each room has a window, both the hallways have a window)
- Smoke Detectors: Total 4 smoke detectors (2 in the hallway downstairs, 1 on first floor near the vent and 1 inside the fire room to check the activation time of vent). The smoke

detectors are placed according to the building regulations [Building Regulations, Smoke Detectors, UK].

- Wind: Wind is blowing in the direction of x-axis at a speed of 8m/s.

### 4.4.2.2 Model specifications

For modelling the above mentioned scenarios using SMARTFIRE fire simulation tool.

- Model: Combustion, Smoke, and Toxicity model
- Fire source: Sofa (size of a regular sofa)
- Mesh Size: Nx = 110 × Ny = 45 × Nz = 51 (Total = 252,450 cells)
- Vent Opening: It is activated by the smoke detector in the fire room.
- Doors opening: Only fire room door is open (No windows are open)
- Leakage: On the sides of the doors
- Simulation Time: 300 seconds simulation time (44 hours CPU time on a PC with a processor of 3.60 GHz and a memory of 64 GB)
- Time step: 1 second

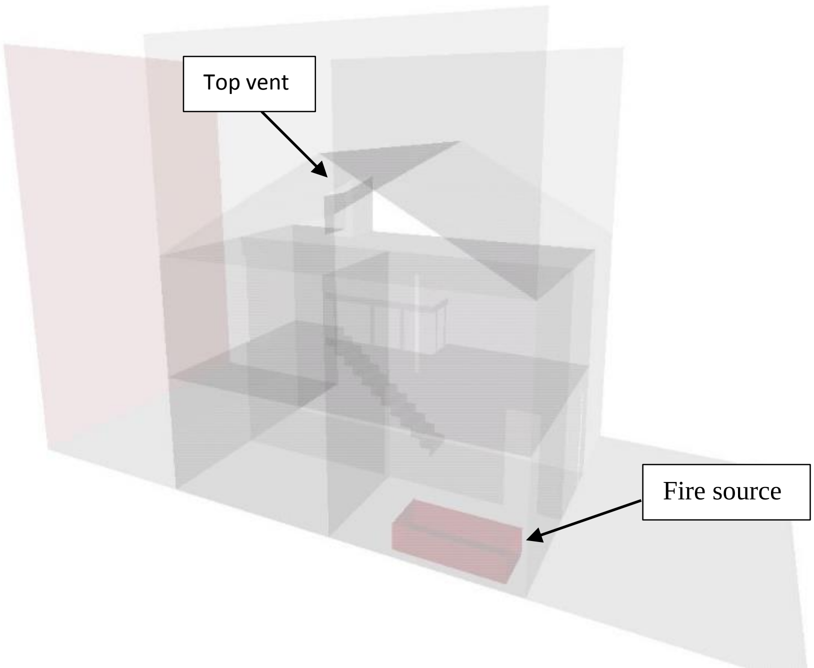


Fig. 4.7 SMARTFIRE data viewer dwelling fire specification

### 4.4.2.3 Parameters

The parameter values that have been used in the simulation are [Wang, *et al.*, 2013]:

Table. 4.1 SMARTFIRE Parameter Input Values

| | |
|---|---|
| Heat of Combustion (J/kg) | 2.62 E+007 |
| Wall Emissivity | 0.8 |
| Heat Flux Coefficient W/($m^2$K) | 15 |
| Wall Thickness (m) | 0.01 |
| Oxygen to Fuel Ratio | 2.62 |
| Initial Temperature (K) | 288.15 |
| Emissivity/Concrete Floor | 0.95 |
| Combustion Efficiency | 0.7 |
| Eddy Dissipation Constant | 4.0 |
| Smoke to Fuel Ratio | 0.024 |

### 4.4.2.4 Simulation Results

The results from the simulations using SMARTFIRE CFD tool enables to represent the MLR obtained using the defined methodology of simulation and correction method based on the oxygen rate entering the fire plume. According to the mentioned methodology the oxygen rate plays an important role. The fire is ventilation controlled and since not enough oxygen is available to the fire to survive thus depending on that the fire should start to extinct. As defined in the methodology the time at which the oxygen rate and the MLR became equal can be seen in Fig. 4.8. In Fig. 4.8, the oxygen rate is scaled to the equivalent fuel rate using the fuel to air ratio for complete combustion.

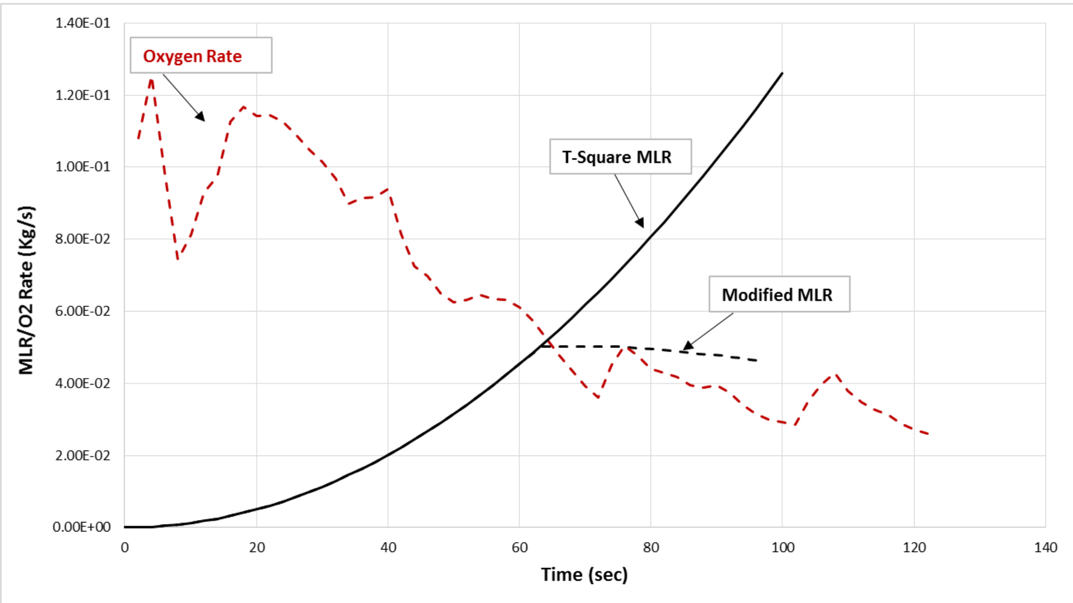


Fig. 4.8 Scaled Oxygen Rate v/s MLR

As seen in Fig. 4.8, the mass loss rate initially follow a T-square curve. It gradually increases to 0.05 Kg/s at 64 seconds when the $O_2$ rate decrease an equivalent level. This implies that the available $O_2$ cannot support the fire to continue increase as the pre-described T-square curve. Therefore, it will keep a constant rate of 0.05 Kg/s after 64 Seconds until a further modification occurs at 76 seconds.

## 4.5 Comparison of HRR/MLR among Various Situations

In this section we will demonstrate the HRR curve derived for the geometry using the method of **Simulation-Correction**, HRR for flashover of the extreme case with open door and the HRR without ventilation with closed door. The heat of combustion in this analysis is that used in Section 4.4 for the sofa, i.e. 2.62 E+007 J/kg. The MLR curves for all the mentioned methods derived for the geometry are compared in Fig. 4.9.

Case 1: With a fully closed house. In this case the HRR is calculated using equation (4.12);

Case 2: With a top open and some leakages as mentioned in (Section 4.4.2.4) using the **Simulation-Correction** method;

Case 3: With a fully opened doorway and without a top vent using equation (4.19);

As we have said before the modified curve with limited ventilation in Case 2 should fall between the two extreme cases, Case 1 and Case 3.

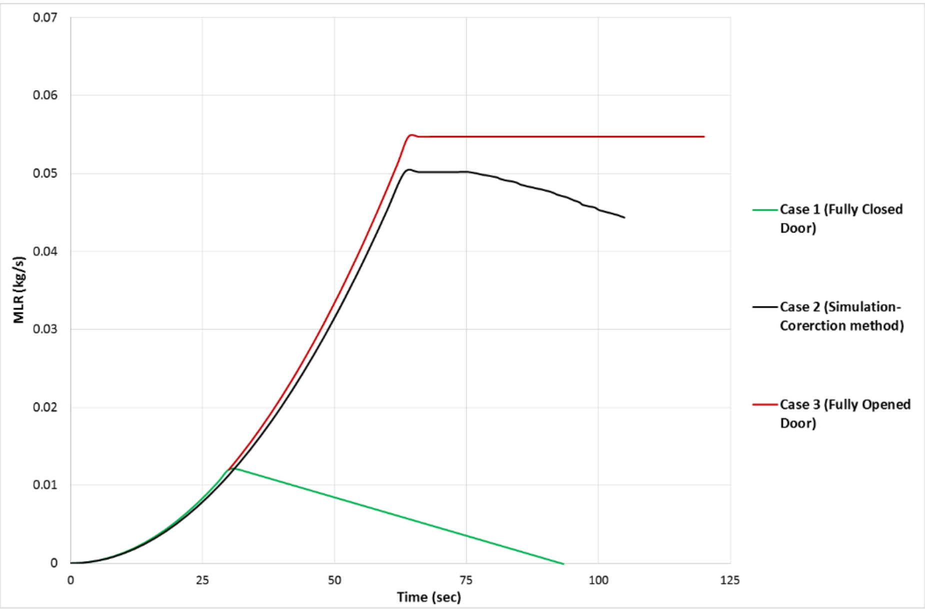


Fig. 4.9 Comparison of MLRs for Various methods

Using Equation (4.12) we have developed the MLR curve and we can see that the fire reached the maximum MLR of 0.012 kg/s at time $t_1$= 32.2 seconds based on an oxygen fraction of $\gamma_1$ = 25%. An assumption that the fire will reach the maximum MLR when 25% of the oxygen inside the room is used. And for the time of extinction we assumed when $\gamma_2$ =50% of the remaining oxygen is consumed by the fire [Quintiere, *et al.*, 2004]. Similarly for Case 2 using the **Simulation-Correction** method we have achieved the MLR curve. And finally for the fully opened door (with a doorway size of 0.59 m ×2.0 m) using Equation (4.19) we have calculated the flashover maximum HRR which was converted to MLR. This is well demonstrated in Fig. 4.9. As expected, the MLR curve from the **Simulation-Correction** method (Case 2) is between the curves for Case 1 with the closed room door (no any leakage) and Case 3 with a fully opened doorway.

## 4.6 Conclusion

Hence from the derivation of the following sets of equations for both cases we were able to understand the impact of air on fire in a compartment using the two extreme scenarios i.e. one with open door and one with closed door. If the unknown coefficients (the fractions of oxygen inside the fire room being consumed for the fire to reach its peak and to start to extinct) are computed then the time for the fire decay and the time of extinction can be evaluated in case of closed door scenario, whereas for open door the fire becomes a steady state after certain time. For open door the flashover HRR can be computed using the mentioned expressions. Hence from the two cases we were able to derive the method to obtain HRR curve for dwelling fires.

The **Simulation-Correction** method is proposed to derive the fuel loss rate for house fires with limited ventilations such as leakages or a top vent. Using the method of T-square HRR curve model we can obtain a modified MLR curve. But this methodology has not been well validated or tested. The validation will show if the method is accurate and reliable for dwelling fires under limited ventilation and with top vent application. Also it will help the future research to see the impact of top vent under different scenarios using different locations of fire.

As expected, the MLR curve from the **Simulation-Correction** method is between the curves for the case with the closed room door (no any leakage) and the case with a fully opened doorway.

On successful completion of the validation, it can be said that any designed fire can be realistically reproduced with a prescribed T-square HRR curve following the developed methodology and the time for extinction can be calculated for dwelling fires with limited ventilation. This study can be taken further and more research can be done in order to see if the proposed methodology is reliable in case of dwelling fires and what factors and parameters are sensitive to the method. Also if the top vent application with proposed methodology will be efficient in case of dwelling fire or not.

# Chapter 5

# Fire Safety Assessment of Dwelling Top Vent—Fire Simulation

## 5.1 Introduction

In this chapter the fire safety of a designed residential house with a top vent is assessed through the fire simulation using SMARTFIRE. Then the simulation results will be used to analyse the survivability in Chapter 6.

The previous chapters gave an insight about how we approached the objective of understanding a dwelling fire with limited ventilation. And now we will enlighten the objective of studying the efficiency of roof top vent application. This chapter will examine the common possible sizes of vent that can be used in dwelling structure for removal of smoke in case of fire. Also how the different sizes will affect the occupant's survivability inside the structure based on the level of smoke, CO, $O_2$, $CO_2$ and the level of temperature inside the structure. All this information will enable us to understand which vent size is useful enough for removal of smoke and how will such a vent size help the occupants inside the structure to evacuate quickly and safely or increase the survivability inside the rooms. Since from the previous chapters we have been able to understand the kind of fire that usually occurs in dwelling structures [Annemarie, *et al.*, 2012, Craig, *et al.*, 2015, Babrauskas, *et al.*, 1992 and 1997, Heskestad, *et al.*, 2002]. Using the same concept of T-square HRR curve model, we will develop a HRR curve based on the literature available about the fire growth coefficient and the time for the growth stage of the fire inside a dwelling [Hyeong, *et al.*, 2000, Bukowski, *et al.*, handbook]. Based on the information available from the literature we will develop a HRR curve, and we will use that curve to develop a fire inside the designed structure. And finally we will study all the possible scenarios with reasonable vent sizes and this will give us an insight about how efficient a roof top vent in case of fire is.

In the remainder of this chapter, firstly, the natural ventilation tactic is applied to residential house by designing a top vent. Then a fire load is suggested for the designed residential house; and eight ventilation scenarios with various vent size and vent locations are defined. And then, SMARTFIRE model is set up for the defined scenarios and simulations are conducted. Finally, the fire simulation results are presented and the fire hazards such as temperature, smoke, CO, $CO_2$ etc. at interesting locations is examined for each designed scenario.

## 5.2 The Geometry and Fire Load

### 5.2.1 The Geometry

The geometry description is provided in Fig. 5.1 And 5.2, which was used in fire experimental study on the impact of top vent on fire safety by BRE [BRE Report, 2013]. The size of the house is 7.53 m × 4.8 m × 4.4 m, which means the total area of the house is approximately 159 m$^3$. There are two floors in the designed house. There are total 4 rooms (2 rooms on each floor). Every room has a door and there is an external/main door. The floor to ceiling heights are 2.39 m for both the upper and lower floor. The internal doors are 2.0 m high and 0.59 m wide with 0.1 m of leakages defined on the sides of the doors [BRE Report, 2013]. The external door is 2.0 m high and 0.59 m wide as well. The bedrooms are all 2.46 m wide and 3.77 m long. The area of the stair case is 2.47 m long and 0.85 m wide. One smoke detector is placed on the wall 0.2 m above the doorway frame of the fire room. This is according to the building regulations [Building Regulations, Smoke Detectors, UK]. This smoke detector is used to activate the top vent for smoke removal.

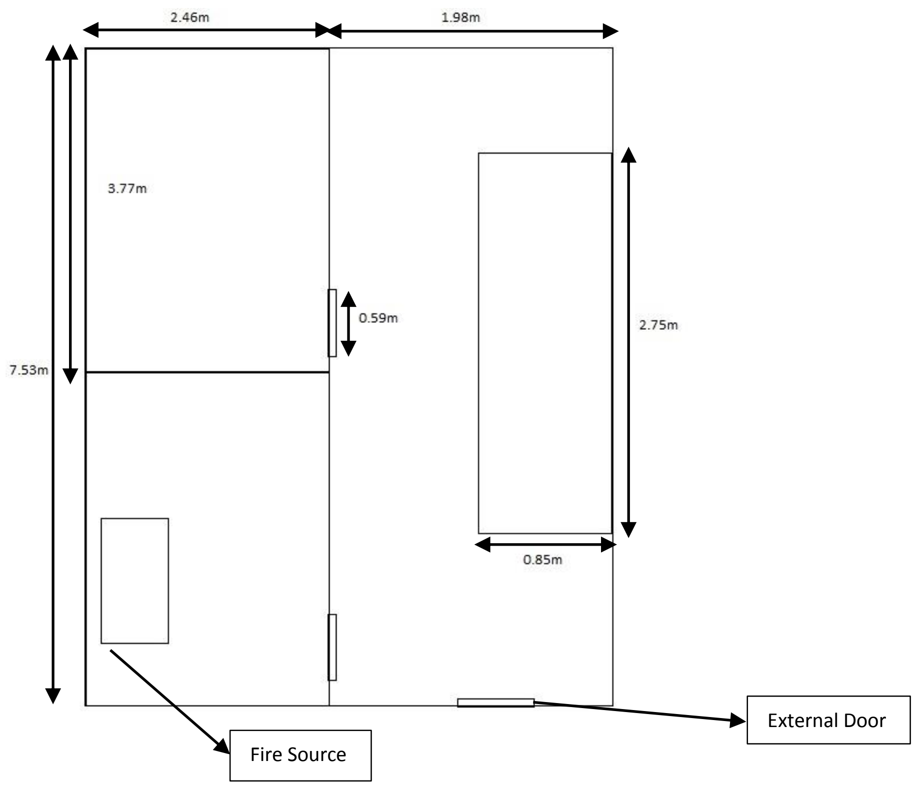


Fig. 5.1 Ground floor plan showing internal dimensions of the rooms, hallway and staircase

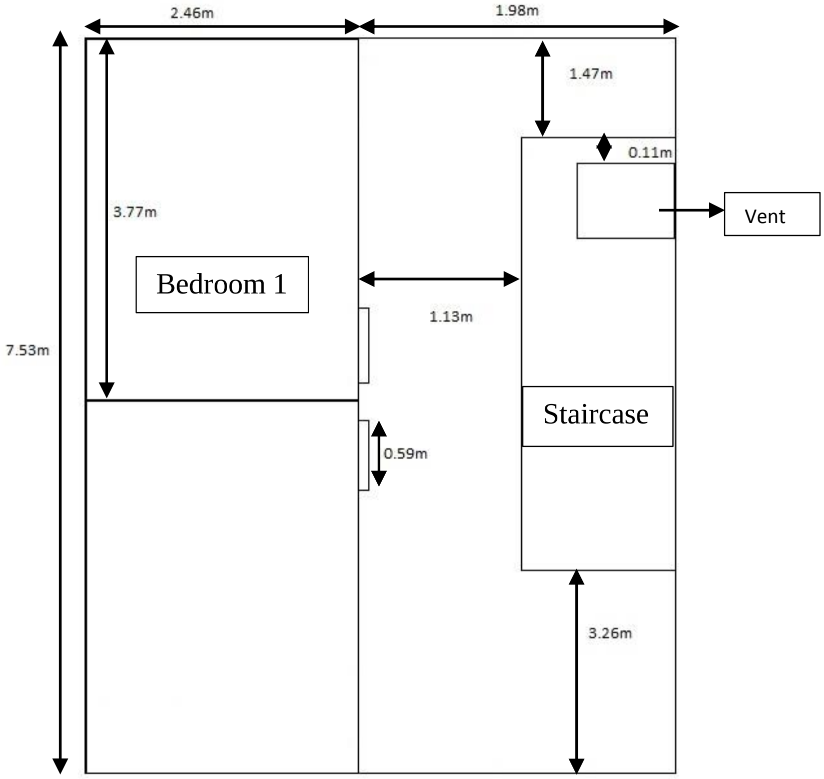


Fig. 5.2 First floor plan showing internal dimensions of the rooms, hallway and vent location

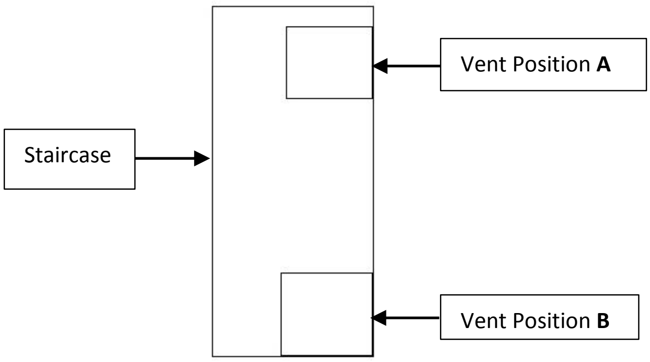


Fig. 5.3 Two locations of vent over the staircase area that have been used in this study

The Fig. 5.3 shows the two locations of vent that has been used for this study of fire and evacuation modelling. The vent will be activated by the smoke detector in the fire room. The critical temperature value to active the vent is 301 K. Hence based on SFPE Handbook and FSE guides in UK the activation time for the detector is 13°C above the room temperature. Whereas according to the literature  temperature rise at activation values of 4°C or 5°C above room temperature provide good agreement with experiments using the current detectors used for installation on ceilings at 2.4 m from the floor [Bukowski, *et al*., 1998]. Hence using the same concept and from literature that shows for several radial distances the activation criteria of 13, 8 and 4$^{o}$C is usually used. So the activation rise in temperature to 8$^{o}$C is used in our research for smoke detector that will activate the vent. The door of the fire room will be kept open for all fire simulations (and evacuation modelling Chapter 6). There are leakages defined on the sides of the doors and these leakages have been defined as porosity faces with 0.2 fraction for the doorway, which represent a 0.1 m wide gap of the doorway as set up in the experimental study in [BRE Report, 2013].

### 5.2.2 Fire Load

After designing the residential house, a fire load will be suggested in this section. As we have already discussed the T-square model before, here we will only give a short description. Since the T-square model is defined as:

$$\dot{Q} = \alpha t^2 \tag{5.1}$$

Where $\dot{Q}$ is the required HRR (kW), α is the fire growth coefficient (kW/s$^2$) and *t* is the incubation period (sec).

After studying the two extreme cases of fire in an enclosure we were able to understand the impact of air on fire. We will use the already developed standards in literatures for dwelling fires to derive a T-square curve. Since in [Hyeong, *et al*., 2000] it has been described that for different fire growth coefficients there will be different intensity of fire. We need to understand the reasonable fire growth coefficient that is reasonable enough to be used to develop a HRR curve for dwelling fires. We will use furniture as the main fuel source of a residential house fire. And in furniture we are mostly interested in sofa as the fire source as sofa is one of the common furniture in houses. Sofa is composed of many chemical materials such as polyurethane, polyester, plastic, wood etc. don't burn quickly and easily but they have the tendency to release smoke. Since our main objective is to study the removal of smoke through top vent and how survivability of the occupants will be affected by this vent. Also from the literature we have managed to find the maximum HRR for sofa fire i.e. polyurethane foam in dwelling structures [SFPE Handbook, Section 3, 2002]. Hence based on all the research we were able to derive a HRR curve for dwelling fire scenarios that will be used in our research.

The derived T-Square HRR curve is:

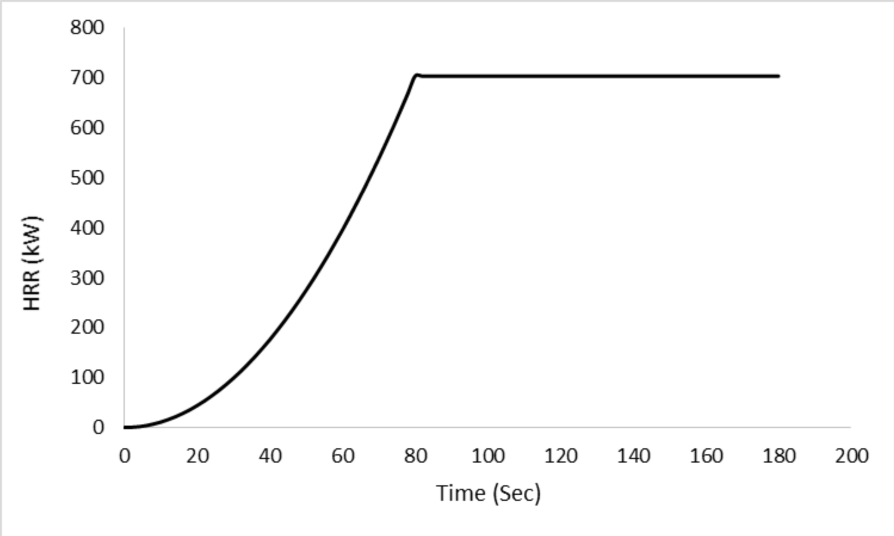


Fig. 5.4 T-Square HRR Curve

Thus based on the information collected from the literature which shows that the maximum HRR for a burning sofa in dwelling fire is approximately 700kW. The fire has been simulated for 300 seconds. Since based on the oxygen concentration inside the room the fire can last for more than 180 seconds. Now this HRR curve will be used in all the designed scenarios and for all the vent sizes in this research. SMARTFIRE has the ability in which we can input a designed HRR curve to study fire modelling and run fire simulations. It should be kept in mind that this HRR curve for all vent scenarios implies an assumption;

**Assumption 1**: the top vent (and size) has no impact on the burning rate of the sofa fire.

## 5.3 Roof Top Vent Scenarios

The fire load described in Section 5.2 will be applied to all the scenarios defined here. Since from the earlier description it has been described that different vent sizes will be studied in order to understand the impact of vent size on the atmospheric condition and survivability inside the house. The designed scenarios for different vent sizes are listed in Table 5.1:

Table. 5.1 Designed fire scenarios with different vent location and size

| Scenario | Vent activity | Vent size | Vent location | Door to Room 1* |
|---|---|---|---|---|
| 1_ac_0.75_A_cl | Active | 0.75m | A | Closed |
| 2_ac_1.0_A_cl | Active | 1.0 m | A | Closed |
| 3_ac_1.25_A_cl | Active | 1.25 m | A | Closed |
| 4_ac_1.5_A_cl | Active | 1.5 m | A | Closed |
| 5_in_NA_NA_cl | Inactive | N/A | N/A | Closed |
| 6_ac_1.0_B_cl | Active | 1.0m | B | Closed |
| 7_ac_1.5_B_cl | Active | 1.5m | B | Closed |
| 8_ac_1.5_A_op | Active | 1.5m | A | Open |

- A 0.1 m wide gap between the door and the doorway frame is set up in cases with closed door.

The scenario labels include the following information: scenario number, activity state of the top vent, size and location of the top vent, and the closure state of the bedroom door on the first floor. For example, Scenario 1_ac_0.75_A_cl is the first scenario with an active square top vent with a side length of 0.75 m at Location A and with the bedroom doors closed. From the above table it is seen that the location, size and the position of the vent will change based on the respective scenario accordingly. Scenarios 1-4 are with the same vent location A, but vent size varying from 0.75 m to 1.5 m. For comparing the impact of a top vent on smoke removal, Scenario 5_in_NA_NA_cl is without any top vent. Scenario 6_ac_1.0_B_cl and Scenario 7_ac_1.5_B_cl are the same as Scenario 2_ac_1.0_A_cl and Scenario 4_ac_1.5_A_cl respectively but with the vent at Location B (See Fig. 5.3 for vent location). Scenario 8_ac_1.5_A_op is the same as Scenario 4_ac_1.5_A_cl but with the door to the first floor bedroom open.

After studying all the vent sizes then we will be able to conclude that which size of vent is reasonable for dwellings and for removal of smoke in case of fire. Also we will conclude the position of vent which is efficient to remove smoke in case of fire to improve survivability. This conclusion will be based on the fire modelling in this chapter and evacuation modelling analysis in Chapter 6. The doors are all closed in all the scenarios except the fire room door which is open in all the scenarios. Only for scenario 8 we have opened the door of the upstairs bedroom 1 to check the survivability. Addition to the top view of the geometry in Figs. 5.1-5.2, Fig. 5.5 shows the side view of the investigated dwelling for fire scenarios and the different vent sizes that have been used in the research.

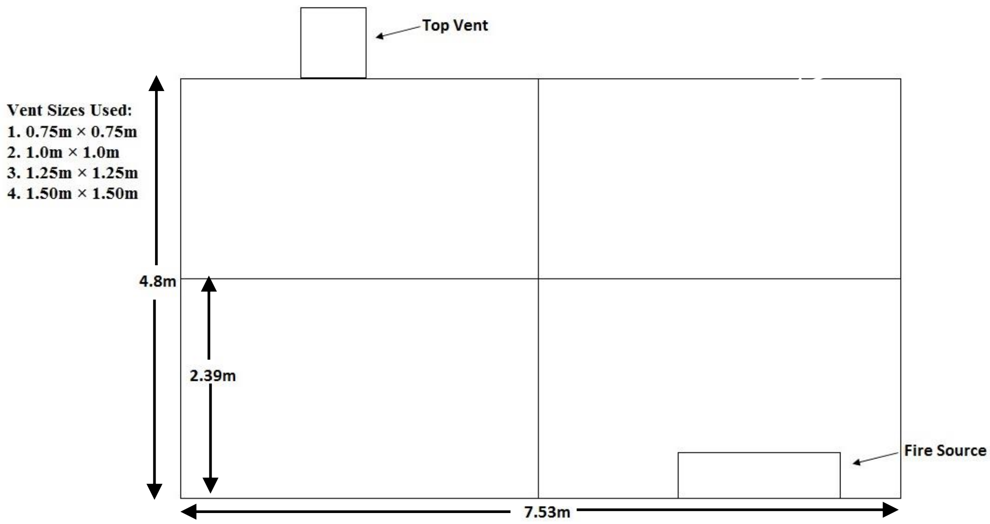


Fig. 5.5 Side view of the dwelling with different vent sizes

## 5.4 Fire Simulations

The simulations for fire modelling have been performed with SMARTFIRE CFD software. The version used is 4.3 which is the up to date version [Galea, *et al*., 2013].

### 5.4.1 Mesh Generation

The mesh size for all the cases are presented in Table 5.2.

Table. 5.2 Mesh budgets for all Vent Sizes

| **Vent Size** | **Nx** | **Ny** | **Nz** | **Total Mesh Size** |
|---|---|---|---|---|
| 0.75 m | 110 cells | 65 cells | 61 cells | 436150 cells |
| 1.0 m | 109 cells | 65 cells | 61 cells | 432185 cells |
| 1.25 m | 109 cells | 65 cells | 62 cells | 439270 cells |
| 1.5 m | 109 cells | 65 cells | 59 cells | 418015 cells |

Through many times simulations with various mesh sizes, it is concluded that a mesh consisting of approximate 400,000 computational cells is able to get converged solutions for the investigated fire with the given geometry size. Due to the changes of vent size and location, the mesh budgets for each scenario are slightly different.

### 5.4.2 SMARTFIRE Simulation Models and Parameters

The SMARTFIRE as discussed in Chapter 3 has the ability to produce results which are closer to the actual facts. The parameters that were used in simulating the scenarios are given below. Tables 5.3-5.5 show the parameters that were used since only the size of the vent was changed but the parameters were kept same for all the scenarios. The fire models that were used in the fire simulations are:

- Radiation Model

  The multi-ray radiation model with 24 rays is used to model the heat exchange via radiation.
- Combustion Model

  The Eddy Dissipation Combustion model is used to release the heat due to combustion. The fuel is represent with polyurethane foam with a molecular structure of $CH_{1.8}O_{0.30}$ [SFPE Handbook, Section 3, 2002]. The combustion model parameter values are those in Table 5.3.

Table. 5.3 Combustion Model Parameters

| | |
|---|---|
| Heat of Combustion (J/kg) | 2.62e+007 |
| Combustion Efficiency | 0.7 |
| Eddy Dissipation Constant | 4.0 |
| Oxygen Mass Fraction | 0.23 |

- Smoke

  The smoke model parameters that were used in fire modelling are:

Table. 5.4 Smoke Model Parameters

| | |
|---|---|
| Smoke Density ($kg/m^3$) | 1800 |
| Smoke Absorption Constant | 1200 |
| Smoke Specific Extinction Coefficient ($m^2/kg$) | 7600 |

- Toxicity

  The toxic model parameters for the yields of CO, $CO_2$ and the consumption of $O_2$ are those used in the simulation of the house fire experiments in [Wang, *et al*., 2013].

The tables above show all the parameters that were used in simulating the fire. The parameters have been taken to be same as considered by BRE Global in their report [Wang, *et al*., 2013, BRE Report, 2013]. Because BRE performed the experiments designing the house structure and using the same parameters.

Table. 5.5 SMARTFIRE Simulation Parameters

| | |
|---|---|
| Flux Coefficient $W/m^2K$ | 10 |
| Wall Thickness (m) | 0.02 |
| Initial Temperature (K) | 288.15 |
| Wall Emissivity | 0.8 |

The material properties in Table 5.5 were taken from [Hertzberg, *et al*., 2005, BRE report, 2013] test case as well.

### 5.4.3 Simulation Control

The simulations were performed on a PC with processor of 3.60GHz and with memory of 64GB. Since from the HRR curve we can see that the maximum HRR is 700kW, after that the HRR has considered to be constant. Thus the simulation time for fire used in SMARTFIRE is 300 seconds to get a clear picture of the situation inside the structure after 180 seconds as well. The time step was taken as 1 second. It took approximately 44 hours for each case to run.

Table. 5.6 SMARTFIRE Specifications

| **Simulation Time of the fire (s)** | **Time Step Size (s)** | **Maximum Iteration in each Time Step** | **Global Tolerance** | **PC Time (h)** |
|---|---|---|---|---|
| 300 | 1 | 50 | 1e-07 | 44 |

### 5.4.4 Simulation Output

The atmospheric properties such as temperature, concentrations CO, $CO_2$ and $O_2$ and smoke at interesting locations as function of time are recorded. These locations include the foot of stairs, the head of stairs, the first floor landing area in front of the bedroom and bedroom 1 upstairs which are on the evacuation paths for the designed house.

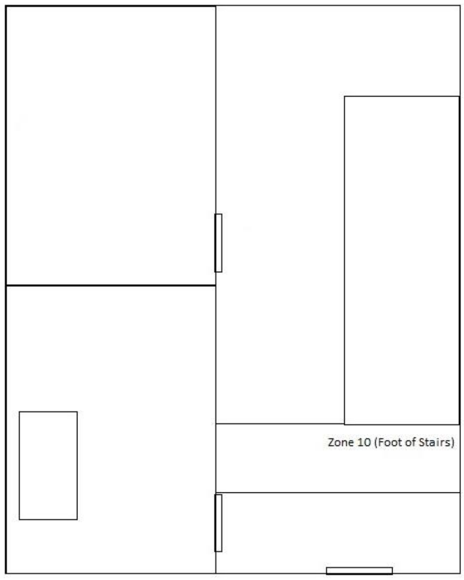


Fig. 5.6 Schematic of Ground Floor Zone used for survivability analysis

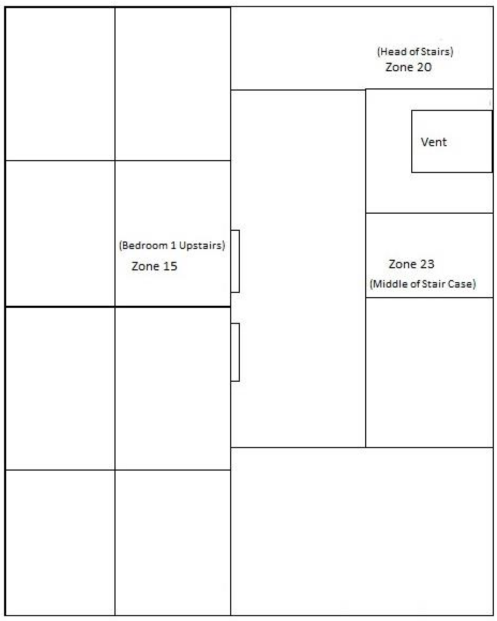


Fig. 5.7 Schematic of first floor zones used for survivability analysis

The house has been divided into 23 zones. Figures 5.6 and 5.7 show the zone distribution. Zone 10 is at the foot of the staircase; Zone 23 is on the middle of the staircase; Zone 20 is on the head of the staircase. These zones are at the evacuation paths in this designed house. Zone 15 is in the bedroom in the first floor. The survivability in the bedroom is critical for occupants remaining in the room during fires. Therefore, zone hazard data in these zones is outputted for survivability analysis.

## 5.5 Simulation Results

The simulation results that are presented in this section are for temperature, smoke and toxic gases like CO, $CO_2$ and level of oxygen will be shown as well.

### 5.5.1 Temperature on evacuation Paths with Varied Vent Size

The temperature profile shown here is the temperature compared for all the vent sizes to see a clear picture of how the temperatures are affected inside the dwelling, and to see how they change when the vent size changes and for which vent size the temperatures are lower and for which they are high respectively. The results presented here are for Scenario 1_ac_0.75_A_cl to Scenario 4_ac_1.5_A_cl.

The temperatures are collected at crawling height of a person. The standard crawling height is 0.3 m from the floor [Fire Safety Regulations 2000]. Thus all the temperature profiles are 0.3 m from the floor level. The first one is the doorway temperature of the fire room. The temperature is computed in the middle of the doorway of fire room 0.3 m above the floor (See Fig. 5.8) since the door of the fire room is open.

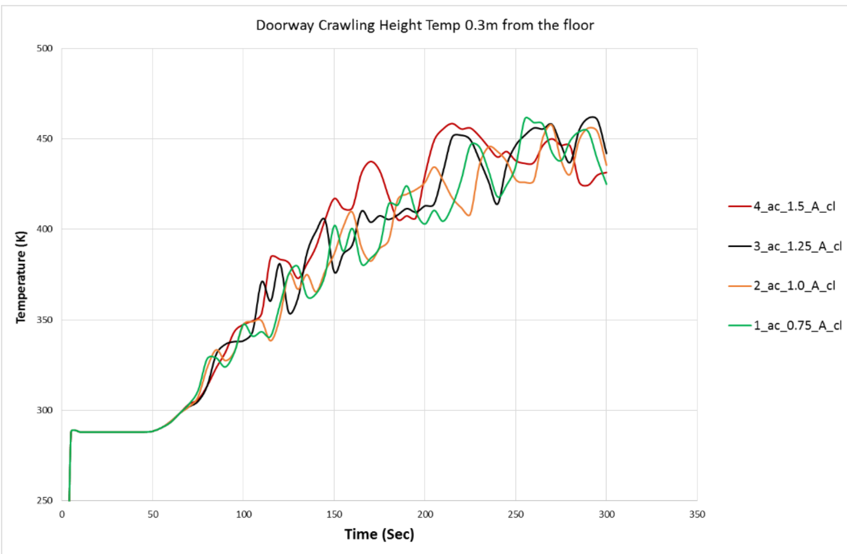


Fig. 5.8 Fire room doorway Temperature Profile

As we can see from the figure that the temperatures are quite similar for all the vent sizes at the doorway of fire room. It keeps the initial value of 288.15 K for 55 seconds. Then it quickly increase to the maximum of approximate 450 K at 200 seconds followed by a quasi-steady temperature state.

The next location is the foot of stairs. This location is at the foot of the stairs on the ground floor and at crawling height from the floor level. This location is selected to check the survivability chances for the occupants around the stair case and especially near the foot of stairs where the occupants will land from upper floor before evacuating. This location also enables to understand if the occupants will be able to survive at this location.

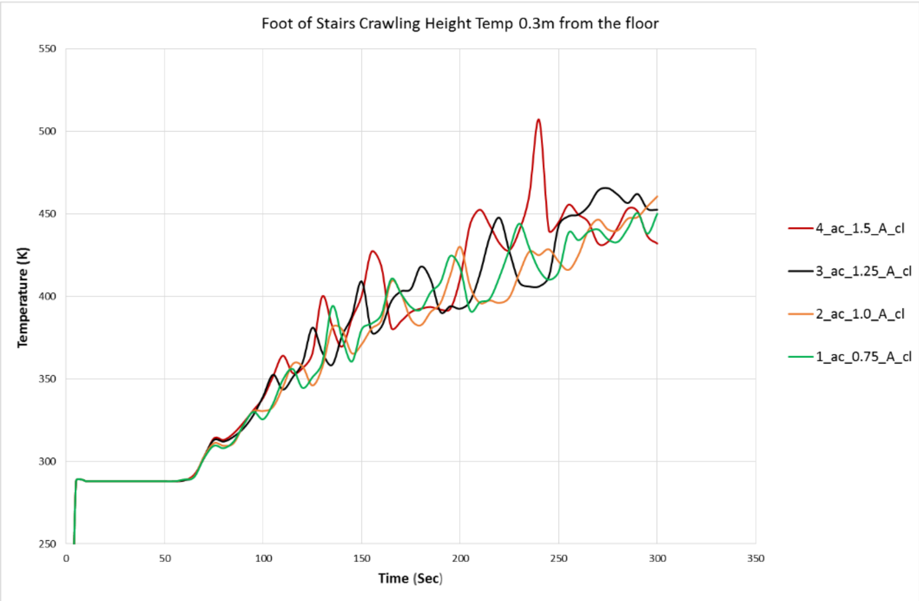


Fig. 5.9 Foot of Stairs Temperature Profile

The head of stairs location is very vital as it is exactly underneath the roof top vent. This location will help us to understand if the top vent will reduce the temperature level near this location which will help the occupants to evacuate from the first floor.

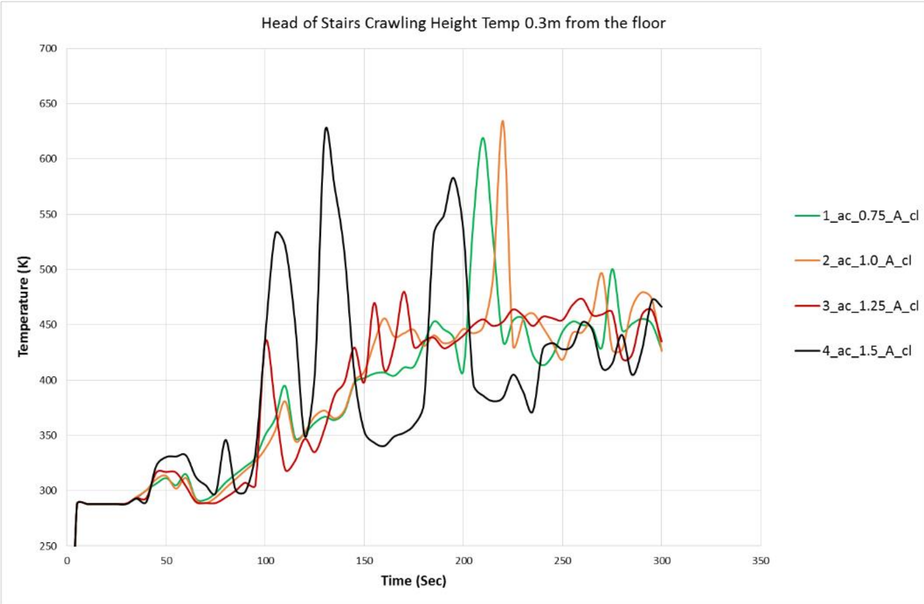


Fig. 5.10 Head of Stairs Temperature Profile

As we can see from the Fig: 5.10 there is big fluctuation in the temperatures at the head of the stair case. These fluctuations were observed for Scenario 4_ac_1.5_A_cl with the largest vent size. These fluctuations are due to the fact that the vent size is big enough to allow the hot air to circulate back inside the dwelling. The hot gases were observed circulating back inside through the vent which makes the temperatures fluctuate from time to time.

The last location is the area in front of the bedroom upstairs. This location will enable us to look at the possibilities if it will help the occupants evacuate from the room. If the temperatures are high enough so probably the occupants will have to stay inside the room rather than leaving the room and risking their lives. In reverse it can increase the chances for the occupants to evacuate from the room.

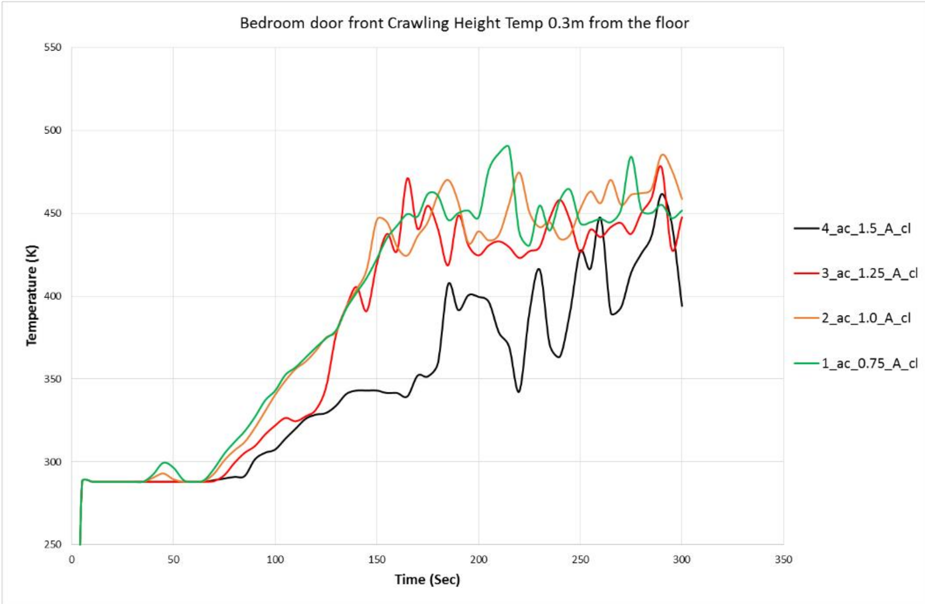


Fig. 5.11 Upstairs bedroom door front Temperature Profile

From all these temperatures it is seen that there is not much significant impact of the top vent on the ground floor on the doorway of fire room and the foot of stairs but there is fluctuation in temperatures at the head of the stairs. At one time point the temperatures are high and then there is a sudden drop in temperature. However, the predicted temperatures at the front of the first floor bedroom in Scenario 4_ac_1.5_A_cl with a vent side of 1.5 m is much lower than other scenarios with vent sizes between 0.75 m and 1.25 m. For the bedroom front area upstairs the temperatures are lower for 1.5m vent among all the vent sizes. This results imply that significant impact on smoke removal only occur for reasonably large top vents. Table 5.7 shows the average temperature at bedroom front door for scenario 1, 2, 3 and 4 during a quasi-steady state between 150 and 300 seconds.

Table. 5.7 Average Temperature at bedroom door front for Scenario 1, 2, 3 and 4

| **Scenario** | **Average Temperature (K)** |
|---|---|
| 1_ac_0.75_A_cl | 452.3 |
| 2_ac_1.0_A_cl | 451.5 |
| 3_Ac_1.25_A_cl | 439.5 |
| 4_ac_1.5_A_cl | 390.1 |

From Table 5.7 we can see that the average temperature for Scenario 4_ac_1.5_A_cl is the lowest among all the scenarios. It means that the largest size top vent was able to produce significant impact on the first floor area which will improve evacuation and survivability chances for the occupants.

### 5.5.2 Temperature on Evacuation Paths with and without Top Vent

In this section we will compare the above mentioned scenarios 1-4 to scenario 5 with closed vent closed throughout the simulation. This scenario will enable us to study the effect of temperature in case of fire when there is no removal of heat from the structure and how it will affect the survivability chances. Also it will help to understand the importance of top vent.

The temperatures have been compared at the same locations of doorway, foot of stairs etc. The comparison is between the temperature profiles for scenario 1 to 5.

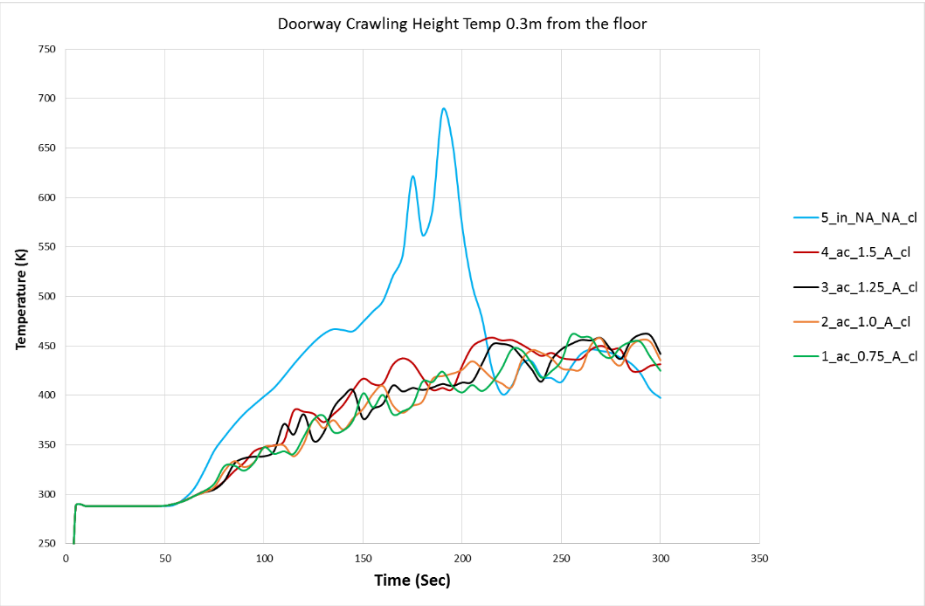


Fig. 5.12 Temperature profile at doorway 0.3m from the floor

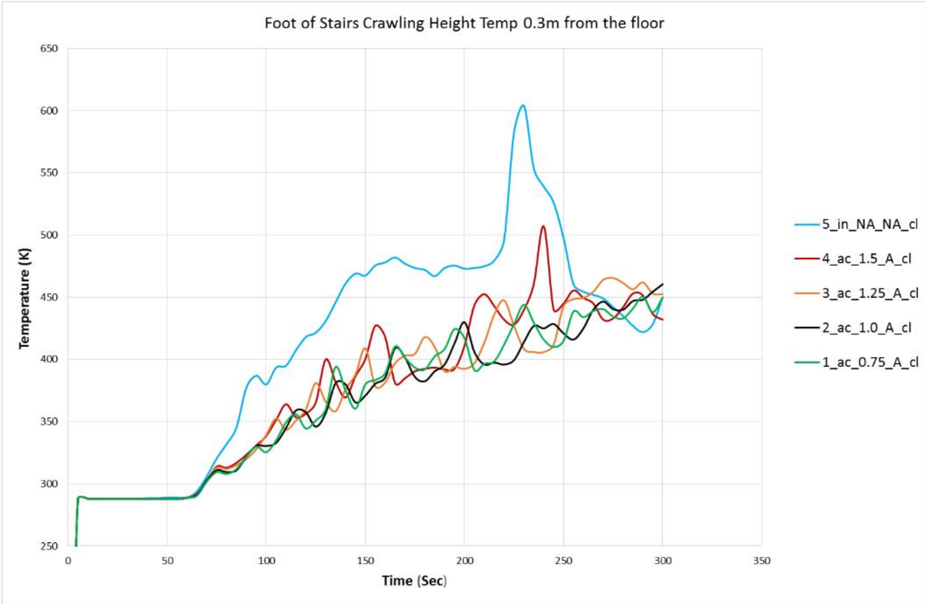


Fig. 5.13 Temperature profile at Foot of Stairs 0.3m from the floor

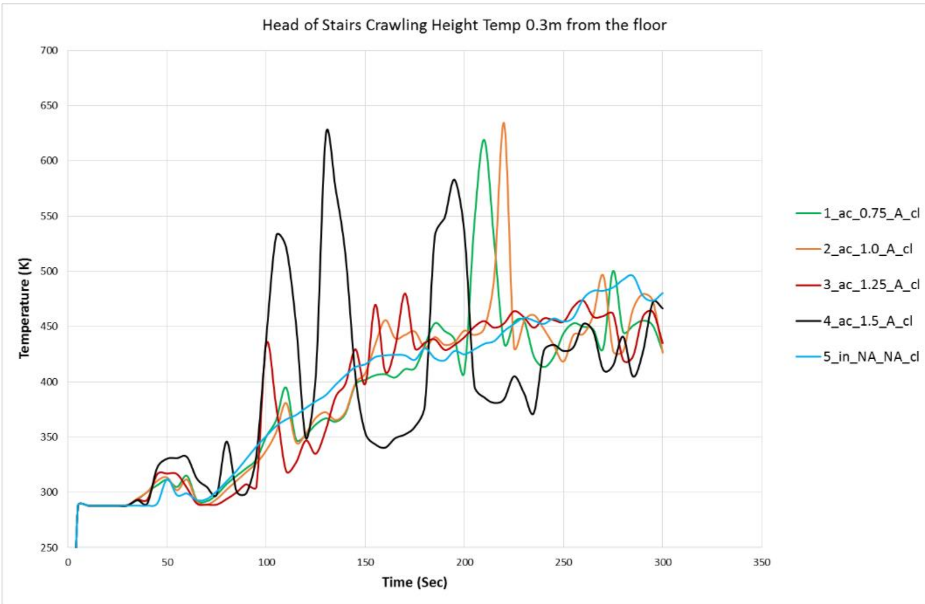


Fig. 5.14 Temperature profile at Head of Stairs 0.3m from the floor

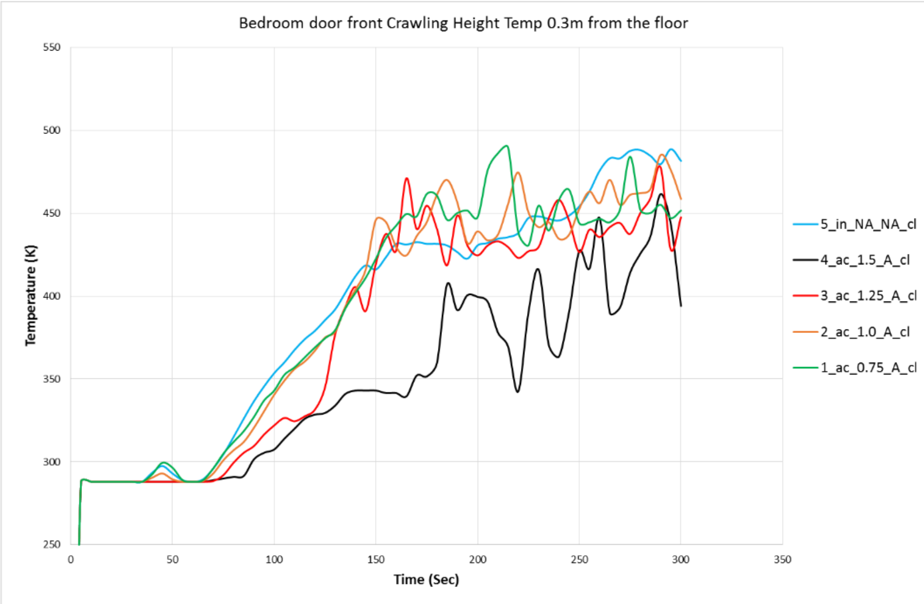


Fig. 5.15 Temperature profile at front of bedroom 2 upstairs 0.3m from the floor

The temperatures in all the scenarios show that the closed vent in scenario 5_in_NA_NA_cl has significant impact on the temperatures on the ground floor by increasing the peak temperature from approximate 450 K to 600-700 K (Fig. 5.12 and Fig. 5.13). However, the top vent has insignificant impact on the temperature on the first floor landing area (Fig. 5.14) except for Scenario 4_ac_1.5_A_cl with the largest vent (1.5 m). Whereas at the predicted upstairs floor the temperatures are quite similar when compared to the 0.75, 1.0 and 1.25m vent sizes. Hence we can conclude that the closed vent scenario has big impact on the ground floor whereas on the first floor less impact. This shows that the vent active scenarios had better survival chances looking at the temperatures on the ground floor.

## 5.5.3 Temperature with Different Vent Locations

In this section we will investigate the impact of the vent position on the simulation results. We changed the position of the vent from Position A to a new location, Position B, and studied the impact of temperature inside the structure and also analysed the survivability chances of the occupants based on the new vent location. This new location will enable to analyse that how critical is the location of the vent for removal of smoke and how does it affects the temperatures inside the dwelling. Only two vent size are considered in this analysis, 1.0 m and 1.5 m. Scenario 2_ac_1.0_A_cl and Scenario 6_ac_1.0_B_cl are with 1.0 m vent size but with vent at Location A and Location B respectively. Scenario 4_ac_1.5_A_cl and Scenario 7_ac_1.5_B_cl are with 1.5 m vent size but with vent at Location A and Location B respectively.

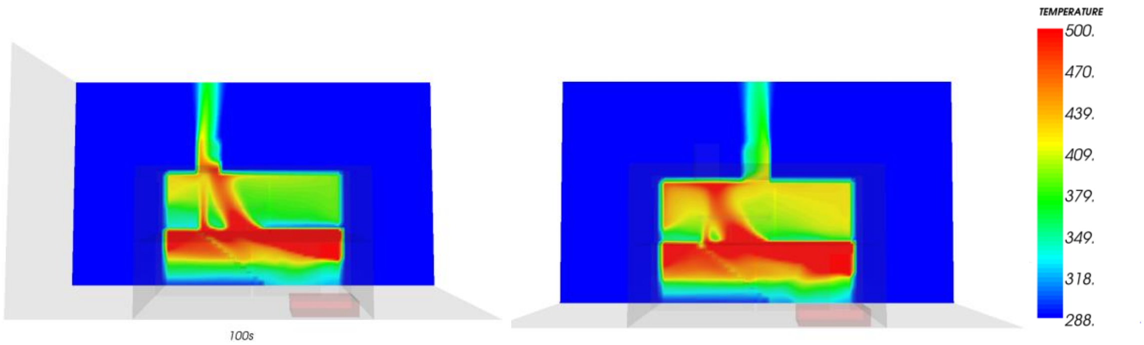


Fig. 5.16 Temperatures (K) at vertical plane passing the staircase and the top vent at 100 seconds with vent at Position A (left) and Position B (right) for 1.0 m Vent

The predicted temperatures at the vertical plane passing the staircase and the top vent at 100 seconds for Scenario 2_ac_1.0_A_cl and Scenario 6_ac_1.0_B_cl are depicted in Fig. 5.16. It is clearly seen that the temperatures near the head of the stairs are higher in Scenario 6_ac_1.0_B_cl with the vent at Position B than that in Scenario 2_ac_1.0_A_cl with the vent at Position A.  Also less hot gases are leaving the through the vent when it is placed at Position B, which is near the front end of the stair case. Whereas more hot gases are leaving through the vent when it is placed at Position A, which is at the rare end of the stair case. That's why the temperatures are lower near the head of the stair case which will help the occupants to evacuate easily.

Similar kind of results to the scenarios with a 1.0 m vent were observed in the scenarios with a 1.5m vent. The results for Scenario 4_ac_1.5_A_cl with the 1.5 m vent at Location A and Scenario 7_ac_1.5_B_cl with the vent at Location B are depicted in Fig. 5.17.

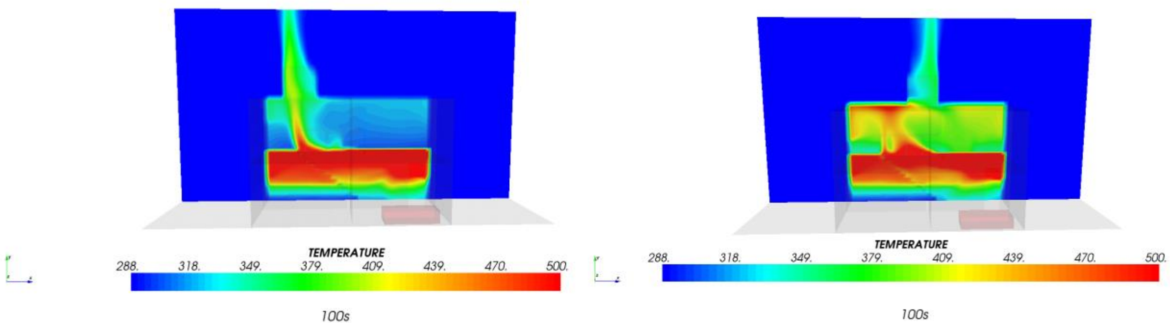


Fig. 5.17 Temperatures (K) at vertical plane passing the staircase and the top vent at 100 seconds with vent at Position A (left) and Position B (right) for 1.5 m Vent

Thus it is concluded that the position of the vent is also very vital when studying the impact of roof top ventilation. Also it is seen that the flow of hot gases is across the stair case and then upstairs. If the vent is placed right at the top of the head of stair case then the hot gases leave through the vent, but in the other case they start to gather around the same position but because the vent is at the top of the foot of the stairs then they have to travel across the roof to leave through the vent. Thus the position of the vent is also very vital in order to study the evacuation process and for the survivability of the occupants.

### 5.5.4 Temperature in Bedrooms with closed/open Door

From Section 5.5.1, the evacuation paths (staircase, ground floor) will be blocked with high temperatures. Therefore, occupants in the first floor likely have to stay in the bedrooms. The predicted temperatures as functions of time for cases with the room door closed and open are compared. Scenario 4_ac_1.5_A_cl and Scenario 8_ac_1.5_A_op are the same but are with a first floor bedroom door closed and open respectively. When the room door is closed, a 0.1 m wide gap between the door and doorway frame is assumed representing the leakage. And the vent size that we have considered in this scenario is 1.5m and its location is Position A, which is the best ventilation scenario. Looking at the temperature profile in the bedroom in the two scenarios in Fig. 5.18, it is concluded that the occupant inside that room with the closed door (with a 0.1 m wide gap) will have enough chances to survive based on the temperatures inside as the temperature less than 325K. In contrast, the temperature in the scenario with an open door increase to 425 K quickly, exposed to which the survivability is around one minute only [Purser, 2002].

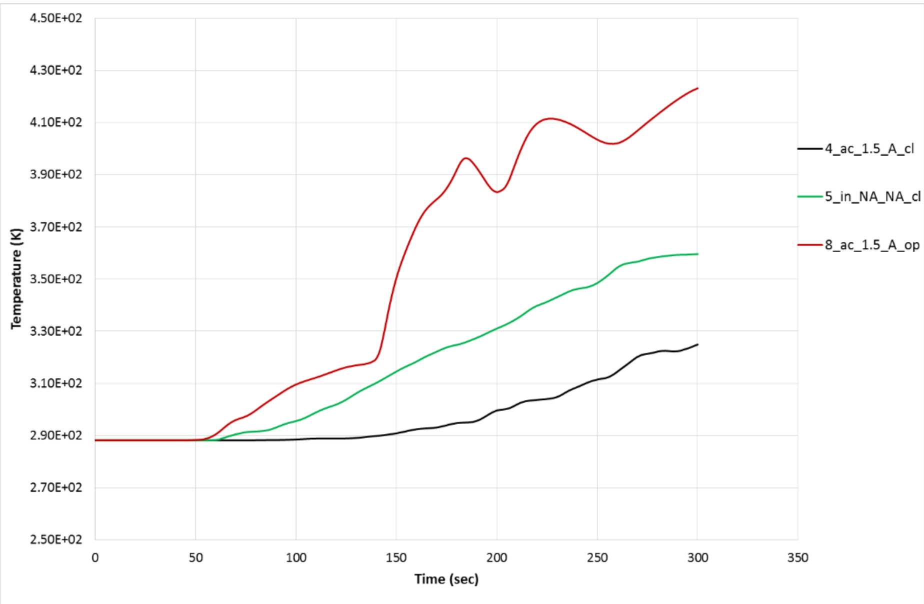


Fig. 5.18 Temperatures (K) in the upper layer of Zone 15 in bedroom 1 in scenarios with the door closed/open

Without a top vent (Scenario 5_in_NA_NA_cl), the temperature increases to 360 K at 300 seconds even with bedroom door closed whereas for Scenario 4_ac_1.5_A_cl the maximum rise in temperature is 325 K. Thus this shows that the top vent is able to provide a relative safer place in the upper floor of the fire house even when the room door was kept closed. This is an important conclusion drawn from the temperature profiles.

### 5.5.5 Smoke Profile

Visibility of exit signs, doors, and windows can be of great importance to an individual attempting to survive a fire. To see an object requires a certain level of contrast between the object and its background. Most visibility measurements through smoke have relied on test subjects to determine the distance at which the object was no longer visible. Hence smoke optical density and light extinction coefficient or smoke optical density plays a vital role in defining these limits where a person can or cannot see through smoke. The extinction coefficient is related to visibility through the smoke.

Thus in order to analyse the visibility and the efficiency of top vent we have compared the results of smoke for different vent sizes. Similar trends to the temperature profiles have also been seen for smoke for all the investigated scenarios. We have used optical density to analyse the visibility at head of stairs using different vent sizes. The optical density of 1/m is critical for evacuation, with which the visibility is approximately 1 m for non-light-reflecting objects.

As we can see from Fig. 5.19 that the optical density for the bigger vent size is lower than the other vent sizes. Hence the bigger the vent the higher will be the visibility.


Fig. 5.19 Optical Density at head of stairs for all vent sizes at location A

From Fig. 5.19 we can see that the optical density reaches 1/m for Scenario 1_ac_0.75_A_cl at around 50 seconds whereas for the largest vent Scenario 4_ac_1.5_A_cl it reaches the threshold of 1/m at 70 seconds. This means that the occupants will have low visibility which will make the occupants to start to crawl after 50 seconds with the smallest vent and after 70 seconds for the largest vent size. Hence the largest vent provides additional 20 seconds for the occupants at standing height to evacuate.

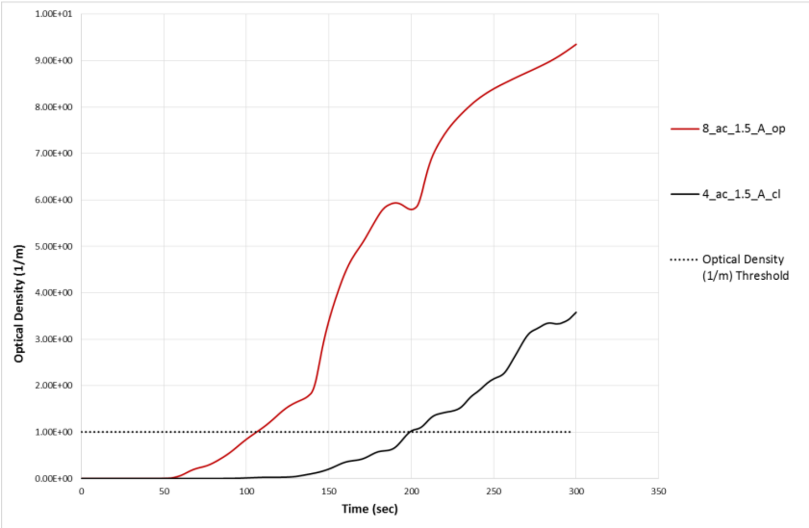


Fig. 5.20 Represents the comparison of bedroom visibility of 4_ac_1.5_A_cl and 8_ac_1.5_A_op scenario

From Fig. 5.20 we can see that the optical density reaches 1/m for Scenario 4_ac_1.5_A_cl at around 200 seconds whereas for the largest vent Scenario 8_ac_1.5_A_op in which the door of the bedroom is open it reaches the threshold of 1/m at 108 seconds. The time for the occupants to start to crawl because of low visibility at head height is almost double in Scenario 4_ac_1.5_A_cl with the bedroom door closed.

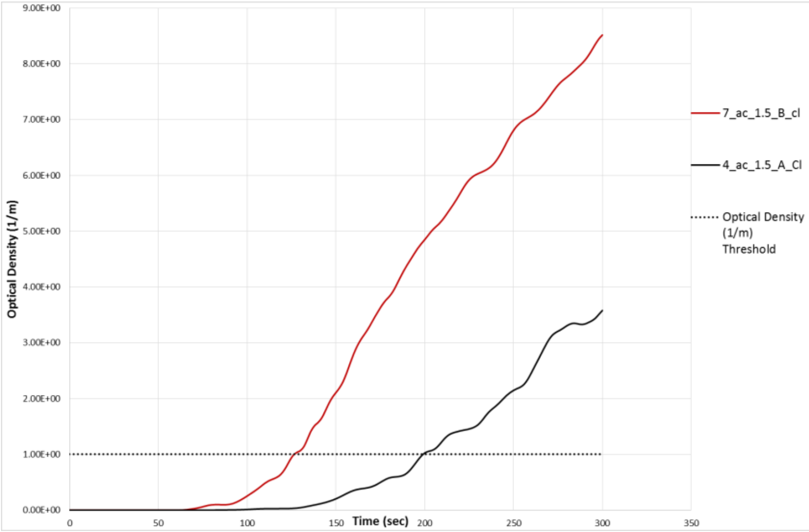


Fig. 5.21 Represents the comparison of bedroom visibility of 4_ac_1.5_A_cl and 7_ac_1.5_B_cl scenario

The above Fig. 5.21 shows the comparison of the two vent locations on visibility. Again we can observe that for Scenario 7_ac_1.5_B_cl the optical density reaches the threshold of 1/m at 128 seconds whereas for Scenario 4_ac_1.5_A_cl it reaches at 200 seconds. Hence it provides the occupants to stand for longer time. Hence we can say that location A of the vent has better impact on evacuation compared to location B when the door of the bedroom is closed. Also it provides longer duration to the occupant which will be essential for evacuation.

## 5.5.6 Gaseous Species

The SMARTFIRE predictions of the toxicity gas species, CO, $O_2$ and $CO_2$ for sofa fire in dwelling structure are analysed in this section.

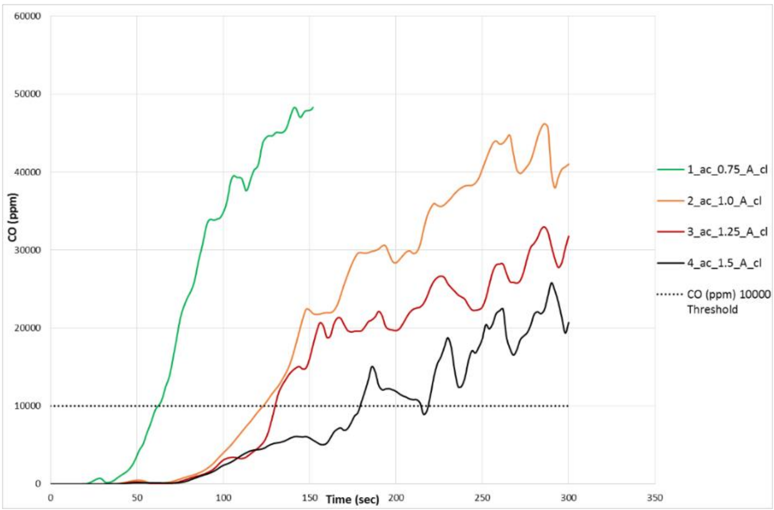


Fig. 5.22 Represents the Lower Layer CO concentration at head of stairs

From Fig. 5.22 we can see that the CO concentration is high for smaller vents but as the vent size increases the concentration level drops down. And hence for the bigger vent of 1.5m the concentrations are lowest compared to other vent sizes. All these results are for scenarios with vent at location A and with upstairs bedroom door closed. Thus the lower concentrations at the head of the stairs will help the occupants to evacuate easily from the upstairs floor. Occupants will be incapacitated at approximate 1 minute if the CO concentration is 10,000 ppm. From Fig. 5.22, the predicted CO will reach this critical value as sooner as 62 seconds in Scenario 1_ac_0.75_cl with the smallest vent and the time will be as long as 180 seconds with the largest vent size. Thus we can say that the time for the occupant to get incapacitated is three times more with the largest vent size at crawling height.

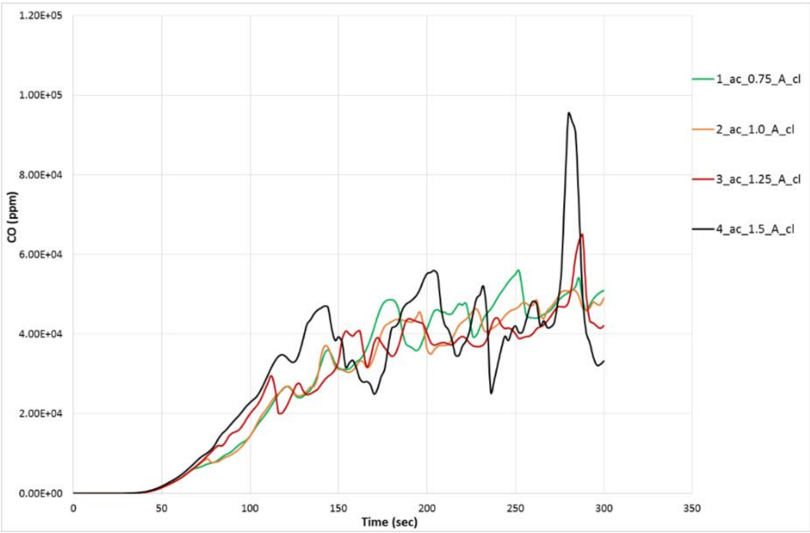


Fig. 5.23 Represents the Lower Layer CO concentration at Middle of Stairs

At the middle of the stairs the impact of vent is similar for all the vent sizes at location A. as shown in Fig. 5.23 at the lower layer the CO concentration is similar which is due to the fact that the vent is located at the top of the stair case and the size of the vent has not made much impact on the level of CO concentration at this location.

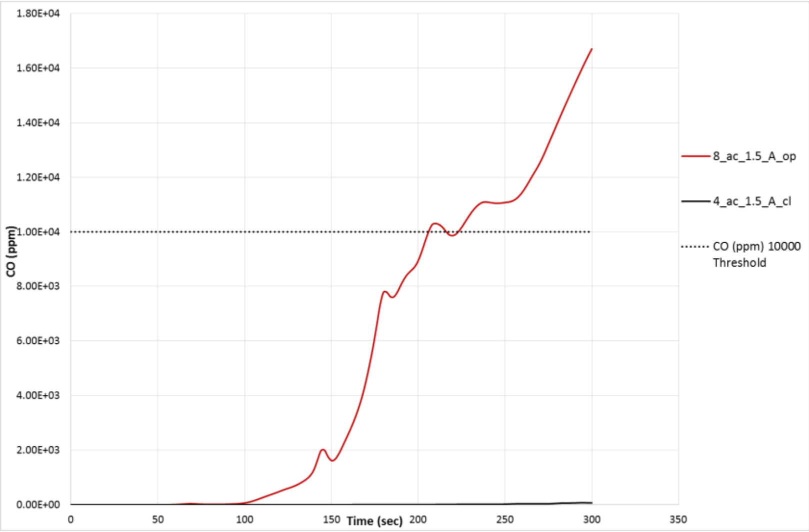


Fig. 5.24 CO concentration at lower layer for scenario 4_ac_1.5_A_cl and 8_ac_1.5_A_op inside the upstairs bedroom

Whereas when we look at the bedroom CO concentration levels in Fig. 5.24. The CO concentration is very high for scenario 8_ac_1.5_A_op as compared to the 4_ac_1.5_A_cl. This main difference is due to the fact the door of the bedroom is closed in Scenario 4_ac_1.5_A_cl which does not allows much toxic gases to enter the room even with some leakage defined on the sides of the doors. Hence this gives the occupant a longer survival time inside the bedroom. From Fig. 5.24, the CO will reach the critical value of 10000 ppm at 202 seconds in Scenario 8_ac_1.5_A_op while it is still almost 0 ppm at the end of simulation in Scenario 4_ac_1.5_A_cl with the door closed.

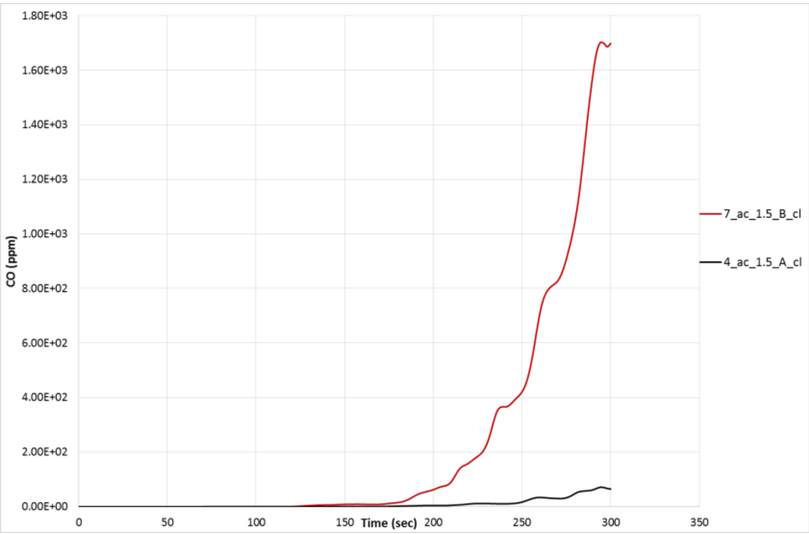


Fig. 5.25 CO concentration at lower layer for scenario 4_ac_1.5_A_cl and 7_ac_1.5_B_cl in upstairs bedroom

Similarly we compared the scenario 4_ac_1.5_A_cl and 7_ac_1.5_B_cl to see the impact of vent location on the bedroom survivability (see Fig. 5.25) inside the upstairs bedroom. The CO concentration is again very low almost zero for the scenario 4_ac_1.5_A_cl. As compare to the scenario 7_ac_1.5_B_cl, where the only difference is the location of the vent. The vent location made a big impact on the survivability inside the bedroom even with the door of the bedroom closed. Hence it becomes easier to conclude that the location of the vent is also very vital in order to improve the survivability chances. This study suggest that the vent location is much critical to survivability. Even with the location of vent at Position B the CO concentrations are still as low as1700 ppm at the end of simulation.

Hence we have computed the $O_2$ and $CO_2$ concentrations as well at certain locations. The location at which both these concentrations have been computed is the bedroom upstairs. The results have been collected at other locations as well. But since the survival is the main objective for the study so we have presented the results for the bedroom only.

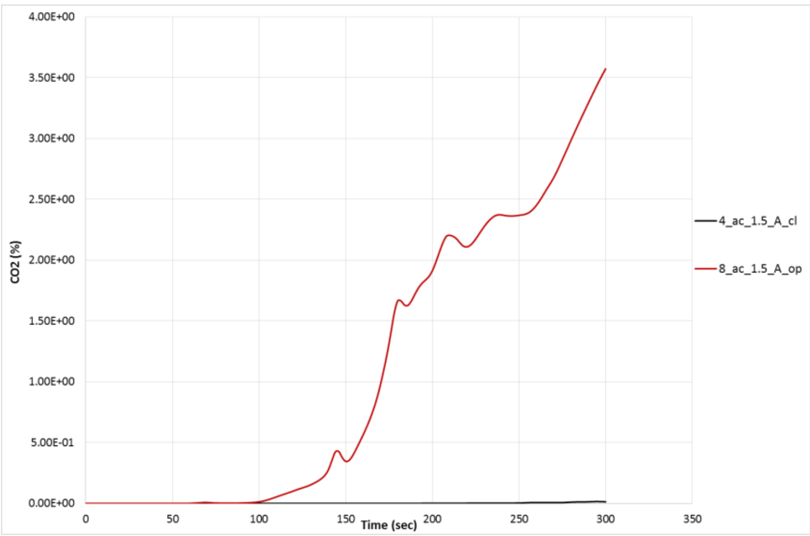


Fig. 5.26 $CO_2$ concentration at lower layer for scenario 4_ac_1.5_A_cl and 8_ac_1.5_A_op

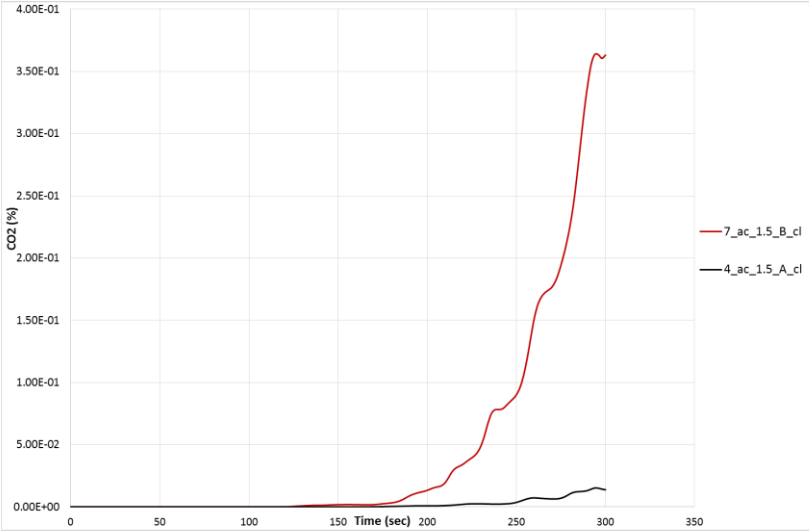


Fig. 5.27 $CO_2$ concentration at lower layer for scenario 4_ac_1.5_A_cl and 7_ac_1.5_B_cl

Hence we can observe (see Fig. 5.26 and 5.27) similar trend are seen in CO concentration. The results are better inside the bedroom for the bigger vent with bedroom door closed and location of vent being at A. Hence the size and the location of the vent plays a dominant role in the survivability.

Results for $O_2$ are presented as well. The results presented here are again for the scenarios 4_ac_1.5_A_cl, 7_ac_1.5_B_cl and 8_ac_1.5_A_op inside the bedroom. Fig. 5.28 below represents the oxygen level inside the bedroom at both upper layer and lower layer for all the three scenarios.

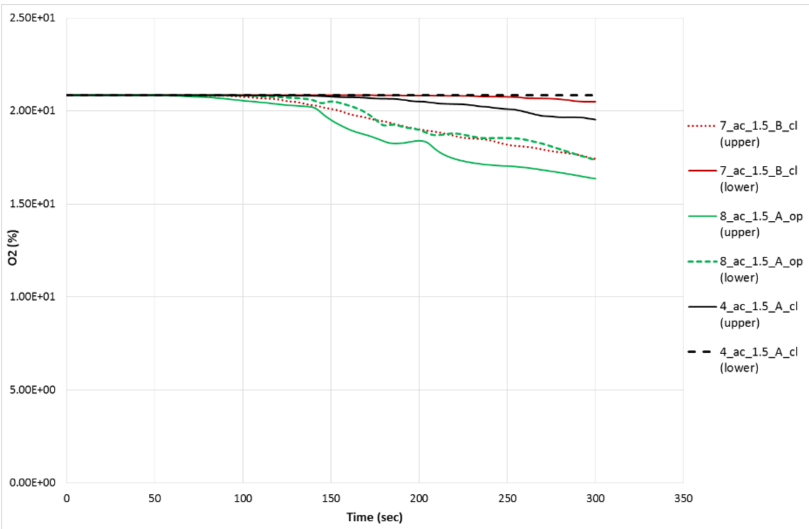


Fig. 5.28 $O_2$ (%) for scenario 4_ac_1.5_A_cl, 7_ac_1.5_B_cl and 8_ac_1.5_A_op at both upper and lower layer heights

Thus looking at Fig. 5.28 we can say that the oxygen concentrations are above 15% in all scenarios. The level of oxygen again are observed higher in scenario 4_ac_1.5_A_cl, whereas for scenarios 7_ac_1.5_B_cl and 8_ac_1.5_A_op the level of oxygen is lower.

Hence from these toxic gases and oxygen level we can conclude that the size of the vent is essential but the location of the vent is also important. The occupant survivability is higher in case when the door of the bedroom is closed during fire. Thus the top vent is affective in case of fire when the vent is located at location A and the size is bigger enough to improve the fire conditions inside the dwelling.

## 5.6 Conclusion

SMARTFIRE simulation tools have been used to study the application of top vent in dwelling fire scenarios. The first part of the analysis involves the temperature profiles for all the scenarios at two possible locations of vent A and B. Also we simulated a case in which the bedroom door was kept open at the time of the fire. The second part of analysis is based on the smoke and toxic gases concentrations level at certain locations for all the scenarios. In the simulation fire parameters, burning location and fire room opened door was been kept same for all the scenarios. Then the impact of vent for sofa as the burning material have been examined. This analysis also enabled to understand the survivability chances at particular locations for the occupants.

A total of 8 scenarios have been simulated which includes different vent sizes, different location of vent and bedroom door open scenario. All these scenarios allowed us to conclude the impact of vent at various locations looking at the temperature, smoke and toxic gases levels. The key findings related to the impact of vent on various locations are:

- A top vent is able to significantly reduce the peak temperature on the ground floor (from 600 K without a vent to approximate 450 K with vent); however,
- The vent size has minor impact on the predicted atmospheric conditions on the ground floor;
- The atmospheric conditions are much improved for the given house and fire load only when the square vent size as big as 1.5 m in side length;
    - o Temperature on the first floor lading area is reduced from an average of 452 K in Scenarios with vent size no more than 1.25 m by approximate 390 K in the scenario with a 1.5 m vent;

    - The time for visibility to be 1 m increases from 50 seconds in the scenario with 0.75 m vent to 70 Seconds in the scenario with a 1.5 m vent by 40%;
- For the designed house structure, vent Position A will produce a better atmospheric conditions than Position B does; the latter produced much higher level of hazards in the first floor landing area and inside the bed rooms;
- The closure of the bedroom doors will greatly increase the time for the fire hazards inside the room to reach life threating levels;

Associated with fire modelling there is evacuation modelling as well. This will allow to study and analyse the survival times, evacuation chances and the time and reasons for fatality of the occupants inside the dwelling. For this purpose the zone data defined in SMARTFIRE will be exported to EXODUS to study the survivability based on the fire data collected. The analysis on survivability and evacuation is discussed in Chapter 6.

# Chapter 6

# Fire Safety Assessment of Dwelling Top Vent—Survivability Analysis

## 6.1 Introduction

Fire simulations for various vent scenarios have been simulated in Chapter 5 for a designed residential house. The coupled fire and survival analysis technique is adopted here to analyse the survivability for each scenario with the predicted fire hazards such as temperature, smoke, CO, $CO_2$ etc. in this chapter.

For survivability and evacuation analysis we have used EXODUS. This software enables the user to input the fire simulation data and analyse the scenario with occupants inside the designed structure. Placing occupants with different characteristics at different locations, their survivability can be analysed. Agents are placed with certain behaviour and attributes, which involves age, gender, height, weight, walking speed etc. And then each agent is placed accordingly at different locations in the structure to see how they approach towards the fire incident, how quickly and productively they evacuate. And for some reason if they cannot evacuate, how long they can survive inside the structure? In the coupled fire and evacuation analysis presented here the following fire related parameters are considered:

- PET – Personal Evacuation Time
- FIH – Fractional incapacitating dose of heat
- FIN – Fractional incapacitating dose of narcotic agents

In simulation results the PET is replaced by survival time to understand the phenomenon of survival time of the occupant.

## 6.2 Simulations

The main purpose of our objective is to see how effective the roof top vent is in term of fire safety. In our simulations and analysis we have used a single agent placed at different locations inside the dwelling, to see for how long the agent can survive at that particular location without evacuating.

Based on the zone data collected from the fire simulations in SMARTFIRE, using the coupled fire and evacuation technique we have computed the survivability chances which is reflected with time of death indicated with the level of fractional effective dose (FED). The level of FED based on the inhalation of toxic gases and cumulative heat exposure enables us to analyse the causes of death.

### 6.2.1 Geometry Setup

The geometry designed in buildingEXODUS is identical to that used in SMARTFIRE. The hazard data from SMARTFIRE was exported to EXODUS to analyse the survivability of the occupants in dwelling fire. The geometry setup in EXODUS is same where the size of the door is 2.0m high and 0.59m wide, the floor to ceiling height is 2.39m. And the stair case is 2.47m long and 0.85m wide. The area of the house in EXODUS is represented by nodes. All the nodes are connected to give the full geometry layout. The agent is placed on the node and the agent moves through the connected nodes following a path [Manual Exodus, 2012].

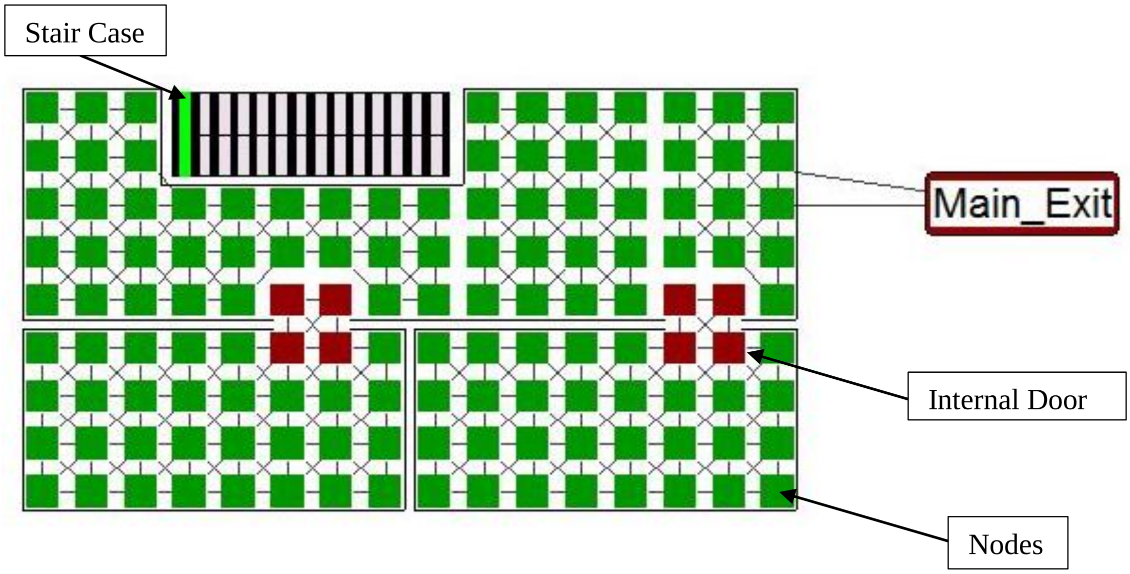


Fig. 6.1 Geometry Layout of dwelling first floor in EXODUS

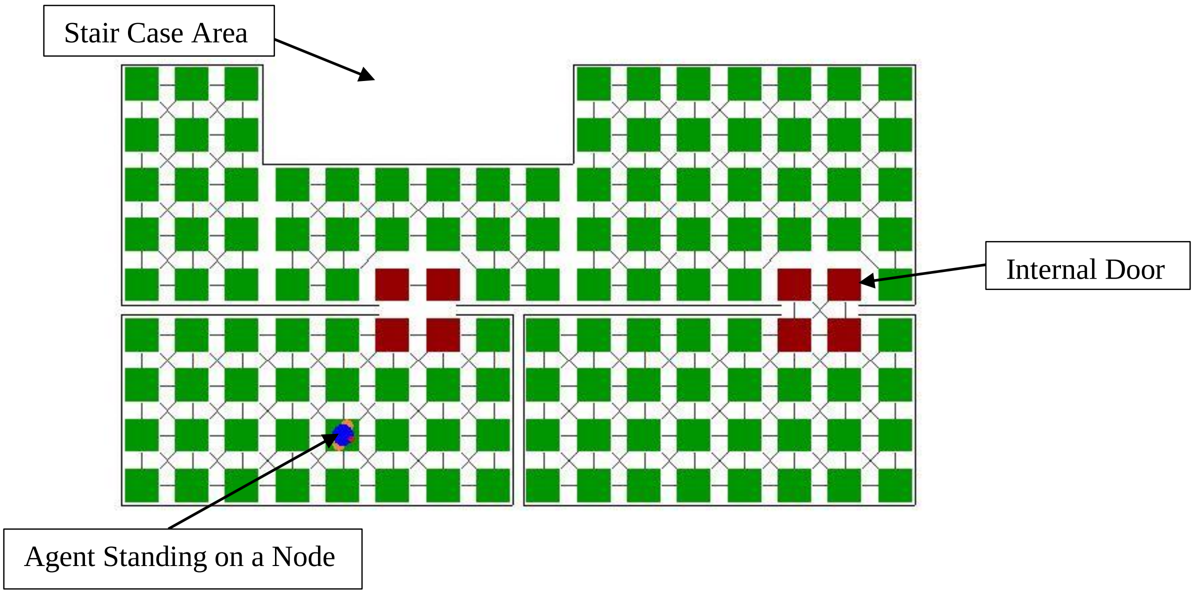


Fig. 6.2 Geometry Layout of dwelling second floor in EXODUS

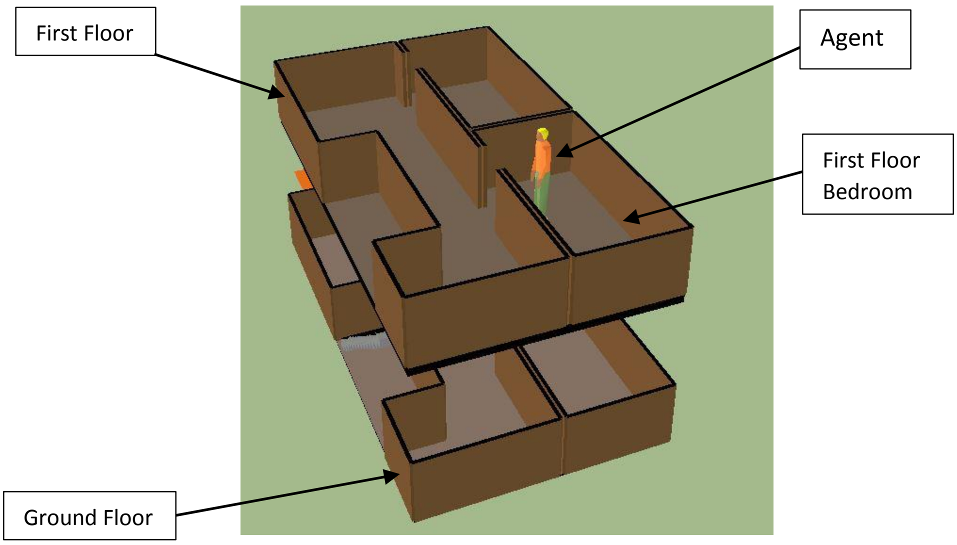


Fig. 6.3 buildingEXODUS VR image of dwelling fire scenario

Fig. 6.3 shows the virtual reality image of the dwelling structure and the location of agent.

## 6.2.2 Hazard Model

In EXODUS we have imported the hazard data from SMARTFIRE fire simulations. This data will be used to run the simulations in EXODUS and analyse the survivability of the occupants inside based on those hazard levels. The survivability will be analysed based on the toxic gases and smoke levels at both upper layer and lower layer. This will allow the agent to stand and crawl based on the level of the hazard data. The hazard model output includes FIH, FIN, which indicating survivability. All these parameters will help to analyse the agent's incapacitation levels at different locations and the time for death (i.e. survivability time).

### 6.2.3 Hazard Zones

The zones defined in SMARTFIRE will be used to study the survivability in EXODUS as well. In EXODUS same zones have been defined to link the hazard data from SMARTFIRE to EXODUS. The locations that will be used to study the survivability in EXODUS are the same as defined in SMARTFRE. The main locations are the foot of stairs, the head of stairs and the first floor bedroom. The locations of some special zones have been shown in the Figs. 6.4-6.7. The highlighted areas are the zones used for the survivability analysis. These highlighted zones are disconnected from the other zones. This is done in order to make the agent stay in that zone and the time of death and incapacitation level can be measured. The agent will stay in that particular zone until the agent dies. This will help to analyse that for how long the agent can survive in that zone without evacuating.

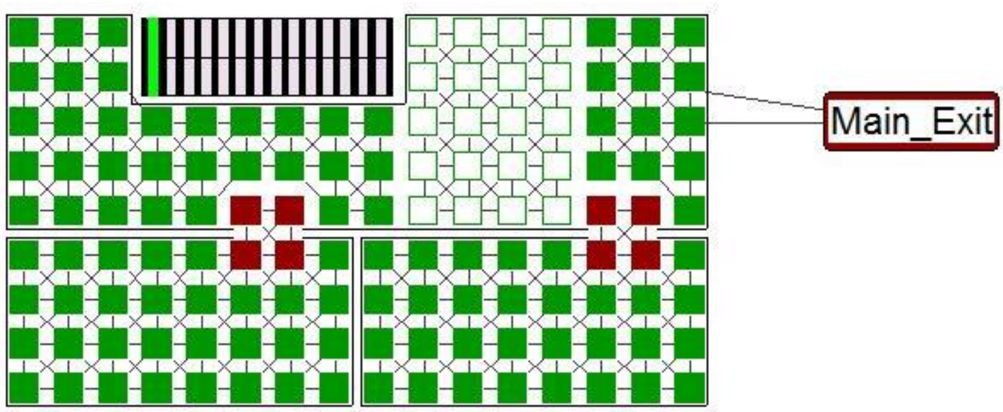


Fig. 6.4 Hazard Zone 25 highlighted at foot of stairs on ground floor

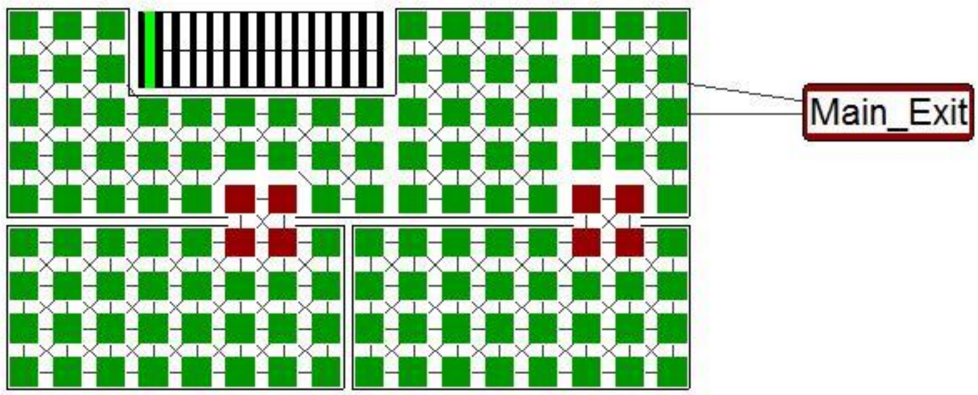


Fig. 6.5 Hazard Zone 27 highlighted at middle of stairs

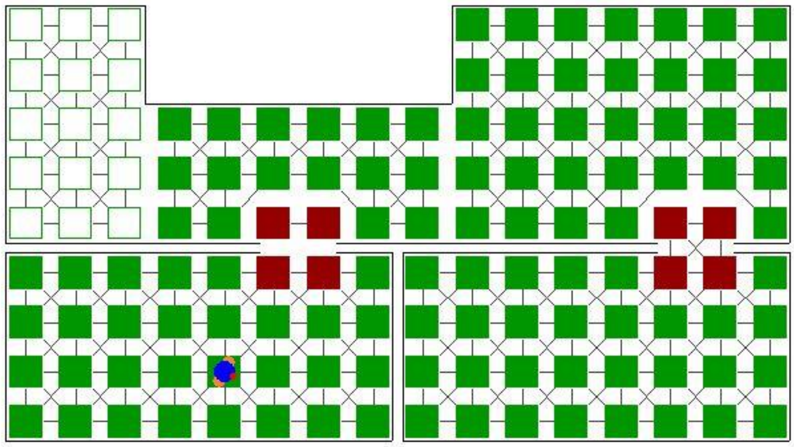

Fig. 6.6 Hazard Zone 28 highlighted at head of stairs on first floor

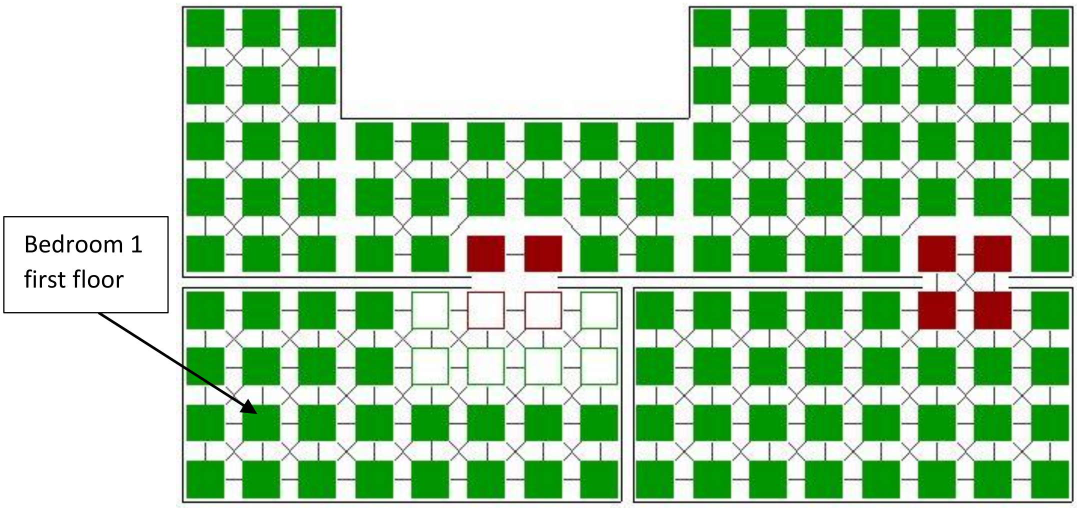


Fig. 6.7 Hazard Zone 38 highlighted inside first floor bedroom

## 6.2.4 Agent Characteristics

Two different options of agent's characteristics have been used. For one case we have used a single agent and for the other case we have used a group of 100 agents randomly generated by buildingEXODUS. The single agent that has been used for all the simulations is same. The characteristics are usually based on the buildingEXODUS existing specifications. The single agent is used to rank the scenarios based on the survivability. After the best ventilation scenario has been derived with the use of a single agent, a group of 100 agent is used to derive the survival distribution which is population dependent.

Table 6.1: Agent Characteristics used for survivability analysis

| **Agent Characteristics** | **Attributes** |
|---|---|
| Age (years) | 45 |
| Gender | Male |
| Weight (kg) | 90 |
| Height (m) | 1.8 |
| PID (%) | 25-35 |

**PID: Personal Incapacitation Dose**

PID is defined as the measure of COHb (carboxyhaemoglobin) concentration. This concentration measure is used for incapacitation. It is the TOXICITY sub-model and is used to calculate FICO (Fractional Incapacitation Dose of CO). This incapacitation dose is found to be dependent on the agent's age, gender, weight and state of health. In buildingEXODUS a fixed value is assigned based on the age, weight and height. Since not much reliable data is available thus fixed value gives an approximate idea of the agent's PID attribute [Manual EXODUS, 2012].

## 6.3 Results

### 6.3.1 Effect of Vent Size on Survivability

We will study the impact of top-vent on survivability. This analysis is based on the highlighted zones mentioned in section 6.2.2. The agent will be placed in the respective zone and the simulations will be ran based on the hazard file exported to EXODUS from SMARTFIRE. The results include survivability, FIH and FIN.

Table. 6.2 Survivability Results for Scenarios 1-5

| Location | Scenario | Survivability (s) | FIH | FIN |
|---|---|---|---|---|
| **Foot of Stairs** | **1_ac_0.75_A_cl** | 97.3 | 1.09 | 0.13 |
| | **2_ac_1.0_A_cl** | 97.4 | 1.11 | 0.13 |
| | **3_ac_1.25_A_cl** | 94.0 | 1.04 | 0.11 |
| | **4_ac_1.5_A_cl** | 94.1 | 1.08 | 0.12 |
| | **5_in_NA_NA_cl** | 93.0 | 1.05 | 0.18 |
| **Middle of Stairs** | **1_ac_0.75_A_cl** | 109.2 | 1 | 0.21 |
| | **2_ac_1.0_A_cl** | 109.5 | 1.01 | 0.21 |
| | **3_ac_1.25_A_cl** | 113.7 | 1.01 | 0.14 |
| | **4_ac_1.5_A_cl** | 124.7 | 1.01 | 0.1 |
| | **5_in_NA_NA_cl** | 118.2 | 1.01 | 0.15 |
| **Head of Stairs** | **1_ac_0.75_A_cl** | 142.7 | 0.34 | 1.04 |
| | **2_ac_1.0_A_cl** | 144.5 | 0.52 | 1.03 |
| | **3_ac_1.25_A_cl** | 153.5 | 0.53 | 1.03 |
| | **4_ac_1.5_A_cl** | 190.6 | 0.14 | 1.02 |
| | **5_in_NA_NA_cl** | 140.3 | 0.68 | 1.04 |
| **Bedroom 1 Upstairs** | **1_ac_0.75_A_cl** | 863.5 | 0 | 1 |
| | **2_ac_1.0_A_cl** | 892.7 | 0 | 1 |
| | **3_ac_1.25_A_cl** | 1525.4 | 0 | 1 |
| | **4_ac_1.5_A_cl** | 7060.7 | 0 | 1 |
| | **5_in_NA_NA_cl** | 715.7 | 0 | 1 |

The results obtained using buildingEXODUS for Scenarios 1, 2, 3, 4, and 5 are presented in Table 6.2. Firstly we can see, the top vent has not much affect the survivability at the foot of the stairs. The survivability at the foot of stairs without a top vent is 93.04 seconds (Scenario 5_in_NA_NA_cl). It only increase by a few seconds for scenarios with a top vent with various vent size between 0.75 m and 1.5 m. Secondly we have observed that, the impact of top vent on the survivability on the stairs is complicated. Compared with the survivability of 124.7 seconds in Scenario 5_in_NA_NA_cl without a top vent, the survivability decreases in Scenarios with a small top vent (Scenario 1_ac_0.75_A_Cl, 2_ac_1.0_A_cl and 3_ac_1.25_A_cl) by approximate 10 seconds. In contrast, the survivability increase by 6 seconds for Scenario 4_ac_1.5_A_cl with a 1.5 m top vent. At another location which is head of stairs, the top vent has improved the survivability for all scenarios. However, the impact for scenarios with small vent is minor. Compared with the survivability of 140.3 seconds in the scenario without a top vent, it increase by only approximate 14 seconds for smaller vents (Scenario 1_ac_0.75_A_Cl, 2_ac_1.0_A_cl and 3_ac_1.25_A_cl). However, for a vent size of 1.5 m, the survivability increase to 190.6 seconds by 36 %. And lastly, the most impact of the top vent on the survivability is seen in the upstairs bedroom. The survivability without a top vent is only 715.7 seconds. It increased to 7060.7 seconds by almost 9 times if the vent is 1.5 m in size. Finally we have observed that all the deaths on the middle of the staircase and on the ground floor are due to the exposure of heat (with FIH reaching 1.0) and all the deaths on the first floor (head of staircase and bedroom) are due to the inhalation of toxic gases (with FIN reaching 1.0).

### 6.3.2 Effect of Vent Location on Survivability

The results for scenarios with different vent locations are presented in Table 6.3 and Table 6.4, Table. 6.3 Survivability comparison for scenarios with different vent locations

| Agent Location | Scenario | Survivability (s) | FIH | FIN |
|---|---|---|---|---|
| **Foot of Stairs** | **2_ac_1.0_A_cl** | 97.4 | 1.11 | 0.13 |
| | **6_ac_1.0_B_cl** | 95.7 | 1.04 | 0.12 |
| **Middle of Stairs** | **2_ac_1.0_A_cl** | 109.5 | 1.01 | 0.21 |
| | **6_ac_1.0_B_cl** | 105 | 1.01 | 0.19 |
| **Head of Stairs** | **2_ac_1.0_A_cl** | 144.5 | 0.52 | 1.03 |
| | **6_ac_1.0_B_cl** | 120.2 | 0.42 | 1.06 |
| **Upstairs Bedroom 1** | **2_ac_1.0_A_cl** | 892.7 | 0 | 1 |
| | **6_ac_1.0_B_cl** | 599.3 | 0 | 1 |

From Table 6.3, the survivability is reduced when the vent was placed at Position B for a vent size of 1.0 m (Scenario 6_ac_1.0_B_cl). And significant change or reduction in the survivability occurs in the bed room, from 892.7 seconds (Scenario 2_ac_1.0_A_cl) to 599.3 seconds (Scenario 6_ac_1.0_B_cl) with a decrease of 33%. This means that the position of the vent is also very vital. Thus the vent should be placed in such a way that when the smoke travels along the stair case it should not gather on the first floor in fact it should be removed, where the position of the vent plays an important role. Position A is on top of the head of the stair case where as Position B is at the other end which is the top of the foot of stair case. Hence this is the reason why the survival chances are high at first floor for vent at Position A.

Table. 6.4 Agent Survivability Analysis (Scenario 4_ac_1.5_A_cl and 7_ac_1.5_B_cl)

| Agent Location | Scenario | Survivability (s) | FIH | FIN |
|---|---|---|---|---|
| **Foot of Stairs** | **4_ac_1.5_A_cl** | 94.1 | 1.08 | 0.12 |
| | **7_ac_1.5_B_cl** | 94.4 | 1.05 | 0.1 |
| **Middle of Stairs** | **4_ac_1.5_A_cl** | 124.7 | 1.01 | 0.1 |
| | **7_ac_1.5_B_cl** | 109.2 | 1.01 | 0.2 |
| **Head of Stairs** | **4_ac_1.5_A_cl** | 190.6 | 0.14 | 1.02 |
| | **7_ac_1.5_B_cl** | 128.5 | 0.56 | 1.05 |
| **Bedroom 1 Upstairs** | **4_ac_1.5_A_cl** | 7060.7 | 0 | 1 |
| | **7_ac_1.5_B_cl** | 677.8 | 0 | 1 |

Hence in case of upstairs rooms we can see from the Table 6.4 that the agent has the maximum survival chance when the agent was placed in the first room upstairs. This maximum survival time is for the biggest vent size which is 1.5m. Also the maximum time inside the bedroom was calculated for vent Position B, where the agent died far more quickly than that for Position A. The hazard zone used for this analysis is Zone 38. Thus from this it is concluded that the vent position plays a very vital role in survivability of the occupants. Hence we can say that the vent size is not as effective if the vent is placed at wrong position. Hence along with the size the position has the most prime role in survivability.

From the results it is concluded that along with the size, the vent position is the dominant factor. Also the agent can survive longer when the agent was on the upstairs floor. Whereas the survival chances are low on the ground floor area excluding the bedrooms on both the floors. Hence this means that if the occupant stays on the ground floor and doesn't evacuates quickly then the occupant will die quickly as compare to the first floor. Thus first floor survivability chances have improved due to the top vent which means that the top vent application is very efficient in case of fire for the survivability. As we can see from the Scenario 5_in_NA_NA_cl in which the vent was closed the agent died quickly but again the agent survived longer as compare to smaller vent size on the ground floor. Compared to smaller sizes the closed vent scenario was not very bad but the difference becomes big when the vent size becomes bigger.

### 6.3.3 Effect of Closures of Bedroom door on Survivability

Lastly compared the results for the scenario in which the door of the upstairs room is open for bigger vent size 1.5m with closed door scenario. Table 6.5 compares the survivability results for two scenarios 4_ac_1.5_A_cl and 8_ac_1.5_A_op. Both have same vent size the only difference is the open/close door of bedroom 1 upstairs.

Table. 6.5 Agent Survivability Comparison with Bedroom Door Open/Closed (scenario 4_ac_1.5_A_cl and 8_ac_1.5_A_op)

| Scenario | Bedroom door | Survivability (s) | FIH | FIN |
|---|---|---|---|---|
| **4_ac_1.5_A_cl** | Closed | 7060.7 | 0 | 1 |
| **8_ac_1.5_A_op** | Open | 225.2 | 0.07 | 1.03 |

Hence from the results in Table 6.5, if the occupants are upstairs in the rooms and the doors are closed then they can survive for longer period which will give enough time for the firefighters to help them evacuate in case of fire. Whereas in case of open door the occupant needs to evacuate the first floor quickly until and unless the occupants are in closed room. Also FIH=0.07 for the open door scenario makes the agent exposed to the heat and it will lightly injure the agent even with bigger vent. We can say that the time for survival from Scenario 4_ac_1.5_A_cl to Scenario 8_ac_1.5_A_op reduced almost 96%. It is a very big difference. Thus this means that the survival time will be longer if the door of the bedroom is closed and the vent is 1.5 m in size. This will provide enough time for the firefighters to help and evacuate the occupants. The reason for reduction is the fact the door of the bedroom is open which allows access to toxic gases to enter the room. Since we can see from Table 6.5, FIN is 1.03 on the first floor for Scenario 8_ac_1.5_A_op the FIH is also 0.07 which means that the agent started to get exposed to heat as well because of open door. From these results for single agent we were able to show that the survival time is dependent on the scenario. As the best scenario with the highest survival time is 4_ac_1.5_A_cl.

## 6.4 Survivability Distribution

Using the group of 100 agents we are able to achieve a range showing the maximum and the minimum survival time for different agents having different age and characteristics. The results has been presented here for the best scenario which is 4_ac_1.5_A_cl. This scenario is considered on the basis of the results obtained from previous analysis of survival time where a single agent's survival time is the highest under the maximum vent size and with upstairs bedroom door closed with vent located at position A.

Table. 6.6 Group of Agents Survivability Analysis for Scenario 4_ac_1.5_A_cl

| No. of Agents | Maximum Survival Time (sec) | Minimum Survival Time (sec) | Average Survival Time (sec) |
|---|---|---|---|
| 100 | 10724.9 | 6271.4 | 7990.6 |

From Table 6.6, the survivability in the bedroom with closed door in Scenario 4_ac_1.5_A_cl is between 6271.4 seconds and 10724.9 seconds with an average of 7990.6 seconds. The average survivability is closer to the time of 7060.7 seconds in the previous analysis using a single agent. This implies that the single agent used in the previous analysis in the scenario order ranking is representative.

Figure 6.8 is the survivability distribution from the 100 agents which almost follows a normal distribution curve. This distribution demonstrate that, for the given fire hazards, the survivability strongly depend on the characteristics of the resident.

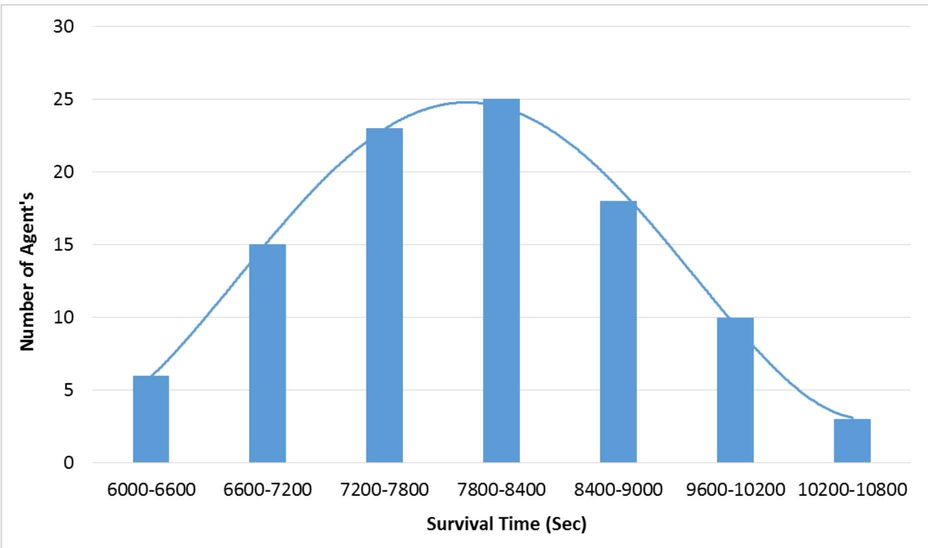


Fig. 6.8 Group of Agents Survivability Distribution for Scenario 4_ac_1.5_A_cl

## 6.5 Discussion

From the chart 6.1 we can see the difference in survival time that has been observed when the vent was inactive compared to the scenario 4_ac_1.5_A_cl and 7_ac_1.5_B_cl where the vent was located at position A and B respectively. In all the mentioned scenarios (see Chart 6.1) the door of the bedroom was closed.

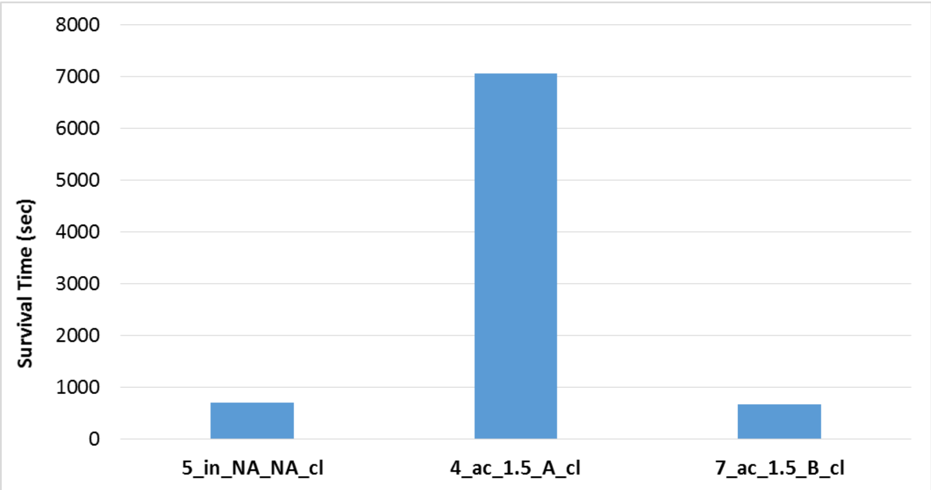


Fig. 6.9 Represents the survival time in the bedroom for vent at position A, B and without vent

From the chart we can observe that for the largest vent with the bedroom door closed and vent located at position A the survival time is highest. This means that the vent location along with the size is a very dominant factor for survival. The largest vent size has improved the survival chances inside the bedroom whereas for vent at location B the survival time is not very different from the scenario in which the vent is inactive. Hence this concludes that the position of vent makes a big difference in the survival of the occupants during fire. Therefore, when install a top vent system to a residential house, it is necessary to conduct a fully assessment on the location of the vent for various house inside layout.

## 6.6 Conclusion

The survivability inside the dwelling with the atmospheric conditions predicted in Chapter 5 is analysed using buildingEXODUS. It is used to study the impact of top vent in dwelling fire scenarios on survivability. The analysis involves the impact of different size top vent on survivability, different location of vent on survivability and opening and closure of bedroom door on the first floor on survivability. This analysis enabled us to understand the survivability chances at particular locations. These locations are selected on the basis of the evacuation path. Also these locations enabled us to understand if the occupant stays in that particular location, what the chances are for survival under different scenarios.

Total 8 scenarios have been simulated as in SMARTFIRE we did. These 8 scenarios fire hazard data was linked to buildingEXODUS using the coupled fire and evacuation technique. All these scenarios allowed us to conclude the impact of vent at various locations looking at the survival time, FIH, and FIN levels. The key findings related to the impact of vent on various locations based on the survivability for a single agent are:

- The top vent is able to significantly increase the survival time on the head of stairs (from 140.3 seconds without a vent to 190.6 seconds with vent); however,
    - The vent size has minor impact on the predicted survival time, values of FIH and FIN on the ground floor.
- The conditions and survival time is much improved for 1.5 m vent;
    - The survival time on the head of stairs increased from 142.7 seconds for smallest vent of size 0.75 m to 190.7 seconds for the largest vent size of 1.5 m.
    - Also the FIH level i.e. the impact of exposure to heat reduced from 0.34 to 0.14.
- For the designed house structure, vent Position A will produce a better survival chance than Position B does; the latter produced much higher level of FIH and FIN in the first floor landing area whereas the survival time for location A of vent was high inside the bed room upstairs;
    - **It is highlighted here that care should be taken in vent position selection when applying a top vent system to resident houses**
- The closure of the bedroom door will greatly increase the time for survival inside the room to reach life threating levels; whereas in case of open door there was a 96% reduction in survival time inside the bedroom.

The survival time for a group of agents inside the upstairs closed bedroom room 1 almost follow a normal distribution with a minimum 6271.4 seconds, a maximum of 10724.9 seconds and an average of 7990.6 seconds.

# Chapter 7

# Conclusion

The objective of this chapter is to describe the conclusions drawn from the derived methodology to obtain the HRR curve. Also the conclusions of the fire modelling and evacuation modelling analysis using the top vent application in dwelling fires.

Reviews to the research background and the fire/evacuation modelling are given in Chapter 2 and Chapter 3 respectively. From the literature review we were able to find that what will be the impact of ventilation system on fire. Other factors like size of the ventilation, size of the fire whether these parameters will make a difference on the behaviour of fire were also studied. Different locations and sizes were studied, different openings like doors and windows were studied as well. The main idea was to understand the behaviour of fire under ventilation condition and whether the position, size along with other openings like doors and windows will affect the fire behaviour.

We were able to conclude from the literature review that there is not much research available regarding the house fire and using roof top ventilation as a source for removal of smoke in case of fire. Mostly the research is based on the behaviour of fire under top vent application. Not much research has focused on the fact that how the top vent application can improve the survivability chances of the occupants inside the residential structure under fire scenario. Also we managed to conclude that whether different openings can affect the survival and where should be the top vent placed to improve survivability in case of fire. Also the size of vent plays a very vital role and will it improve the survivability of the occupants in case of fire. Thus a specially designed ventilation system was used to study the impact of top vent on fire and especially on smoke and whether it will improve the chances for survivability. The main objective of our research is to remove smoke and improve the atmospheric conditions inside the dwelling to improve survival chances.

Hence in Chapter 3 CFD modelling and specifically fire modelling was discussed. Different kinds of modelling approaches like field fire models and zone models were discussed. CFD fire field modelling plays a vital role in everyday fire safety. Different and improved fire models have been studied and described which gives an insight to understand the models better and select the best possible models for fire scenarios. The structure and models of the fire simulation tool SMARTFIRE were used to simulate a complex cabin fire.

Evacuation modelling for emergencies was discussed in detail. Human behaviour in all the possible fire situations can help to understand the possible ways the people can evacuate the building in case of an emergency or fire. The structure and functions of the evacuation tool EXODUS has been familiar. The coupled fire and evacuation analysis technique is widely used in fire reconstruction, accident analysis and building design. In the remainder of this thesis, this coupling technique is applied in the optimal design of the top vent for removing smoke and increasing survivability in house fires whose application in SMARTFIRE and buildingEXODUS can be seen in Chapter 5 and 6.

Hence from the knowledge gap found in the literature a methodology to develop a HRR curve was derived in Chapter 4. Derivation of the derived sets of equations for both extreme cases (with and without door open) we were able to understand the impact of air on fire in a compartment. If the unknown coefficients in the derived set of equations are computed then the time for the fire to decay and the time of fire extinction can be evaluated in case of closed door scenario. The proposed methodology can be used to obtain the HRR curve. But this methodology has not been well validated or tested in the current study. This work can be taken further and more research can be done in order to see if the proposed methodology is reliable in case of dwelling fires and what factors and parameters are sensitive to the method. Also if the top vent application with proposed methodology will be efficient in case of dwelling fire or not.

Chapter 5 and Chapter 6 assess the impact of a top vent on the fire development and survivability within a residential house using the coupled fire and survivability analysis technique. Some assumptions are made in the numerical fire/evacuation investigation. Therefore, it is important to keep in mind the nature of the assumptions required to simplify the analysis. These include

Assumption A. The fire used for the fire modelling is fixed fire i.e. with fixed HRR no matter there is a top vent or not.

Assumption B. Windows and the external door are closed in all the fire scenarios;

Assumption C. A 0.1 m wide leakage on the sides of the bedroom door has been defined and represented at the doorway with an air porosity of 0.2.

Assumption D. The human features for the agent used for the survivability analysis are fixed for all scenarios;

SMARTFIRE simulation tool was used to study the impact of top vent in dwelling fire scenarios. This analysis also enabled to understand the survivability chances at particular locations for the occupants. A total of 8 scenarios have been simulated which includes different vent sizes, different location of vent and bedroom door closure state. All these scenarios allowed us to conclude the impact of vent at various locations looking at the temperature, smoke and toxic gases levels. The key findings related to the impact of vent on various locations are:

- A top vent is able to significantly reduce the peak temperature on the ground floor (from 600 K without a vent to approximate 450 K with vent); however,
- The vent size has minor impact on the predicted atmospheric conditions on the ground floor;
- The atmospheric conditions are much improved for the given house and fire load only when the square vent size as big as 1.5 m in side length;
    - Temperature on the first floor landing area is reduced from an average of 452 K in Scenarios with vent size no more than 1.25 m by approximate 390 K in the scenario with a 1.5 m vent;
    - The time for visibility to be 1 m increases from 50 seconds in the scenario with 0.75 m vent to 70 Seconds in the scenario with a 1.5 m vent by 40%;
- For the designed house structure, vent Position A will produce a better atmospheric conditions than Position B does; the latter produced much higher level of hazards in the first floor landing area and inside the bed rooms;
- The closure of the bedroom doors will greatly increase the time for the fire hazards inside the room to reach life threating levels;

The survivability is analysed using buildingEXODUS. The analysis involves the impact of different size top vent on survivability, different location of vent on survivability and opening and closure of bedroom door on the first floor on survivability. A total of 8 scenarios have been studied. All these 8 scenarios the fire hazard data from SMARTFIRE was linked to buildingEXODUS using the coupled technique of fire and evacuation. All these scenarios allowed us to conclude the impact of vent at various locations looking at the survival time, FIH, and FIN levels. The key findings related to the impact of vent on various locations are:

- The top vent is able to significantly increase the survival time on the head of stairs (from 140.3 seconds without a vent to 190.6 seconds with vent); however,

    - The vent size has minor impact on the predicted survival time, values of FIH and FIN on the ground floor.
- The conditions and survival time is much improved for 1.5 m vent;
    - The survival time on the head of stairs increased from 142.7 seconds for smallest vent of size 0.75 m to 190.7 seconds for the largest vent size of 1.5 m.
    - Also the FIH level i.e. the impact of exposure to heat reduced from 0.34 to 0.14.
- For the designed house structure, vent Position A will produce a better survival chance than Position B does; the latter produced much higher level of FIH and FIN in the first floor landing area whereas the survival time for location A of vent was high inside the bed room upstairs;
    - **It is highlighted here that care should be taken in vent position selection when applying a top vent system to resident houses**
- The average survival time for a group of agents inside the upstairs closed bedroom room 1 is 7990.6 seconds which is close to the survival time of a single agent for the same scenario which is 7060.7 seconds. Hence the scenario comparison is independent of the number of agents whereas the survival time depends on the scenarios similarly like the single agent.

The closure of the bedroom door will greatly increase the time for survival inside the room to reach life threating levels; whereas in case of open door there was a 96% reduction in survival time inside the bedroom.

The survival time for a group of agents inside the upstairs closed bedroom room almost follow a normal distribution with a minimum 6271.4 seconds, a maximum of 10724.9 seconds and an average of 7990.6 seconds.

While a top vent is capable of increasing the survivability for residential house especially inside the closed room just with leakages and especially for a large vent size, the location of the vent is much sensitive to the survivability. Therefore, fire safety assessment should be taken for individual houses when installing a top vent for smoke removal due to the various house structures around the staircase area. The study has addressed the concerns and questions raised in Chapter 1 as the main aim and motivation of this study.

**Can a top natural ventilation system efficiently improve the survivability in domestic dwelling?**

This study has demonstrated that a top vent is able to improve the survivability in dwelling fires under Assumptions A-D mentioned previously.

- How does the limited ventilation affect the heat release rate (HRR) of dwelling fires?

A Simulation-Correction method is developed to produce the HRR in dwelling fires with limited ventilations; however, it need to be further validated and improved;

- What factors of a vent affect its function?

The improvement of the survivability with a top vent is sensitive to it size and location.

# Chapter 8
# Future Work

The objective of this chapter is to describe the further work that can be done based on the derived methodology to obtain the HRR curve. Also from the conclusions of the fire modelling and evacuation modelling analysis using the top vent application in dwelling fires what improvements can be made and how a better system to remove smoke in case of dwelling fire can be designed.

## 8.1 The impact of top vent on HRR

As summarised in Chapter 7, the conclusion on the improving of the survivability with a top vent in this study is under a rough assumption:

> **Assumption A. The fire used for the fire modelling is fixed fire i.e. with fixed HRR no matter there is a top vent or not.**

As reviewed in Chapter 2, a top vent to an enclosure will more or less affect the inside fire development. Therefore, the conclusion is limited with this assumption.

Attempts are taken to develop a general method for the HRR curve for ventilation controlled fires in Chapter 4. The derived **Simulation-Correction** methodology has not been fully validated under any real fire scenarios. The validation of the method will enable the future researchers to analyse if the proposed methodology is reliable in case of dwelling fires and what factors and parameters are sensitive to the method. Also if the top vent application with proposed methodology will be efficient in case of dwelling fire or not. This method is designed to develop a HRR curve that can be used for fire modelling, but the future researchers might have to see if the method is correct or what possible changes can be made in the method to achieve a reasonable HRR curve for fire modelling. Since dwelling fire is a limited ventilation scenario, hence HRR curve plays a vital role. The fire will be developed under-ventilation controlled conditions, limited amount of air will enter the fire. Hence the development of the fire will be very vital. Because proper study will enhance the factors that can affect the fire development under limited air entrainment. The amount of air entering the fire is the vital parameter that needs to be studied. And hence the fire development will be based on the following factor as well.

## 8.2 Fires with external door open

Another critical assumption in this study is:

**Assumption B Windows and the external door are closed in all the fire scenarios;**

Fires with a window or external door open are in quite different situations from that in the current study especially when an external wind is involved. In this situation, the estimation of the HRR would be easier than that with the door closed in the current study. The maximum HRR inside the house can be simply limited with the predicted flow rate entering the house via the opening window or door in CFD simulations. However, the fire is expected to be strong than that investigated in this study. For such a situation, it is interesting to examine the impact of a top vent on the survivability in closed bedrooms with certain leakage around the doors.

## 8.3 Additional Vent

Instead of an external door suggested in Section 8.2, an additional vent on the ground floor can also be considered as well for the purpose of studying the impact of two or more vents on the spread of fire and transport of smoke inside the dwelling.

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