COMPUTATIONAL FLUID DYNAMICS MODELING OF SMOKE SPREAD DUE TO FIRE IN BUILDINGS

by

Hussam Eldin Salah Abuelnour Babiker

15706

Dissertation submitted in partial fulfilment of
the requirements for the
Bachelor of Engineering (Hons)
(Mechanical)

AUGUST 2014

Universiti Teknologi PETRONAS
Bandar Seri Iskandar
31750 Tronoh
Perak Darul Ridzuan

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

Hussam Eldin Salah Abuelnour Babiker

CERTIFICATION OF APPROVAL

COMPUTATIONAL FLUID DYNAMICS MODELING OF SMOKE SPREAD DUE TO FIRE IN BUILDINGS

by

Hussam Eldin Salah Abuelnour Babiker

15706

A project dissertation submitted to the

Mechanical Engineering Programme

Universiti Teknologi PETRONAS

in partial fulfilment of the requirement for the

BACHELOR OF ENGINEERING (Hons)

(MECHANICAL ENGINEERING)

Approved by,

____

(Dr. Mohammad Shakir Nasif)

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

AUGUST 2014

ABSTRACT

This research aims to analyze smoke contamination using computational fluid dynamics (CFD) software in high-level atrium. The reasons beyond the rise of this study are; the dangerous extent of smoke effects upon human beings as it is found to be a major lives threat in fire incidents. The choice of high-level atrium was due to its large construction rate worldwide and in Malaysia particularly as there are more than 200 shopping malls in Malaysia. The developed model will be altered various times according to the combination of parameters changed; therefore, many cases will be simulated in order to propose a new correlation that aid designers/engineers to produce safe designs. The objectives of this research are; investigate the behavior of smoke due to fire in upper balconies at an atrium and utilize (CFD) software, Fire Dynamics Simulator (FDS) in modelling fire incident. 36 cases will be simulated and evaluated for 3, 5, and 7 balcony buildings. The findings of this project show that smoke contamination increases with the increment of building height as well as the presence of down stand structures (brand display). Eventually, there are three correlations generated from the obtained results and it is recommended for engineers and architects to utilize them in designing safer Atrium in the future.

ACKNOWLEDGMENT

I would like to take this opportunity to thank all parties involved in making the final year project a great educational experience and a tremendous success.
All thanks are due to **ALLAH** the almighty for his infinite blessings and graces, which enabled me to finish the dissertation fruitfully.

I am indebted to many individuals who helped me throughout the project whom without their appreciated efforts, I would not reach such level of achievement. I would like to express my very great gratefulness to my respected supervisor and must address him as a teacher as well **Dr. Mohammad Shakir Nasif** (Mechanical Engineering department) for his valuable and constructive assistance even before the initiating of the project up to the last moment. His willingness to give his time so generously has been extremely appreciated. I would like to express my deep gratitude as well to **Mr. Ali Hasnain** for his priceless lectures regarding Fire Engineering and the unique support he expressed throughout the project period.

Finally but yet importantly, extreme thankfulness for those behind the scene, my dear **parents, my three little sisters, family and friends** for their unending support, prayers, and for giving me courage and advices throughout my academic journey.

CONTENTS

ABSTRACT III

ACKNOWLEDGMENT IV

LIST OF FIGURES VII

LIST OF TABLES VIII

CHAPTER 1: INTRODUCTION 1

1.1 Background 1

1.1.1 Nature of fire 1

1.1.2 Nature of smoke 1

1.2 Important terminologies 2

1.2.1 Atrium 2

1.2.2 down stand structure 3

1.3 Problem Statement 3

1.4 Scope of Study 4

1.5 Objectives 5

CHAPTER 2: LITERATURE REVIEW 6

2.1 Physical Modeling 6

2.2 Numerical simulation model using CFD 8

2.3 Inwards curls of smoke plume into balconies 9

2.4 Down stand structure model 9

2.5 Fire Dynamic Simulator (FDS) 11

CHAPTER 3: METHODOLOGY 12

3.1 Research Methodology 12

3.2 Project activities 13

3.3 Gantt chart and key Milestones 14

CHAPTER 4: RESULTS AND DISCUSSION 15

4.1 Model development & Data interpretation 15

4.1.1 Selection of Experiment Model 15

4.1.2 Fixed dimensions and materials 16

4.1.3 Smoke Contamination 19

4.1.4 Height of Smoke Contamination 20

4.1.5 Modelling Parameters 20

4.2 Developed models 21
4.3 Results.. 22
4.3.1 Stability of Temperature Reading 22
4.3.2 Comparison of Smoke Layer Depth at Spill Edge 24
4.3.3 Comparison of smoke contamination severity 25
4.3.4 Correlations.. 27
4.4 Discussion.. 30
4.4.1 Delay of Smoke Contamination at Upper Balcony... 30
4.4.2 Mechanism for Re-attachment... 30
4.4.3 Smoke Contamination Starts from the Highest Balcony 31
4.4.4 Cause of Increased Smoke Contamination in Higher Atrium 32
CHAPTER 5: CONCLUSION AND REOMMENDATIONS... 33
5.1 Conclusion... 33
5.2 Recommendations 34
REFERENCES... 35
APPENDIX.. 36

LIST OF FIGURES

Figure 1: Atrium example - Berjaya Times Square in Kuala Lumpur... 2
Figure 2: Schematic diagram for inwards curl and down stand structure.................................... 3
Figure 3: Schematic diagram of physical scale model and locations of sensors........................... 7
Figure 4: Comparison of temperature distribution between Ho's results (right) and Hasnain et al ones (left).. 10
Figure 5: Five balconies atrium with down stand structure using FDS....................................... 10
Figure 6: Research methodology 12
Figure 7: Gantt chart and key milestones.. 14
Figure 8: Schematic of Front view of the model with dimensions 16
Figure 9: Schematic of Side view of the model with dimensions 17
Figure 10: 30°C temperature profile of exp 3 for three balcony 19
Figure 11: Height of smoke contamination 20
Figure 12: 3 level balcony model 21
Figure 13: 5 level balcony model 21
Figure 14: 7 level balcony model 21
Figure 15: 7 leve balcony – smoke rising during the simulation.. 21
Figure 16: Stability of temperature for exp1 – 3L 213
Figure 17: Stability of temperature for exp1 – 5L.. 214
Figure 18: Stability of temperature for exp1 – 7L.. 214
Figure 19: 3 level Atrium correlation 218
Figure 20: 3 level Atrium correlation 219
Figure 21: 3 level Atrium correlation 30
Figure 22: Delay of smoke contamination 31
Figure 23: Smoke-view air re-attachement 21
Figure 24: Smoke-view air entrainment in a balcony 21

LIST OF TABLES

Table 1: Twelve primary scenarios scaled dimensions and HRR 15
Table 2: Materials properties utilized for model development.. 18
Table 3: Comparison of smoke layer depth at spill edge.. 24
Table 5: Comparison of smoke contamination severity of 5 level Atrium 25
Table 4: Comparison of smoke contamination severity of 3 level Atrium 25
Table 6: Comparison of smoke contamination severity of 7 level Atrium 26
Table 7: Summary of results of simulated 3 level Atrium configuration 27
Table 8: Summary of results of simulated 5 level Atrium configuration 28
Table 9: Summary of results of simulated 7 level Atrium configuration 29

CHAPTER 1: INTRODUCTION

1.1 Background

Smoke is a direct inevitable consequence of fire that has massive capability of spreading around long distances. The study of smoke behavior, its generation, spread, and consequences is one of the core fields of Fire Engineering.

1.1.1 Nature of fire

Fire is revered and sacred throughout history, as some people considered it a divine substance that has direct effects on souls and contains power. However, fire is not a tangible material but rather it is a visible result of continuous process called combustion were involved substances are chemically reacting. Fire occurrence is conditioned by the simultaneous existence of three elements which are: air (specifically oxygen), fuel (any combustible material), and heat (ignition temperature of the material) these in turn are called “The fire triangle components”. Recently, a forth element has been included that formed “The fire tetrahedron”, the new component is the uninhibited chain reaction which provides the heat necessary to maintain the fire and it’s utilized for certain fire suppression mechanism. Typically, resulting components (mainly smoke and the toxic waste of fire’s leftovers) are totally different from reacting ones.

1.1.2 Nature of smoke

Throughout this research, the term smoke will be employed in accordance with the explanation obtained from National Fire Protection Association (NFPA). According to NFPA 92A and NFPA 92B smoke consists of various components; the airborne solid, liquid particulates and gases evolved when a material undergoes pyrolysis or combustion, in addition to remarkable quantity of air that is entrained into the mass. Usually, the products of combustion include particulates, unburned fuel, water vapor, carbon dioxide, carbon monoxide, and some other toxic and corrosive gases.

As smoke moves through a building, air mixes into the smoke mass and the concentration of combustion products in the smoke decreases. Generally, smoke is thought of as being visible, but the above definition includes "invisible smoke" produced by burning of materials that produce little or no particulate matter, such as hydrogen, natural gas, and alcohol.

1.2 Important terminologies

There are significant terminologies used in this research. However, understanding them is crucial throughout the research to fully visualize the fruitful results at the end.

1.2.1 Atrium

An atrium within a building is a large space which connects openings in floors, and which is wholly or partially enclosed at the top by a floor or roof, and which is used for purposes other than those normally associated with the small shafts commonly enclosing stairways or lifts. The essential difference between an atrium and a traditional inner courtyard is that atrium is roofed over, and smoke from fire cannot readily escape to the outside atmosphere.

Atriums have become popular because they are attractive as a means of allowing daylight into lower levels and creating an outdoor atmosphere which is protected from the extremes of climate. An atrium can contribute to visual appeal, achieve economies in the use of heat and light, and can provide recreational space.

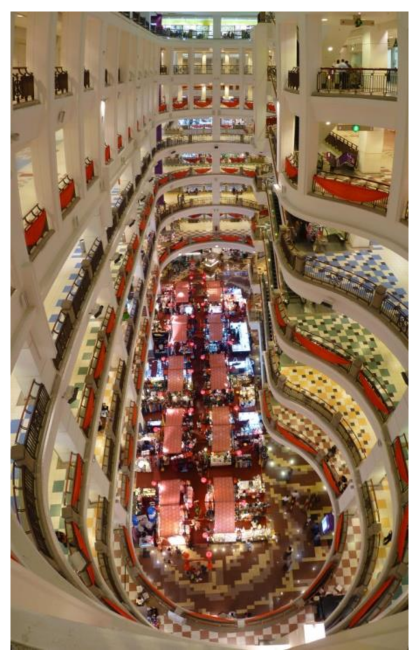


Figure 1: Atrium example - Berjaya Times Square in Kuala Lumpur

1.2.2 down stand structure

A down stand structure is a vertical body required in any shop in a shopping mall to display the trade name of the shop. As it can be seen in next figure, the existence of a down stand structure will affect the behavior of smoke tremendously. Typically, smoke management in atrium focus on removing the smoke from the atrium and avoid personnel encountering with the smoke. One of the concerns is that smoke may curl into the balconies from balcony spill plume as shown in Figure 2.

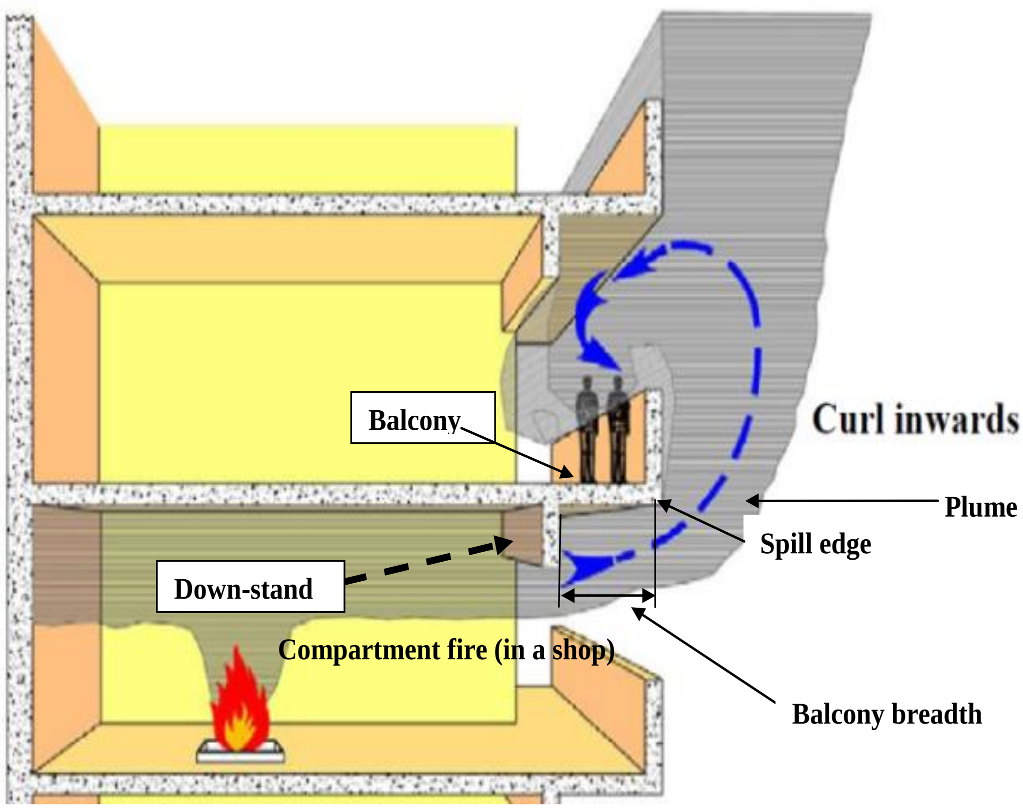


Figure 2: Schematic diagram for inwards curl and down stand structure (Morgan *et al*, 1999)

1.3 Problem Statement

There are two main driving causes that influenced the decision of proceeding with the project which are; Smoke jeopardy upon human being lives and the wide spread of atrium designs across the whole world and Malaysia in particular where there are more than 200 shopping mall nation wise. Smoke is a furious enemy of human beings; more than 50% of deaths in fire incidents are due to smoke contamination. Toxicity of smoke components is proved to be a major cause of fatality upon humans. Smoke is always accompanied with fire events, which in turn threats humans' souls as it is capable of reaching people in a relative far distance from the fire source due to its notable spread ability. Nowadays, shopping malls in the form of atrium have been widely constructed for the reason of its attractive design and its massive open spaces which increases the possibility of smoke spread during fire incidents by curling inwards balconies and hence causes fatal contamination. Moreover, complex designs of atrium do not correspond to perspective standards, therefore a performance based design process is recommended to identify the characteristics of that specific design. Due to these motivations, this project is carried out as it is concerned about the causes of smoke spread in atria from various aspects and angles.

1.4 Scope of Study

The event of fire and analysis of smoke contamination in a high Atrium has unlimited scenarios and conditions as the involved causal factors are variant. Therefore, the core of this research is a process of developing a model using computational fluid dynamics (CFD) software, Fire Dynamic Simulator (FDS). Eventually there will be total of 36 different cases or models, each model will differ in terms of at least one parameter than the others but the main fixed parameter is the existence of 1m depth down stand structure. The model will be an atrium with dimensions obtained from previous researches and targeted number of levels will be three, five, and seven levels, each one includes 12 cases. The main parameters that will be varied and analyzed are; number of floors of the atrium (height of the building), balcony breadth, plume width (channel opening width), heat release rate (fire size), and smoke layer height. Ultimately, various cases will be systematically simulated in order to obtain empirical correlations of the aforementioned parameters in order to propose effective ways to increase the safety measurements in atrium designs.

1.5 Objectives

- To investigate the behavior and spread of smoke due to fire in upper balconies at an atrium by utilizing computational fluid dynamics (CFD) software, Fire Dynamics Simulator (FDS)
- To produce a new correlation of smoke contamination of specific height of Atrium to be utilized by engineers and architects to ensure optimal safe designs for new Atrium

CHAPTER 2: LITERATURE REVIEW

Reviewing the literature is a crucial tool at the first stage of the project as it has been used to spot the gaps of previous researches and consider these gaps for high precision findings and conclusions.

Fire is a major threat where miserable catastrophes result in loss of human life and property damage. Actually, smoke as well is acknowledged as a serious threat during fire events as it assassins lives unexpectedly due to its spread ability. Hence, the concentration during this study will be on smoke behavior in open spaces, atria in particular. In order to carry out the assigned tasks, performance base design approaches will be dedicated throughout the project as the analyzed atrium is not simply standardized. It is stated that fire releases fatal toxic gases into the atmosphere as a result of the combustion process such as CO, CO_2, and HCN (Hasnain et al, 2013).

Nowadays, Atrium has been widely found worldwide due to its attractiveness and roominess. However, this open space and lack of floor to floor separation exposes high risks in the case of fire, for the reason that smoke is capable of spreading within a large volume (Tan et al, 2009) and (Ho C. , 2010).

2.1 Physical Modeling

There are quite a number of previous and ongoing researches regarding the analysis of smoke behavior in high level atrium, and the probability of smoke contamination to occur in upper balconies. Various methodologies have been utilized to understand the behavior of smoke in atrium. One of the methodologies employed a physical scale modeling of in an atrium to detect smoke contamination in upper balconies (Tan et al, 2009). Tan et al. considered five story atrium with 1/10 modeling scale, utilized visual observations and photography of the experiments to interpret them into useful data, and focused on certain parameters in the study which have direct impact on extent of smoke behavior. They found that increment of smoke contamination possibility is directly proportional to decreasing balcony breath, and increasing plume width, whereas fire size has insignificant effect upon contamination extent. The aspect ratio of plume width to balcony breadth (w/b) is highlighted an alternative handful parameter in atrium designs regarding smoke

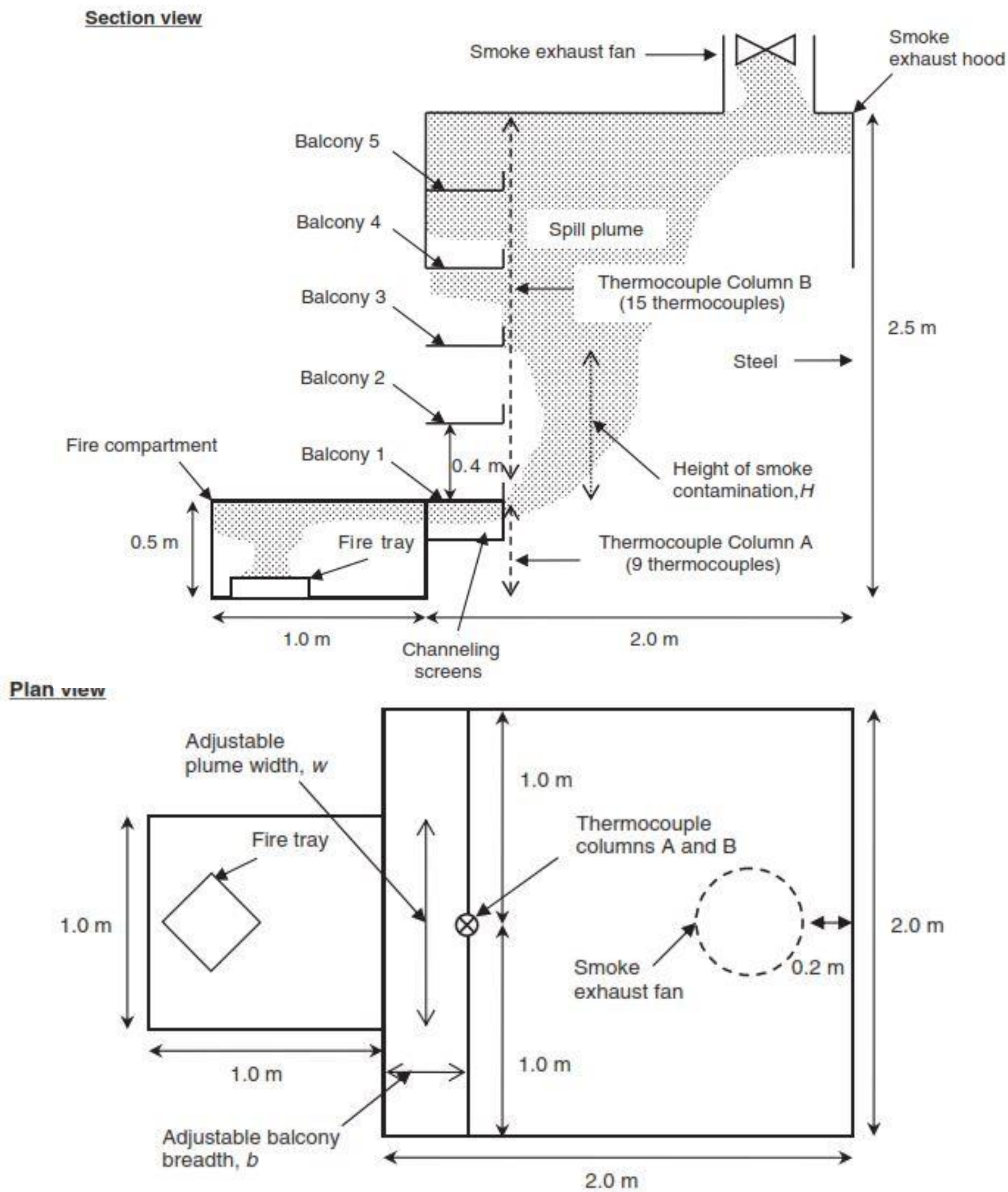


Figure 3: Schematic diagram of physical scale model and locations of sensors (Tan, 2009)

contamination in high balconies. Eventually, Tan et al. (2009) declared that fire release rate changes were vital, as severer contamination was accompanied with lower heat release rate compared to higher one, and they had formulated an empirical correlation to find out the minimum height of contamination.

2.2 Numerical simulation model using CFD

Computational fluid dynamics (CFD) consists of dividing a space into a large number of control volumes and using a computer to calculate approximate solutions to the governing equations for each control volume. These control volumes are often called cells.

Physical modeling is not the preferred way of carrying out researches, as the majority chooses numerical simulation for the sake of cutting cost, effort and time. Ho et al. (2010) had created a numerical simulation of a previous physical scaled model regarding smoke contamination of upper atrium levels by channeled balcony spill plume (Ho et al, 2010). In this study Ho has utilized computational fluid dynamics to verify the results of (Tan et al, 2009) as a validation process, and further upgraded the model to full scale instead of 1/10 scaled model. In addition to verifying Tan et al outcomes, Ho had another purpose of his study which is assessing the capability of Fire Dynamic Simulator software to effectively simulate the scenario of smoke contamination from the previous experiment in order to carry out numerical studies. Again, Ho and Tan et al. had almost similar working parameters e.g. temperature severity, plume width, and height of smoke contamination. Likewise, the outcomes of the simulation via FDS from Ho’s research mostly matched formerly mentioned ones by Tan et al. (2009)

2.3 Inwards curls of smoke plume into balconies

One of the major concerns in the analysis of smoke spread in high level atrium is the inwards curls of smoke plume into the balconies as figure 2 shows. A probable cause of such curls is the Coanda effect which is the phenomena where the fluid jet has a tendency to attach itself to a nearby surface and remains attracted even when it leaves the surface. Identifying the plume configuration is important since the amount of air entrained is dependent on it. Generally, plumes are categorized as the following: Axisymmetric plume, Wall plume, Corner plume, Spill plume, Window plumes (Harrison et al, 2009). Since the project is focusing on spill plume, it is valuable to define it and highlight its features. Harrison et al. described a spill plume as it is basically created from a lateral moving buoyant layer of hot smoke in a confined enclosure, which subsequently rises from the opening of the enclosure and then flows upward after passing the balcony's edge toward the atrium open space. According to Ho et al. (2010) the spill plume will curl inwards a balcony as the balcony breadth is less than 1 m.

2.4 Down stand structure model

A more recent study is in the concern scope of the project as it concentrated on some factors which were neglected for a while. Nowadays, most atria have shopping malls that utilize a vertical down signs to exhibit the trade name of the respective shop. Down stand structures terminology will be denoted throughout the project. Although Harrison and Spearpoint (Harrison and Spearpoint, 2004) have modeled the down stand structure, they only focused on its effect on rising plume behavior and neglected its effect on smoke spread in atrium upper balconies. Hence, another numerical investigation study focused on the presence of down stand structures in fire compartment in atrium upper balconies and its effects upon smoke contamination (Hasnain et al, 2013). The initial stage of Hasnain et al. was the validation of the model against Ho's results, and it is found that the results are in a reasonable agreement. Figure 4 clarifies the similarity of results between Ho et al's results and Hasnain et al ones in the form of temperature distribution.

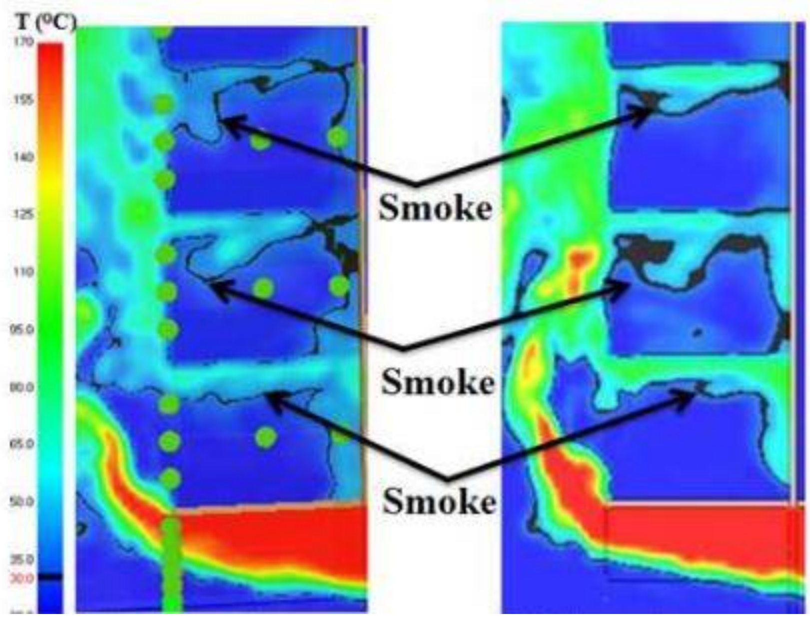


Figure 4: Comparison of temperature distribution between Ho's results (right) and Hasnain et al (2013) ones (left).

Figure 4 shows that Hasnain et al. model development was fully scaled with 5 levels atrium and a 1 m depth down stand structure at the exit of the specified fire compartment. The results of the previous research stated; the extent of smoke contamination increases with the existence of down stand structure in shopping malls.

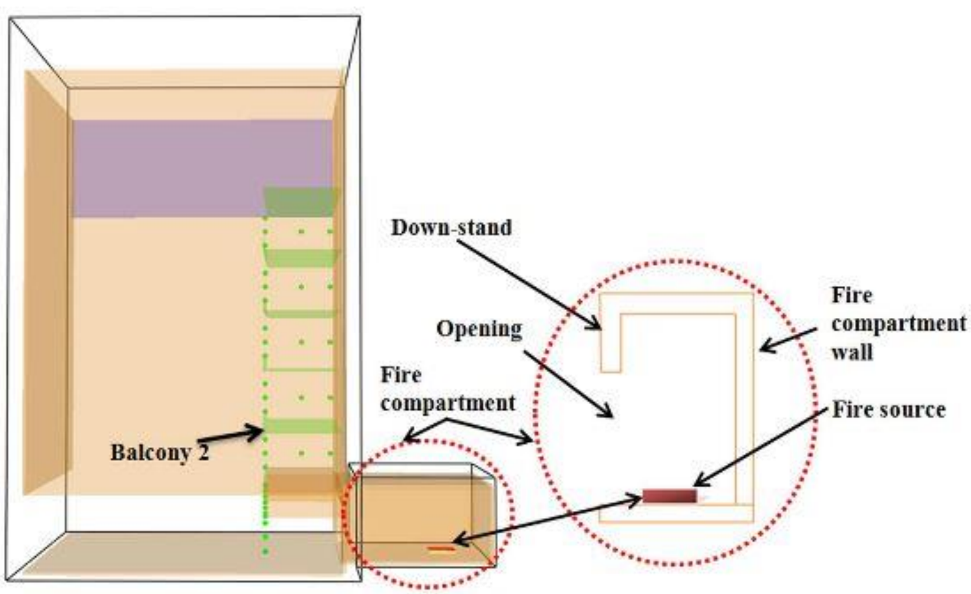


Figure 5: Five balconies atrium with down stand structure using FDS (Hasnain et al ,2013)

The Study of Hasnain et al. (2013) has focused on the existence of the down stand structure considering only one case where the depth of the down stand is 1 m. A recent study analaysed the effect of changing the down stand depth upon smoke contamination carried out by Hassnain et.al proved that the existence of the down stand structure increses the severity of smoke contamination regardless of its depth dimension.

2.5 Fire Dynamic Simulator (FDS)

Users of computational fluid dynamics softwares are increasing, and it is significant to validate any model in order to obtain trustful information for best recommendations. As discussed earlier, Ho et al. used FDS to verify the results found by Tan et al. and stated that the under-prediction could only be approximated by 10%.

Small-scale simulation results have indicated that FDS is capable of rationally modeling the smoke contamination, despite the predicted temperatures might be lower sometimes (Ho, 2010). Similarly, Hasnain et al. have utilized the FDS software to validate the model and then used it to simulate certain cases.

During the process of using FDS, the geometry is considered as a 3-D numerical grid, which solves the related set of equations of mass, momentum, energy and species concentration (Harrison et al., 2009). Harrison et al. adds that the optimum use of CFD is conditional to the user competency and requires intensive knowledge of fire science and numerical analysis.

The Fire Dynamics Simulator (FDS) model has a remarkable advantage among other CFD softwares as it is dedicated in particular for fire applications. Further research regarding FDS performance efficiency is recommended, and it crucial for a designer to be aware in defining the boundary conditions during FDS modeling for optimal results.

However, it seems unpractical to formulate a fixed perspective approach regarding atrium design because that will limit creative and innovative designs; hence, the use of performance based design approach is highly recommended.

CHAPTER 3: METHODOLOGY

3.1 Research Methodology

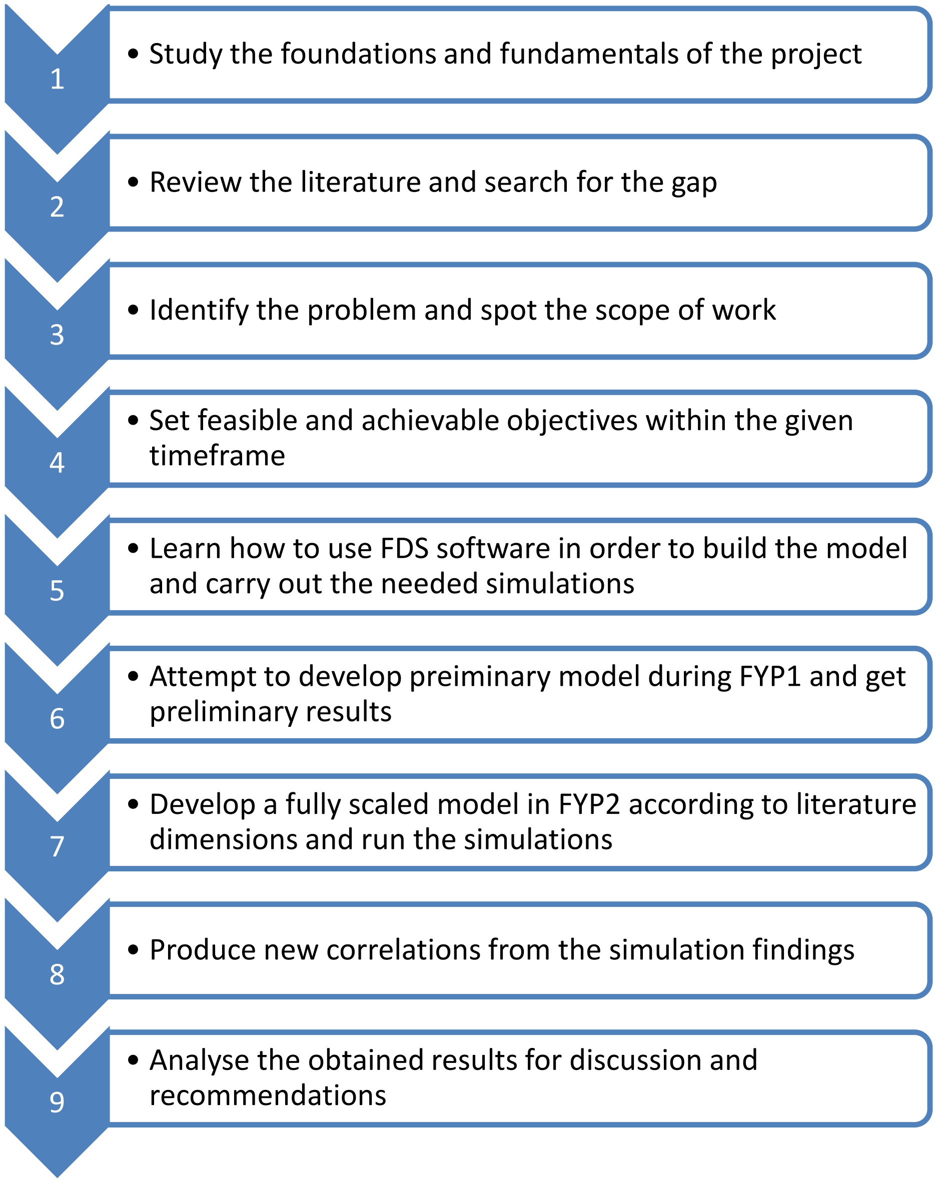
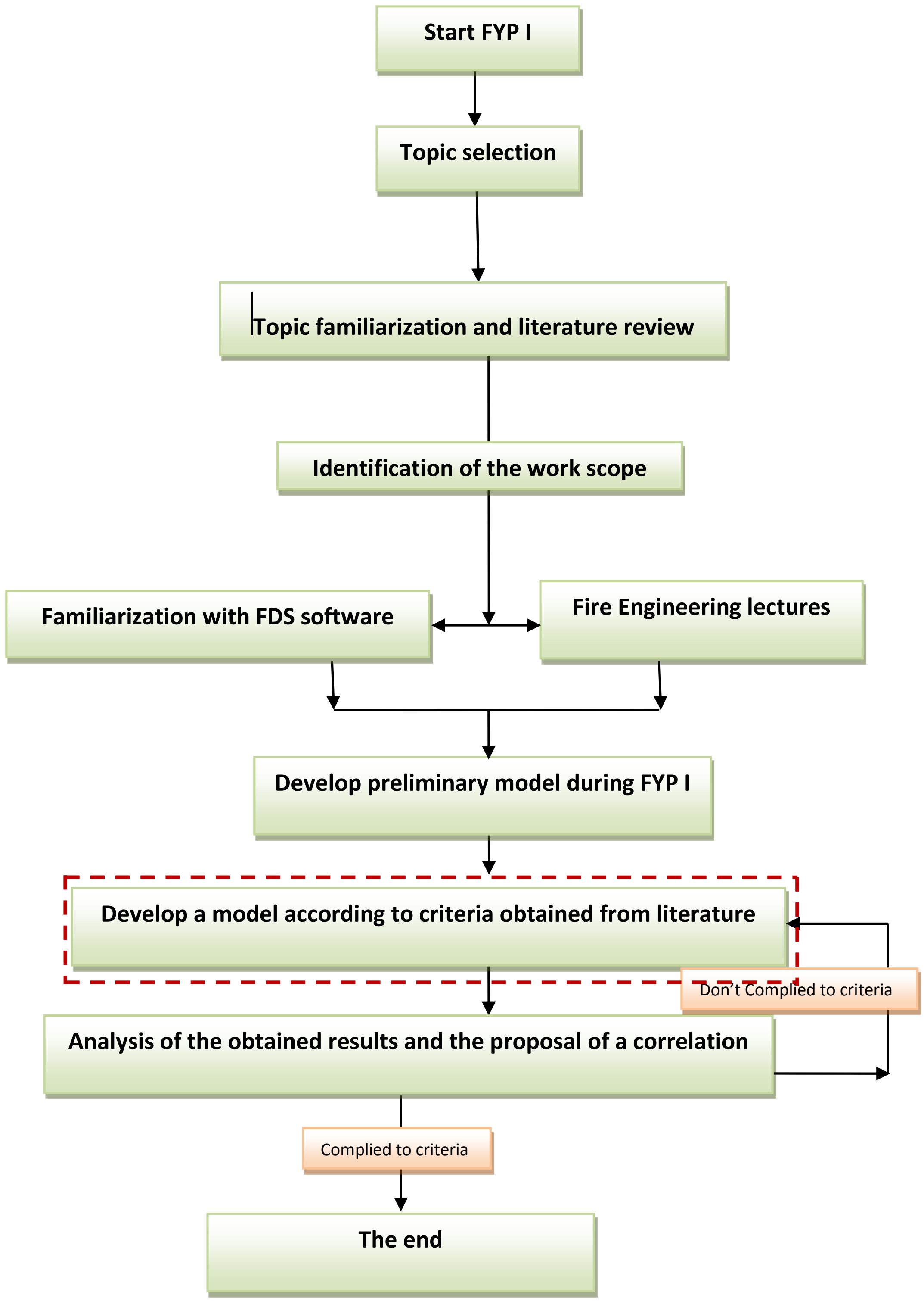


Figure 6: Research methodology

3.2 Project activities

Ongoing official process

- *Extended proposal*
- *Proposal defense*
- *Interim report*
- *Progress report*
- *Pre-sedex*
- *Technical paper*
- *Oral presentation*
- *Dissertation*



3.3 Gantt chart and key Milestones

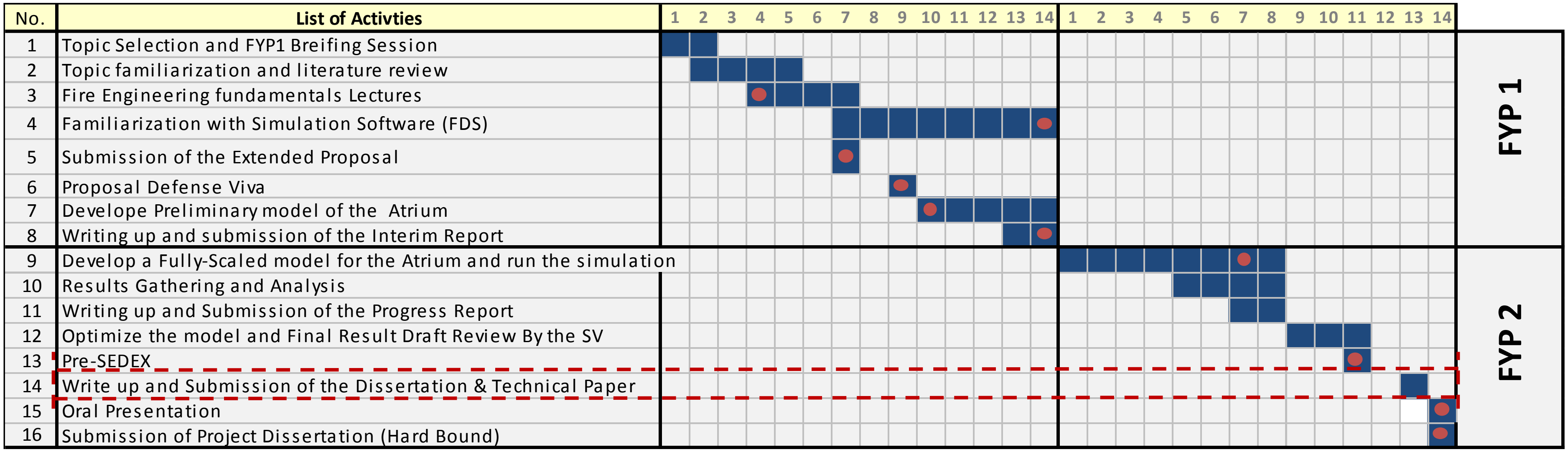


Figure 7: Gantt chart and key milestones

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Model development & Data interpretation

4.1.1 Selection of Experiment Model

Initially, the model development process started with distinguishing 12 primary cases out of 60 in order to generate the correlation equation. The choice of these 12 representative cases is based on the subsequent conditions:

- Wide coverage of aspect ratios (w/b ≤ 3.0) from Tan et al.'s (2009) empirical results
- Wide coverage of plume widths as well as various hear release rates
- Involvement of mixture of contaminated and non-contaminated models

The designated experiments for developing the models are shown below in table1.

Table 1: Twelve primary scenarios scaled dimensions and HRR

Experiment	Balcony Breath, b (m)	Plume Width, w (m)	Aspect Ratio, w /b	Heat Release Rate, Q_T (kW)
1	0.5	1	2	5
3	0.5	1	2	15
8	0.5	0.6	1.2	10
13	0.5	0.2	0.4	5
19	0.3	0.8	2.7	5
23	0.3	0.6	2	10
27	0.3	0.4	1.3	15
38	0.2	0.6	3	10
41	0.2	0.4	2	10
43	0.2	0.2	1	5
56	0.15	0.4	2.7	10
60	0.15	0.2	1.3	15

4.1.2 Fixed dimensions and materials

The dimensions used in this project resemble what Tan et al. (2009) used for the physical model in order to update Ho et al.'s correlation which was originally corresponding to Tan's research dimensions and materials.

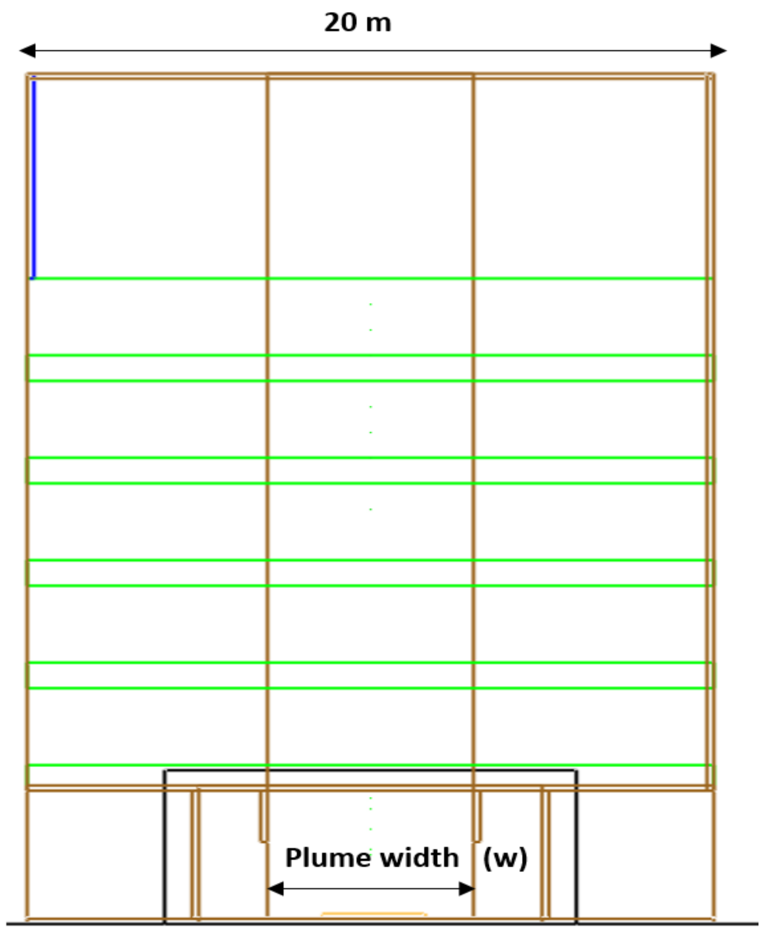


Figure 8: Schematic of Front view of the model with dimensions

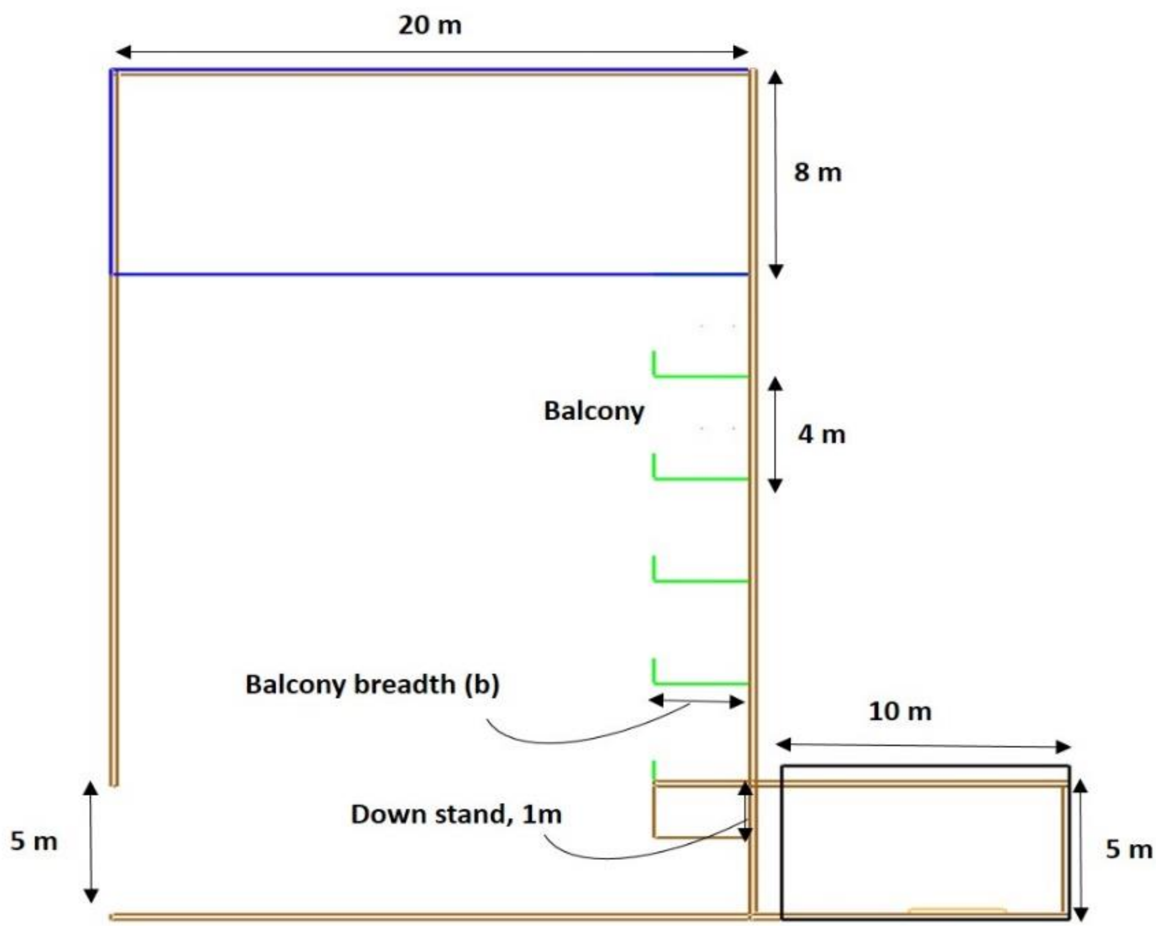


Figure 9: Schematic of Side view of the model with dimensions

The green lines are indicating the balcony's floor and upstand while blue lines are representing the boundaries of the Perspex glass. The total height of the building is dependent on the number of balconies and it's computed as the following:

5 m (height from ground to 1st balcony) + 4 m (height of each balcony) * number of balconies + 8 m of Perspex glass

In the case of 3 balconies, the total height is 25 m. 5 balconies and 7 balconies heights are 33 m, and 41 m respectively.

In this project the top ceiling of the building was removed instead of having a roof equipped with a mechanical exhausting fan since this issue has no relation or any effects upon smoke contamination level in the balconies.

Table 2: Materials properties utilized for model development

CFI Board		
Conductivity (W/mk)	0.041	(Drysdale, 1998)
Density (kg/m^3)	229	
Specific heat (kJ/kgK)	0.82	
Thickness (mm)	160	
Steel		
Conductivity (W/mk)	45.8	(Buchanan, 2002)
Specific heat (kJ/kgK)	0.46	
Density (kg/m^3)	7850	
Thickness (mm)	10	
Acrylic Glass		
Conductivity (W/mk)	0.19	(Drysdale, 1998)
Specific heat (kJ/kgK)	1.42	
Density (kg/m^3)	1190	
Thickness (mm)	120	
Ethanol		
Carbon	2	
Hydrogen	6	
Oxygen	1	
Heat of combustion (kJ/kg)	2680	(Karlsson & Quintiere, 2000)
Radiative Fraction	0.2	(Drysdale, 1998)

4.1.3 Smoke Contamination

One way of identifying whether smoke contamination took place or not is the use of 10°C above ambient temperature profile (30°C). The temperature profile is considered as smoke, when the profile of 30°C spread in more than 50% of the balcony's height, it's then considered as "deep smoke layer", whereas a temperature profile less than 50% height is considered as "shallow smoke layer". The aforementioned measurement was utilized by Tan et al (2009), the next figure is clarifying that.

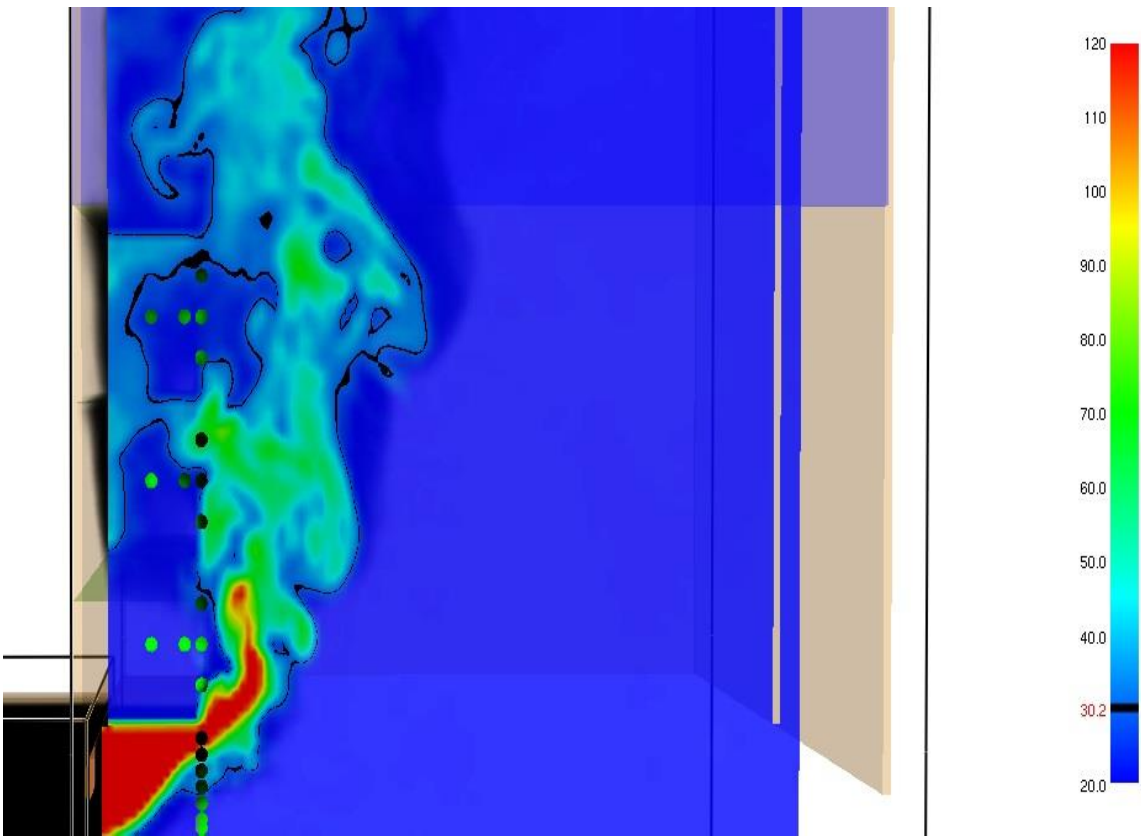


Figure 10: 30°C temperature profile of exp 3 for three balcony

4.1.4 Height of Smoke Contamination

The detection of the height of the smoke contamination is clearly explained in figure 11. This method was used by Tan et al (2009), it has a simple mechanism where the spill edge is a reference. Full contamination is expressed by smoke when it reaches the floor (H = 0 m). In the simulation, smoke contamination is spotted via layer height device in FDS which measures the height precisely apart from human caused errors.

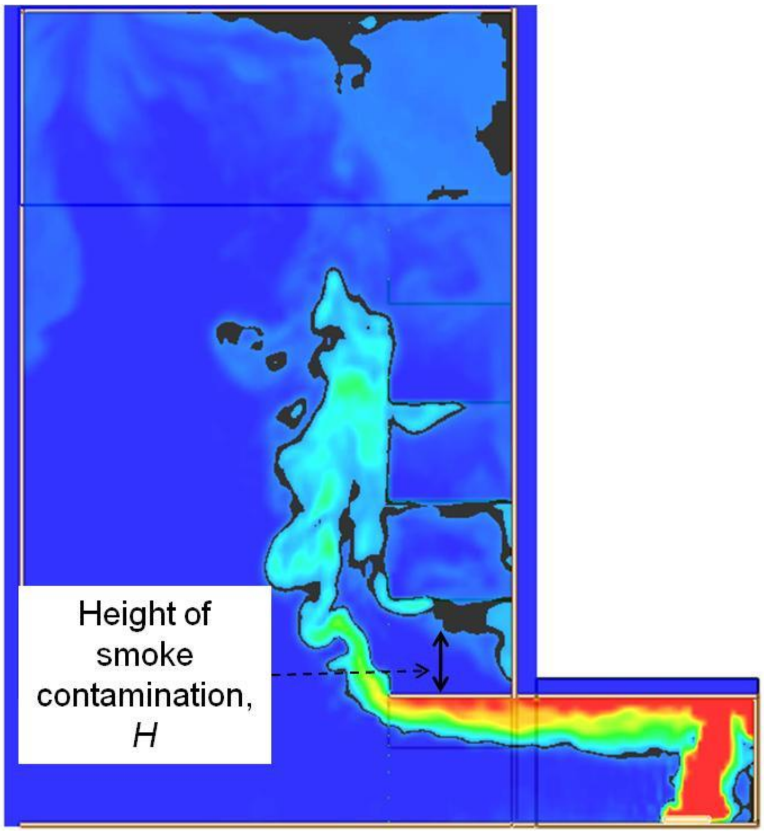


Figure 11: Height of smoke contamination

4.1.5 Modelling Parameters

The fire sizes in this project were varied between 1581 kw, 3162 kw and 4746 kw according to Ho et al.'s findings.

The previous sizes were comparable to 5 kw, 10 w and 15 kw respectively of Tan's scaled model.

The ambient temperature for Tan et all (2009) is not mentioned in his writings. However, since his experiments took place between Nov 2008 and Jan 2009, an assumption was made that it is an ambient lab temperature of 20°C for that summer period.

4.2 Developed models

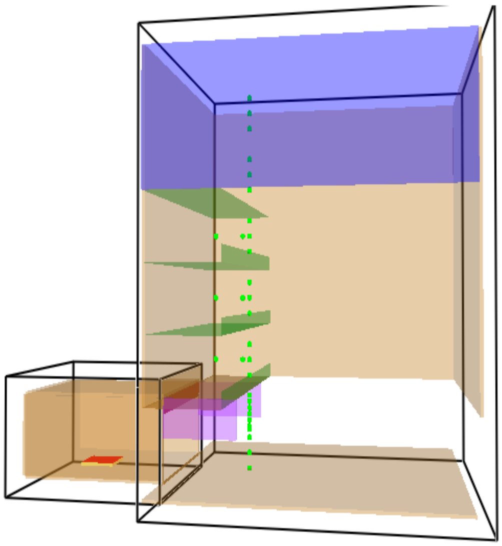


Figure 12: 3 level balcony model

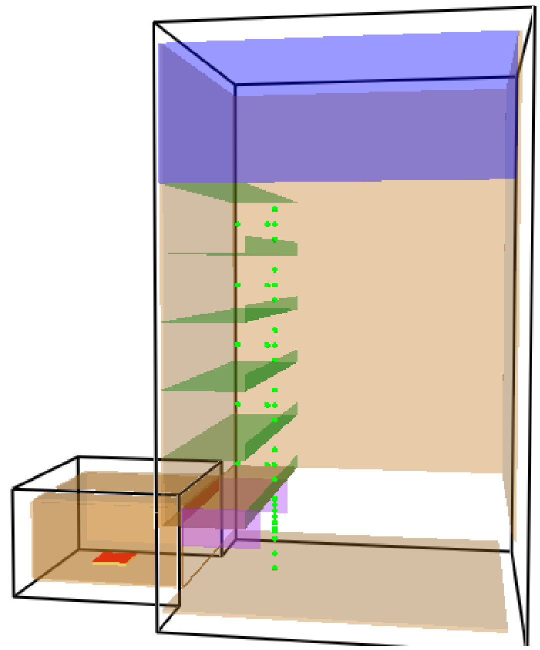


Figure 13: 5 level balcony model

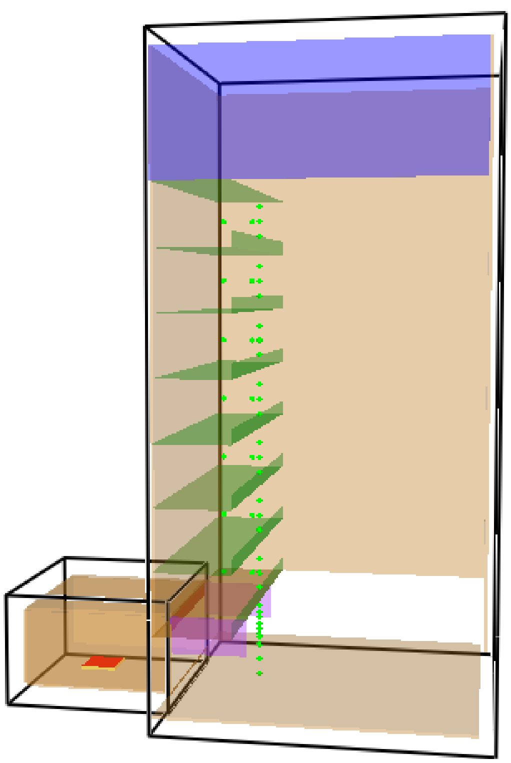


Figure 14: 7 level balcony model

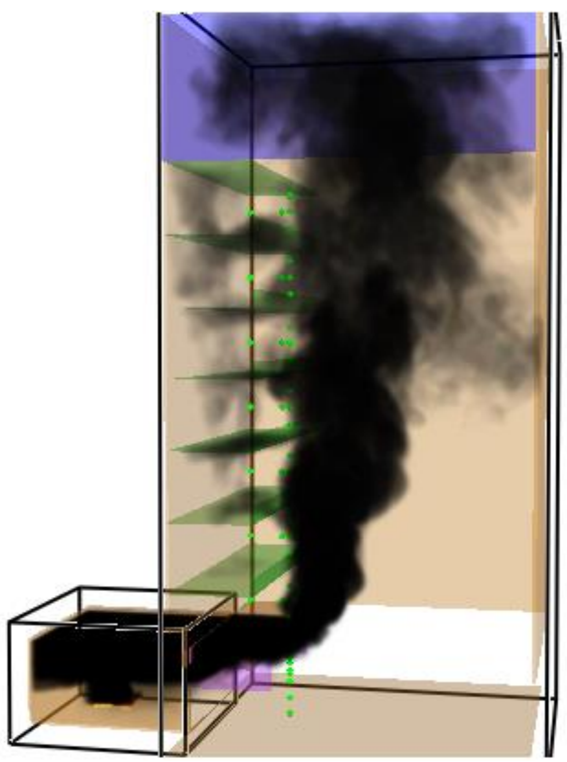


Figure 15: 7 level balcony – smoke rising during the simulation

4.3 Results

4.3.1 Stability of Temperature Reading

Three temperature readings from each balcony are selected for demonstration and the temperatures are from the balcony edge. Figure 17 shows that temperature stability is achieved after 330 s. While figure 18 and figure 19 shows that temperature stability is achieved after 200 s.

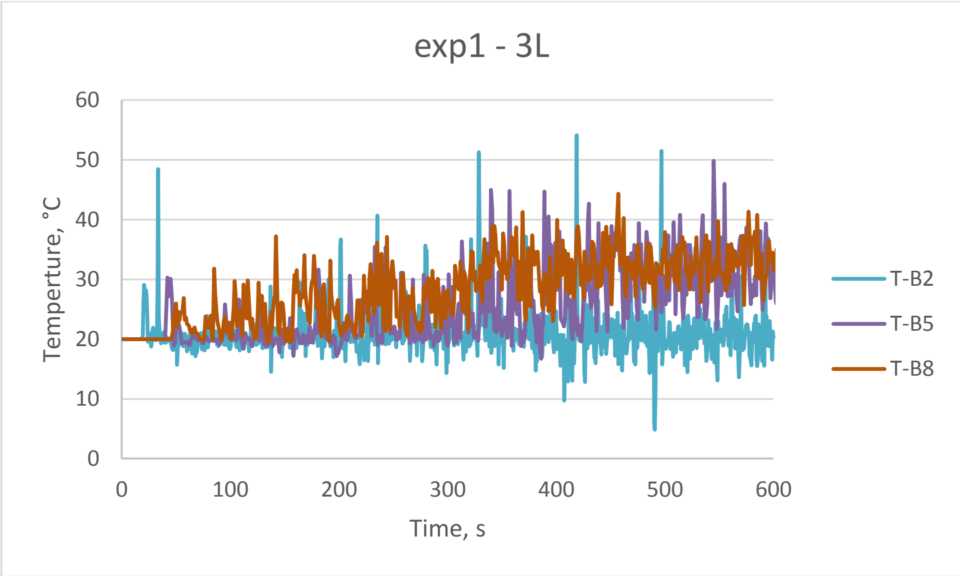


Figure 16: Stability of Temperature for exp1 – 3L

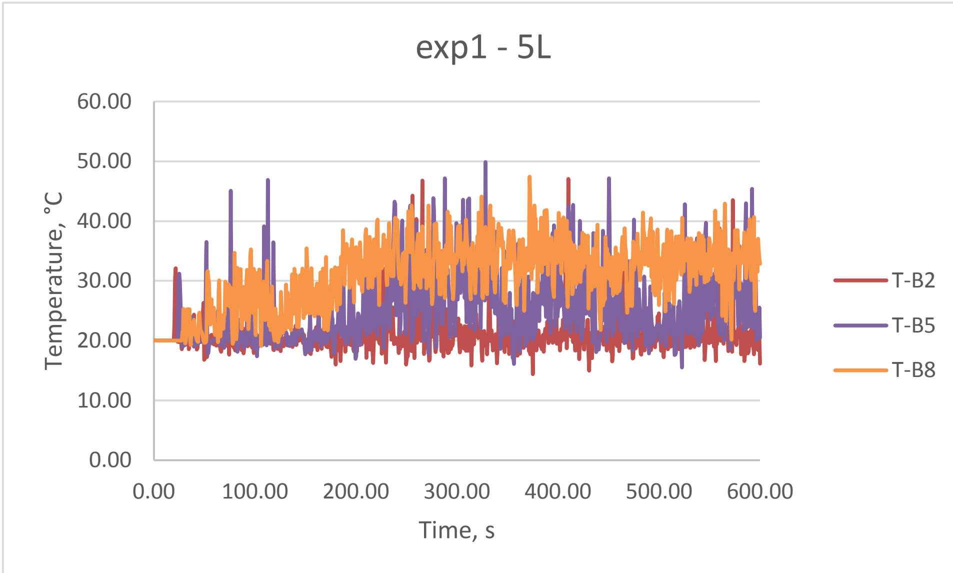


Figure 17: Stability of Temperature for exp1 – 5L

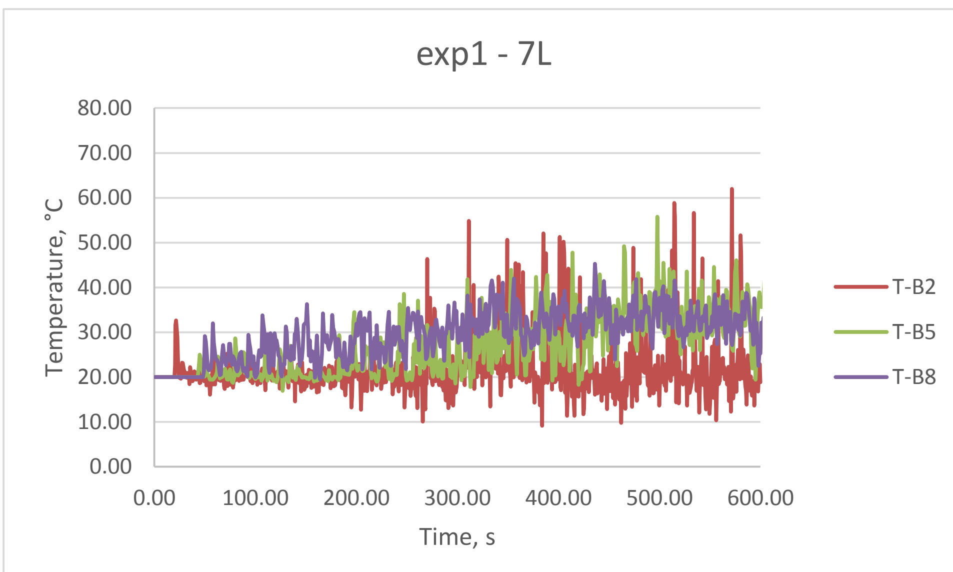


Figure 18: Stability of Temperature for exp1 – 7L

4.3.2 Comparison of Smoke Layer Depth at Spill Edge

Ho et al. (2010) and Tan et al. (2009) have assessed the smoke layer depth at the spill edge via Harrison's (2009) data. The following table shows their numeric values compared to the ones obtained in this project. The data illustrates variations of values as the light green experiments' values are less compared to Ho's data, whereas the blue ones indicate experiments with higher values.

Table 3: Comparison of smoke layer depth at spill edge

Experiment	Depth of Smoke layer at spill edge, d (m) - 3L		
	Tan et al.'s data Scaled (1/10)	Ho et al.'s data Scaled (1/10)	Current data
Exp1	0.1	0.07	0.68
Exp3	0.125	0.09	0.73
Exp8	0.12	0.1	0.82
Exp13	0.12	0.11	0.98
Exp19	0.105	0.10	0.78
Exp23	0.135	0.12	0.98
Exp27	0.145	0.11	1.22
Exp38	0.12	0.13	1.49
Exp41	0.125	0.13	1.75
Exp43	0.135	0.13	1.66
Exp56	0.125	0.14	1.97
Exp60	0.17	0.15	2.14

4.3.3 Comparison of smoke contamination severity

Since Ho has not considered the presence of down stand structures, the findings of this project will be different compared to Ho's data due to the consideration of down stand structure existence. The results show that the severity of smoke contamination has remarkably increased in the new research due to the down stand structure. Tables 7,8, and 9 includes all the parameters used for producing the correlation for 3,5, and 7 levels respectively.

Table 5: Comparison of smoke contamination severity of 3 level Atrium

Experiment	Balcony Breath, b	Plume Width, w	Aspect Ratio, w /b	Heat Release Rate, Q T	Balcony 1	Balcony 2	Balcony 3
1	0.5	1	2	5	o	O	O
3	0.5	1	2	15	o	O	O
8	0.5	0.6	1.2	10	c	c	o
13	0.5	0.2	0.4	5	c	c	c
19	0.3	0.8	2.7	5	o	o	O
23	0.3	0.6	2	10	c	o	O
27	0.3	0.4	1.3	15	c	c	o
38	0.2	0.6	3	10	o	o	O
41	0.2	0.4	2	10	c	c	o
43	0.2	0.2	1	5	c	c	o
56	0.15	0.4	2.7	10	o	O	O
60	0.15	0.2	1.3	15	c	c	o

Ho's results (by letters)	c	Clear
	o	Shallow smoke layer
	O	Deep smoke layer
Current Experiment Result (by color)		Clear
		Shallow smoke layer
		Deep smoke layer

Table 4: Comparison of smoke contamination severity of 5 level Atrium

Experiment	Balcony Breath, b	Plume Width, w	Aspect Ratio, w /b	Heat Release Rate, Q T	Balcony 1	Balcony 2	Balcony 3	Balcony 4	Balcony 5
1	0.5	1	2	5	o	O	O	O	O
3	0.5	1	2	15	O	O	O	O	O
8	0.5	0.6	1.2	10	c	o	o	O	O
13	0.5	0.2	0.4	5	c	c	c	c	c
19	0.3	0.8	2.7	5	O	O	O	O	O
23	0.3	0.6	2	10	o	O	O	O	O
27	0.3	0.4	1.3	15	c	o	o	O	O
38	0.2	0.6	3	10	O	O	O	O	O
41	0.2	0.4	2	10	o	o	O	O	O
43	0.2	0.2	1	5	c	c	o	o	o
56	0.15	0.4	2.7	10	o	O	O	O	O
60	0.15	0.2	1.3	15	c	o	o	O	O

Table 6: Comparison of smoke contamination severity of 7 level Atrium

Experiment	Balcony Breath, b	Plume Width, w	Aspect Ratio, w /b	Heat Release Rate, Q T	Balcony 1	Balcony 2	Balcony 3	Balcony 4	Balcony 5	Balcony 6	Balcony 7
1	0.5	1	2	5	O	O	O	O	O	O	O
3	0.5	1	2	15	O	O	O	O	O	O	O
8	0.5	0.6	1.2	10	o	o	O	O	O	O	O
13	0.5	0.2	0.4	5	c	c	c	c	c	c	c
19	0.3	0.8	2.7	5	O	O	O	O	O	O	O
23	0.3	0.6	2	10	o	O	O	O	O	O	O
27	0.3	0.4	1.3	15	o	O	O	O	O	O	O
38	0.2	0.6	3	10	O	O	O	O	O	O	O
41	0.2	0.4	2	10	o	O	O	O	O	O	O
43	0.2	0.2	1	5	c	c	o	o	O	O	O
56	0.15	0.4	2.7	10	O	O	O	O	O	O	O
60	0.15	0.2	1.3	15	c	o	O	O	O	O	O

Ho's results (by letters)	c	Clear
	o	Shallow smoke layer
	O	Deep smoke layer
Current Experiment Result (by color)		Clear
		Shallow smoke layer
		Deep smoke layer

4.3.4 Correlations

The core of this project is centered on the generation of the design correlations which will assist designers enhances Atrium in terms of smoke contamination safety. There are three correlations, one for each level category wherein the parameters involved are balcony breadth (m), smoke plume width (m), smoke layer height at spill edge (m), and the smoke contamination height (m). Tables 7,8, and 9 includes all the parameters used for producing the correlation for 3,5, and 7 levels respectively.

Table 7: Summary of results of simulated 3 level Atrium configuration

Experiment 3 Levels	H (m)	b (m)	w (m)	d (m)	H/b	w/d
1	3.12	0.50	1.0	0.68	6.24	1.47
3	2.38	0.50	1.0	0.73	4.76	1.37
8	7.23	0.50	0.6	0.82	14.46	0.73
13	0	0.50	0.1	0.98	0	0
19	1.85	0.30	0.8	0.78	6.17	1.03
23	3.25	0.30	0.6	0.98	10.83	0.61
27	6.8	0.30	0.4	1.22	22.67	0.33
38	2.5	0.20	0.6	1.49	12.50	0.40
41	6.68	0.20	0.4	1.75	33.40	0.23
43	11.75	0.20	0.2	1.66	58.75	0.12
56	1.7	0.15	0.4	1.97	11.33	0.20
60	2.2	0.15	0.2	2.14	14.67	0.09

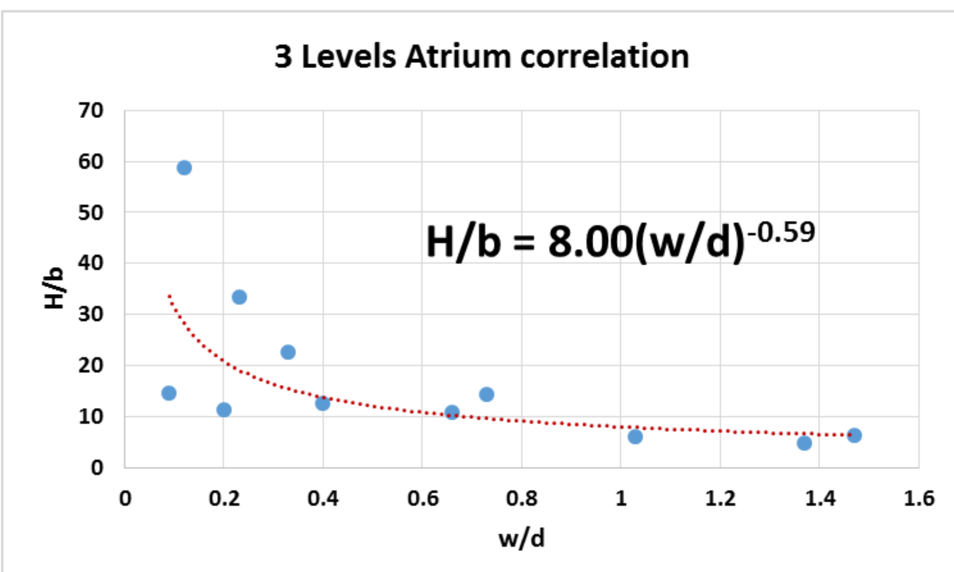


Figure 19: 3 levels Atrium correlation

Likewise for figures 20, 21, and 22 they show the new produced correlations with the respective graphs for 3,5, and 7 Atrium levels respectively.

Table 8: Summary of results of simulated 5 level Atrium configuration

Experiment 5 Levels	H (m)	b (m)	w (m)	d (m)	H/b	w/d
1	3.23	0.50	1.0	0.68	6.46	1.47
3	3.35	0.50	1.0	0.72	6.70	1.39
8	6.5	0.50	0.6	0.8	13.00	0.75
13	0	0.50	0.1	0.99	0	0
19	1.2	0.30	0.8	0.81	4.00	0.99
23	3.54	0.30	0.6	1	11.80	0.60
27	6.9	0.30	0.4	1.19	23.00	0.34
38	1.6	0.20	0.6	1.47	8.00	0.41
41	2.9	0.20	0.4	1.71	14.50	0.23
43	10.7	0.20	0.2	1.65	53.50	0.12
56	1.4	0.15	0.4	1.96	9.33	0.20
60	3.6	0.15	0.2	2.13	24.00	0.09

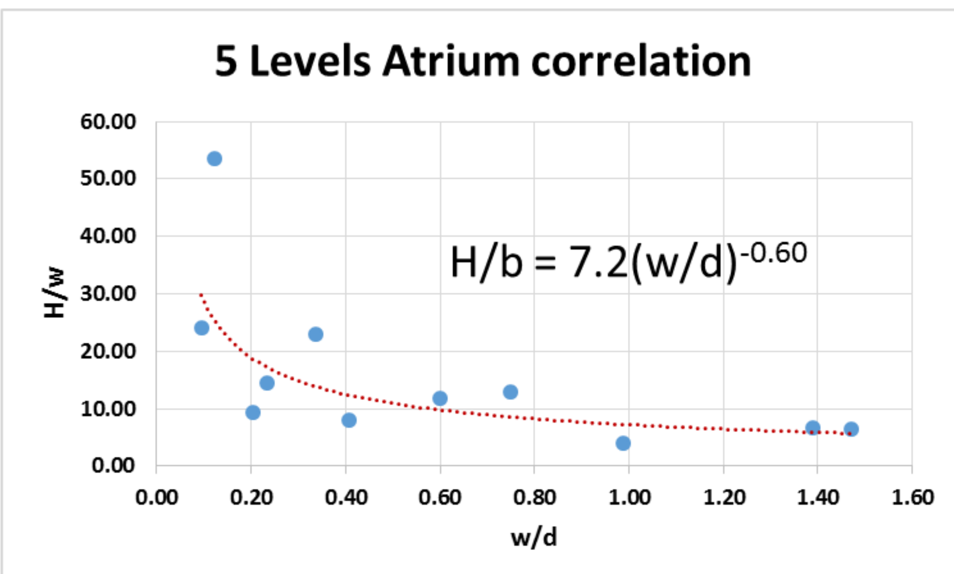


Figure 20: 5 levels Atrium correlation

Table 9: Summary of results of simulated 7 level Atrium configuration

Experiment 7 Levels	H (m)	b (m)	w (m)	d (m)	H/b	w/d
1	0.8	0.50	1.0	0.7	1.60	1.43
3	0.6	0.50	1.0	0.72	1.20	1.39
8	2.7	0.50	0.6	0.8	5.40	0.75
13	0	0.50	0.1	0.97	0	0
19	1.1	0.30	0.8	0.76	3.67	1.05
23	3.15	0.30	0.6	0.97	10.50	0.62
27	6.8	0.30	0.4	1.21	22.67	0.33
38	0.9	0.20	0.6	1.54	4.50	0.39
41	1.8	0.20	0.4	1.75	9.00	0.23
43	10.9	0.20	0.2	1.64	54.50	0.12
56	0.8	0.15	0.4	1.99	5.33	0.20
60	2.4	0.15	0.2	2.13	16.00	0.09

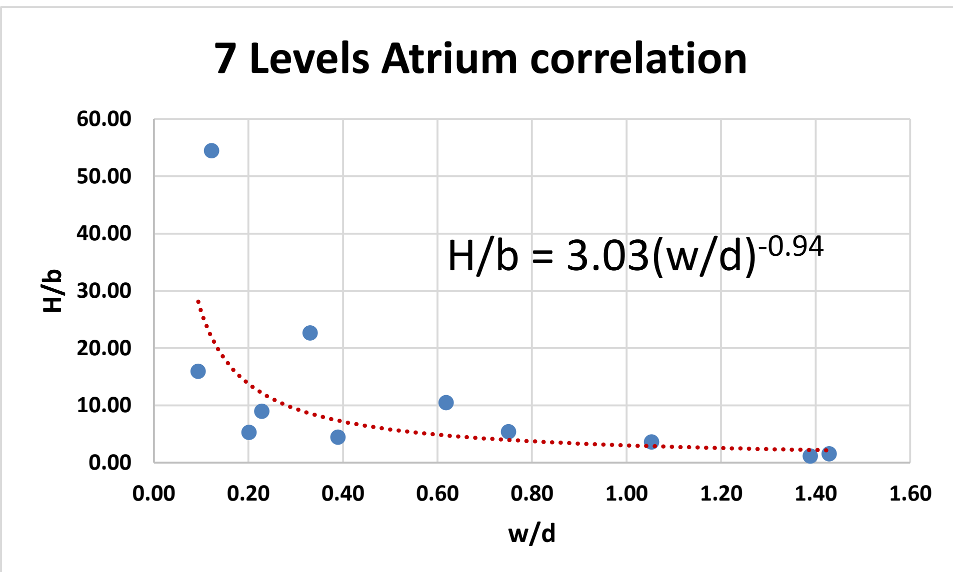


Figure 21: 7 levels Atrium correlation

4.4 Discussion

4.4.1 Delay of Smoke Contamination at Upper Balcony

It has been noticed that smoke contamination is delayed at upper balcony in some cases. The main factors that change the velocity of smoke discharge from fire compartment are the compartment opening (plume width), and the fire size. In the case of wide exist and small fire as in figure 23 (A), the smoke tend to attach to the balcony directly without delay. However, figure 23 (B) represents the other case where the exist is narrow with large fire, wherefore the smoke is discharged far away from the balcony causing the delay of reattachment and contamination.

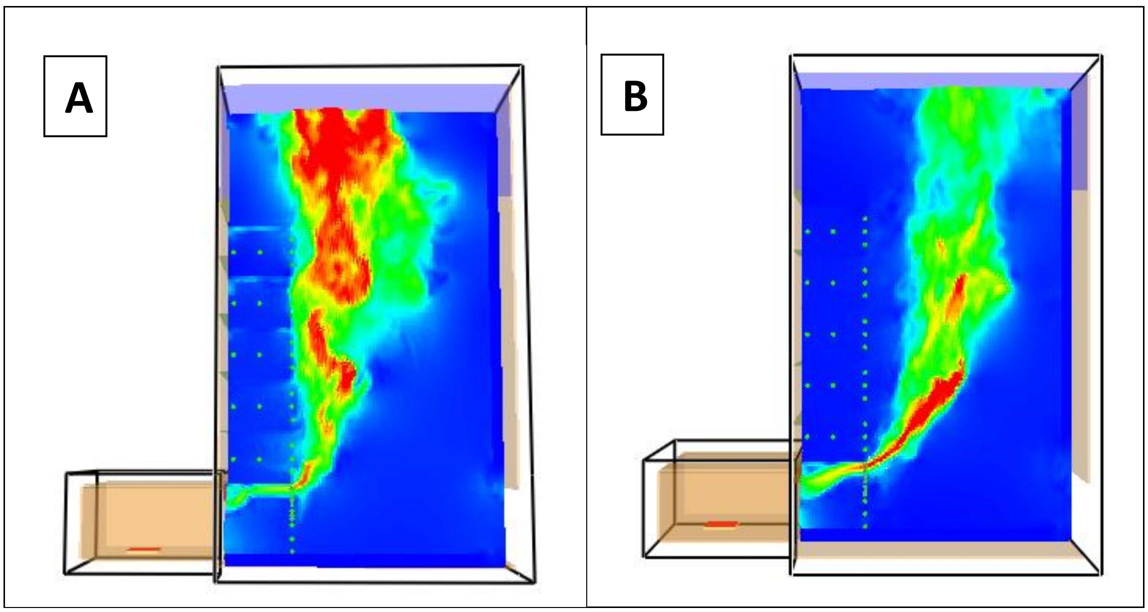


Figure 22: Delay of smoke contamination

4.4.2 Mechanism for Re-attachment

From the simulation, it is clear that there is a pressure change inside and outside the balconies. Velocity vectors are used to spot that change by visualizing the plume and its movements. Figure 24, visualizes experiment 23 for 3 level Atrium, and the color variation indicates numeric value difference for air velocity. It is vivid that air is entrained into the smoke plume from the balcony air causing the plume to be larger and hence increase smoke contamination.

.

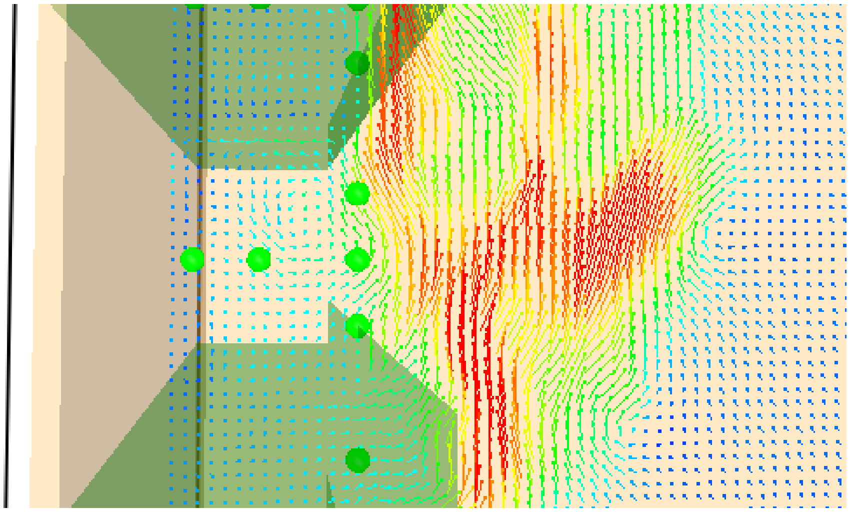


Figure 23: Smoke-view air Re-attachment

4.4.3 Smoke Contamination Starts from the Highest Balcony

The simulations showed that smoke contamination begins from the highest balcony and gradually move downwards. The reason beyond that could be the increment of air entrainment while spill plume is rising. Figure 25 illustrates the movement of air represented be the vectors and the profile color, which point to the entrainment of air towards the spill plume.

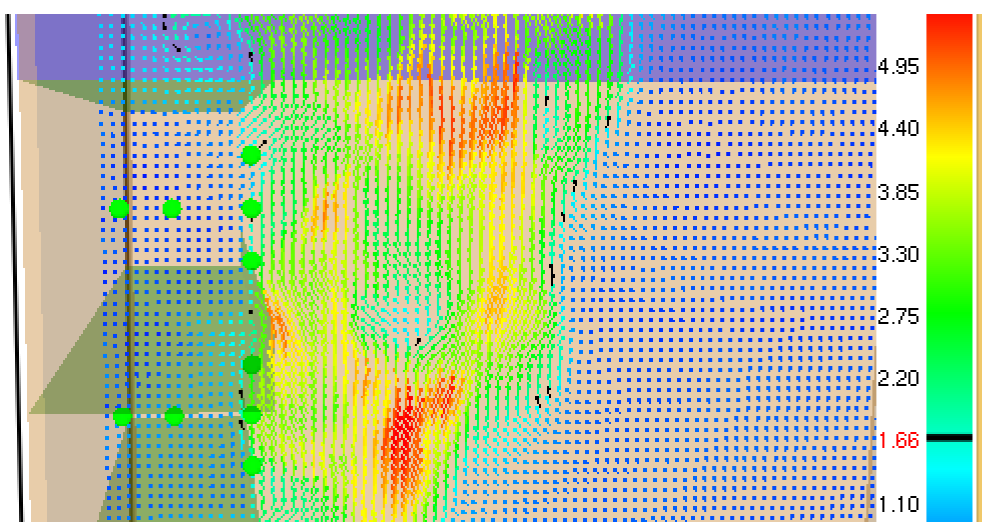


Figure 24: Smoke-view air entrainment in a balcony

4.4.4 Cause of Increased Smoke Contamination in Higher Atrium

The level of smoke contamination is directly proportional to the Atrium height. As the height increases, smoke contamination increases. Tables 4, 5, and 6 show the severity of smoke contamination of 3, 5, and 7 level Atria where a quick glance comparing same experiment from different categories proves that.

As spill plume rises toward the top of the Atrium, it encounters air entrainment, which will enlarge the cross-section of the plume, and in turn higher differential pressure will be created.

For the case of high rising atrium, the pressure difference will be higher wherein it will push the spill plume toward the balcony causing smoke contamination.

One of the major causes that would lead to higher smoke contamination is the presence of down stand structures especially in shopping malls where it is used to display the brand name.

CHAPTER 5: CONCLUSION AND REOMMENDATIONS

5.1 Conclusion

Smoke contamination jeopardy and wide spread construction of atriums were the main drivers for this research as it aims to propose an enhanced correlation that could assist engineers and architects during the process of designs of atria for the sake of optimum safety. Past researches have not studied the effect of down stand structure at fire compartment opening on smoke contamination in upper balconies of the atrium.

Fire dynamics simulator (FDS) has been utilized as a CFD software in order to develop 12 primary scenarios of fully scaled models of Tan (2009) small scale models. The outcomes of the research are fruitful and as planned. Eventually, FYP‘s long term objectives have been successfully accomplished.

The results obtained enabled the researcher to successfully producing new correlation that depicts the behavior of smoke in Atrium (3, 5, and 7 levels). There are moderate differences in the smoke layer height compared to previous findings attained by Tan et al. (2009) and Ho et al. (2010) due to the presence of down stand structures.

Developing a model via FDS requires high level of competency as the boundary conditions are sensitive towards the accuracy of the results. The major hardship in using FDS is that it does not have a flexible interface where clicking and dragging are direct ways of designing. Therefore, commands have to be written as a text file saved as a notepad file with the extension (.fds). Another problem faced was that each simulation of the 36 case needed around 50 continuous hours of running, hence the researcher utilized the lab computers but occasionally some simulations were shut down by user, which created the necessity of monitoring the computers frequently up to the end of each simulation.

5.2 Recommendations

The researcher encourages for further future research regarding the topic in order to produce a collective correlation that include the number of levels as a major factor instead of having specific correlation for certain Atrium height.

Ultimately, the researcher strongly recommends the use of the new developed correlations especially for architects and engineers encountered with direct Atrium design. The new correlations ensure higher safety standards in the incidents of fire where smoke contamination is expected to take place in upper balconies.

Eventually, it is recommended that further research should consider developing new correlation that includes the atrium height as a variable in the new correlation equation.

REFERENCES

Bastings, D. (1988). *Fire Saftey in Atrium Buildings.* Judgeford: Building Reseach Association of New Zealand.

Buchanan , A. (2002). *Structural Design for Fire Safety.* England: John Wiley & Sons, Ltd.

Drysdale, D. (1998). *An Introduction to Fire Dynamics* (2nd Edition ed.). England: John Wiley & Sons.

Harrison, R., & Spearpoint, M. (2004). Smoke Control in Atrium Building: A Study of the Thermal Spill Plume.

Harrison, R., & Spearpoint, M. (2007). The Balcony Spill Plume: Entrainment of Air into a Flow from a Comparment Opening to a higher Projecting Balcony . *Fire Technology*.

Harrison, R., Spearpoint, M., & Fleischmann, C. (2009). Entrainment of Air into Thermal Spill Plume.

Hasnain, S., Nasif, M., Pao, W., & Al-Waked, R. (2013). Numerical investigation on the effect of down stand structure in fire compartment on smoke contamination atrium upper balconies.

Ho, C. (2010). Simulation of smoke contamination in upper balcony by a channelled balcony spill. *Fire Engineering Research Report*.

Ho, C., Li, K., & Spearpoint, M. (2012). Numerical simulation of scale-model smoke contamination of upper atrium levels by a channelled balcony spill plume.

James, A. M., Avidor, E. (., Joseph A. Brooks, Buckley, J. B., Butterworth, L. A., Cahill, C. S., . . . Shudak, L. J. (2005). *NFPA 92B Standard for Smoke Management Systems in Malls, Atria, and Large spaces.* National Fire Protection Association.

Karlsson , B., & Quintiere, G. (2000). *Enclosure Fire Dynamics.* CRC Press. Washington DC.

Klote, J., & Milke, J. (2002). *Principles of Smoke Management.* Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers.

Tan, F., Harrison, R., & Spearpoint, M. (2009). Physical Scale Modeling of Smoke Contamination in Upper Balconies Spill Plume in an Atrium. *Fire Sciences OnlineFirst*.

APPENDIX

FDS input for exp1 – 7L written in a notepad.

```
&HEAD CHID='exp1',TITLE='7L'/


&MESH IJK=105.0,108.0,215.0, XB=0.0,21.0,-0.8,20.8,-1.0,42.0/200mm mesh size for Atrium domain

&MESH IJK=55.0,60.0,37.0, XB=-11.0,0.0,4.0,16.0,-1.2,6.2/200mm mesh size for fire compartment


&TIME T_END=600./


/&MISC RESTART = .TRUE./ RESUME

&VENT MB='XMIN', SURF_ID='OPEN'/

&VENT MB='XMAX', SURF_ID='OPEN'/

&VENT MB='YMIN', SURF_ID='OPEN'/

&VENT MB='YMAX', SURF_ID='OPEN'/

&VENT MB='ZMIN', SURF_ID='OPEN'/

&VENT MB='ZMAX', SURF_ID='OPEN'/


/DEFINING A BURNING OBJECT

&REAC ID='Ethanol'

        C = 2

        H = 6

        O = 1

        HEAT_OF_COMBUSTION = 26800

        CO_YIELD = 0.022

        SOOT_YIELD = 0.11/ Ethanol properties
```

```
-----------------------------------------------------------

/Materials

&MISC SURF_DEFAULT='CFI board'/

&MATL ID='CFI board'

        CONDUCTIVITY = 0.041

        SPECIFIC_HEAT = 0.82

        DENSITY = 229.0/

&SURF ID='CFI board'

        MATL_ID = 'CFI board'

        COLOR = 'BRICK'

        TRANSPARENCY = 0.4

        BACKING = 'VOID'

        THICKNESS = 0.16 / wall properties


&SURF ID = 'STEEL SHEET'

        MATL_ID = 'STEEL'

        COLOR = 'KELLY GREEN'

        BACKING = 'VOID'

        THICKNESS = 0.01

        TRANSPARENCY = 0.4/ STRUCTURAL DESIGN FOR FIRE SAFETY TABLE 3.4

&MATL ID = 'STEEL'

        CONDUCTIVITY = 45.8

        SPECIFIC_HEAT =0.46

        DENSITY = 7850.0/

&SURF ID = 'PERSPEX SHEET'
```

```
        MATL_ID = 'PERSPEX'

        COLOR = 'BLUE'

        BACKING = 'VOID'

        THICKNESS = 0.12

        TRANSPARENCY = 0.4/ FROM HARRISON (2009)

&MATL ID = 'PERSPEX'

        CONDUCTIVITY = 0.19

        SPECIFIC_HEAT =1.42

        DENSITY = 1190.0/


----------------------------------------------------------

/Obstacle dimensions - b=5m - w=10m

/FIRE SIZE

&SURF ID = 'BURNER', HRRPUA = 252.96, COLOR = 'RED'/ To use with 1581kW

/Atruim walls

&OBST XB= 0.0,20.16,-0.12,0.0,33.0,41.0, SURF_ID='PERSPEX SHEET'/ Acrylic glass wall

&OBST XB= 0.0,20.16,20.0,20.16,5.0,41.0/ N wall

&OBST XB= 0.0,0.16,0.0,20.0,5.0,41.0/ W wall

&OBST XB= 20.16,20.32,0.0,20.16,5.0,41.0/ E wall

&OBST XB= 0.0,20.0,0.0,20.0,-0.16,0.0/ The ground floor


/Fire compartment walls

&OBST XB= -10.0,0.0,4.84,5.0,0.0,5.0/ S wall

&OBST XB= -10.0,0.0,15.0,15.16,0.0,5.0/ N wall

&OBST XB= -10.16,-10.0,5.0,15.0,0.0,5.0/ W wall

&OBST XB= -10.0,0.0,5.0,15.0,5.0,5.16/ ceilling
```

&OBST XB= -10.0,0.0,5.0,15.0,-0.16,0.0/ ground

/Balconies & downstand

&OBST XB=0.0,5.0,0.0,20.0,5.0,5.01, COLOR='BRICK' ,TRANSPARENCY = 0.7/BALCONY 1 - FLOOR

&OBST XB=4.99,5.0,0.0,20.0,5.0,6.0, SURF_ID = 'STEEL SHEET'/BALCONY 1 - upstand

&OBST XB=0.0,0.01,5.0,15.0,4.0,5.0, COLOR='FIREBRICK', SURF_ID = 'STEEL SHEET'/BALCONY 1 - DOWN STAND

&OBST XB=0.0,5.0,0.0,20.0,9.0,9.01, SURF_ID = 'STEEL SHEET'/BALCONY 2 - FLOOR

&OBST XB=4.99,5.0,0.0,20.0,9.0,10.0, SURF_ID = 'STEEL SHEET'/BALCONY 2 - upstand

&OBST XB=0.0,5.0,0.0,20.0,13.0,13.01, SURF_ID = 'STEEL SHEET'/BALCONY 3 - FLOOR

&OBST XB=4.99,5.0,0.0,20.0,13.0,14.0, SURF_ID = 'STEEL SHEET'/BALCONY 3 - upstand

&OBST XB=0.0,5.0,0.0,20.0,17.0,17.01, SURF_ID = 'STEEL SHEET'/ BALCONY 4 - FLOOR

&OBST XB=4.99,5.0,0.0,20.0,17.0,18.0, SURF_ID = 'STEEL SHEET'/BALCONY 4 - upstand

&OBST XB=0.0,5.0,0.0,20.0,21.0,21.01, SURF_ID = 'STEEL SHEET'/BALCONY 5 - FLOOR

&OBST XB=4.99,5.0,0.0,20.0,21.0,22.0, SURF_ID = 'STEEL SHEET'/BALCONY 5 - upstand

&OBST XB=0.0,5.0,0.0,20.0,25.0,25.01, SURF_ID = 'STEEL SHEET'/BALCONY 6 - FLOOR

&OBST XB=4.99,5.0,0.0,20.0,25.0,26.0, SURF_ID = 'STEEL SHEET'/BALCONY 6 - upstand

&OBST XB=0.0,5.0,0.0,20.0,29.0,29.01, SURF_ID = 'STEEL SHEET'/BALCONY 7 - FLOOR

&OBST XB=4.99,5.0,0.0,20.0,29.0,30.0, SURF_ID = 'STEEL SHEET'/BALCONY 7 - upstand

&OBST XB=0.0,5.0,0.0,20.0,33.0,33.01, SURF_ID = 'STEEL SHEET'/BALCONY 7 - CEILING FOR BALCONY

/CHANNEL SCREEN - PLUME WIDTH - & OPENING = 10.0M

&OBST XB = 0.0, 5.0, 4.84, 5.0, 2.5, 5.0, COLOR='BLUE VIOLET',TRANSPARENCY = 0.4/ S CHANNEL

&OBST XB = 0.0, 5.0, 15.0, 15.16, 2.5, 5.0, COLOR='BLUE VIOLET',TRANSPARENCY = 0.4/ S CHANNEL

&HOLE XB = 0.0, 4.0, 5.0, 15.0, 0.0, 4.0/ FRONT OPENING

/Fire obstclae dimensions 2.5mx2.5mx0.15m

&OBST XB=-7.5,-5.0,8.75,11.25,0.0,0.15, SURF_IDs='BURNER','INERT','INERT'/Burner location and dimensions

----

/Sensors

/Slice File

&SLCF PBX = 5.0, QUANTITY = 'VISIBILITY'/

&SLCF PBY = 10.0, QUANTITY = 'VISIBILITY'/

&SLCF PBX = 5.0, QUANTITY = 'TEMPERATURE'/

&SLCF PBX = 2.5, QUANTITY = 'TEMPERATURE'/

&SLCF PBX = 5.0, QUANTITY = 'carbon dioxide'/

&SLCF PBX = 5.0, QUANTITY = 'carbon monoxide'/

&SLCF PBX = 5.0, QUANTITY = 'PRESSURE'/

&SLCF PBX = 5.0, QUANTITY = 'oxygen'/

&SLCF PBX = 5.0, QUANTITY = 'VELOCITY', VECTOR=.TRUE./

&SLCF PBY = 10.0, QUANTITY = 'TEMPERATURE'/

&SLCF PBY = 10.0, QUANTITY = 'VELOCITY', VECTOR=.TRUE./

&SLCF PBY = 17.5, QUANTITY = 'VISIBILITY'/

&SLCF PBY = 17.5, QUANTITY = 'TEMPERATURE'/

&SLCF PBY = 17.5, QUANTITY = 'carbon dioxide'/

&SLCF PBY = 17.5, QUANTITY = 'carbon monoxide'/

&SLCF PBY = 17.5, QUANTITY = 'PRESSURE'/

&SLCF PBX = 7.5, QUANTITY = 'oxygen'/

/EXTRA SLCF TO SEE THE PRESSURE DISTRIBUTION AT 2M ABOVE EACH BALCONY

&SLCF PBZ = 7.0, QUANTITY = 'PRESSURE'/

&SLCF PBZ = 11.0, QUANTITY = 'PRESSURE'/

&SLCF PBZ = 15.0, QUANTITY = 'PRESSURE'/

```
&SLCF PBZ = 19.0, QUANTITY = 'PRESSURE'/

&SLCF PBZ = 23.0, QUANTITY = 'PRESSURE'/

&SLCF PBZ = 7.0, QUANTITY = 'VISIBILITY'/

&SLCF PBZ = 11.0, QUANTITY = 'VISIBILITY'/

&SLCF PBZ = 15.0, QUANTITY = 'VISIBILITY'/

&SLCF PBZ = 19.0, QUANTITY = 'VISIBILITY'/

&SLCF PBZ = 23.0, QUANTITY = 'VISIBILITY'/

&SLCF PBZ = 7.0, QUANTITY = 'TEMPERATURE'/

&SLCF PBZ = 11.0, QUANTITY = 'TEMPERATURE'/

&SLCF PBZ = 15.0, QUANTITY = 'TEMPERATURE'/

&SLCF PBZ = 19.0, QUANTITY = 'TEMPERATURE'/

&SLCF PBZ = 23.0, QUANTITY = 'TEMPERATURE'/

&SLCF PBZ = 7.0, QUANTITY = 'carbon dioxide'/

&SLCF PBZ = 11.0, QUANTITY = 'carbon dioxide'/

&SLCF PBZ = 15.0, QUANTITY = 'carbon dioxide'/

&SLCF PBZ = 19.0, QUANTITY = 'carbon dioxide'/

&SLCF PBZ = 23.0, QUANTITY = 'carbon dioxide'/

&SLCF PBZ = 7.0, QUANTITY = 'carbon monoxide'/

&SLCF PBZ = 11.0, QUANTITY = 'carbon monoxide'/

&SLCF PBZ = 15.0, QUANTITY = 'carbon monoxide'/

&SLCF PBZ = 19.0, QUANTITY = 'carbon monoxide'/

&SLCF PBZ = 23.0, QUANTITY = 'carbon monoxide'/

&SLCF PBZ = 7.0, QUANTITY = 'oxygen'/

&SLCF PBZ = 11.0, QUANTITY = 'oxygen'/

&SLCF PBZ = 15.0, QUANTITY = 'oxygen'/

&SLCF PBZ = 19.0, QUANTITY = 'oxygen'/
```

```
&SLCF PBZ = 23.0, QUANTITY = 'oxygen'/

/TEMPERATURE SENSOR FOR COLUMN A, IMMEDIATELY OUTSIDE THE FIRE CELL

&DEVC XYZ = 5.0, 10.0, 4.7, QUANTITY = 'TEMPERATURE', ID = 'T-A1'/ 0.3M BELOW BALCONY 1

&DEVC XYZ = 5.0, 10.0, 4.3, QUANTITY = 'TEMPERATURE', ID = 'T-A2'/ 0.7M BELOW BALCONY 1

&DEVC XYZ = 5.0, 10.0, 3.9, QUANTITY = 'TEMPERATURE', ID = 'T-A3'/ 1.1M BELOW BALCONY 1

&DEVC XYZ = 5.0, 10.0, 3.5, QUANTITY = 'TEMPERATURE', ID = 'T-A4'/ 1.5M BELOW BALCONY 1

&DEVC XYZ = 5.0, 10.0, 3.1, QUANTITY = 'TEMPERATURE', ID = 'T-A5'/ 1.9M BELOW BALCONY 1

&DEVC XYZ = 5.0, 10.0, 2.7, QUANTITY = 'TEMPERATURE', ID = 'T-A6'/ 2.3M BELOW BALCONY 1

&DEVC XYZ = 5.0, 10.0, 2.0, QUANTITY = 'TEMPERATURE', ID = 'T-A7'/ 3.0M BELOW BALCONY 1

&DEVC XYZ = 5.0, 10.0, 1.0, QUANTITY = 'TEMPERATURE', ID = 'T-A8'/ 4.0M BELOW BALCONY 1

&DEVC XYZ = 5.0, 10.0, 0.0, QUANTITY = 'TEMPERATURE', ID = 'T-A9'/ 5.0M BELOW BALCONY 1


/CHECK LAYER HEIGHT

&DEVC XB = 5.0, 5.0, 10.0, 10.0, 0.0, 5.0, QUANTITY = 'LAYER HEIGHT', ID = 'LAY-A1'/


/TEMPERATURE SENSOR FOR COLUMN B, IMMEDIATELY OUTSIDE THE BALCONY

&DEVC XYZ = 5.0, 10.0, 6.0, QUANTITY = 'TEMPERATURE', ID = 'T-B01'/ 1.0M ABOVE BALCONY 1

&DEVC XYZ = 5.0, 10.0, 7.0, QUANTITY = 'TEMPERATURE', ID = 'T-B02'/ 2.0M ABOVE BALCONY 1

&DEVC XYZ = 5.0, 10.0, 8.0, QUANTITY = 'TEMPERATURE', ID = 'T-B03'/ 3.0M ABOVE BALCONY 1

&DEVC XYZ = 5.0, 10.0, 10.0, QUANTITY = 'TEMPERATURE', ID = 'T-B04'/ 5.0M ABOVE BALCONY 1

&DEVC XYZ = 5.0, 10.0, 11.0, QUANTITY = 'TEMPERATURE', ID = 'T-B05'/ 6.0M ABOVE BALCONY 1

&DEVC XYZ = 5.0, 10.0, 12.0, QUANTITY = 'TEMPERATURE', ID = 'T-B06'/ 7.0M ABOVE BALCONY 1

&DEVC XYZ = 5.0, 10.0, 14.0, QUANTITY = 'TEMPERATURE', ID = 'T-B07'/ 9.0M ABOVE BALCONY 1

&DEVC XYZ = 5.0, 10.0, 15.0, QUANTITY = 'TEMPERATURE', ID = 'T-B08'/ 10.0M ABOVE BALCONY 1

&DEVC XYZ = 5.0, 10.0, 16.0, QUANTITY = 'TEMPERATURE', ID = 'T-B09'/ 11.0M ABOVE BALCONY 1

&DEVC XYZ = 5.0, 10.0, 18.0, QUANTITY = 'TEMPERATURE', ID = 'T-B10'/ 13.0M ABOVE BALCONY 1
```

&DEVC XYZ = 5.0, 10.0, 19.0, QUANTITY = 'TEMPERATURE', ID = 'T-B11'/ 14.0M ABOVE BALCONY 1

&DEVC XYZ = 5.0, 10.0, 20.0, QUANTITY = 'TEMPERATURE', ID = 'T-B12'/ 15.0M ABOVE BALCONY 1

&DEVC XYZ = 5.0, 10.0, 22.0, QUANTITY = 'TEMPERATURE', ID = 'T-B13'/ 17.0M ABOVE BALCONY 1

&DEVC XYZ = 5.0, 10.0, 23.0, QUANTITY = 'TEMPERATURE', ID = 'T-B14'/ 18.0M ABOVE BALCONY 1

&DEVC XYZ = 5.0, 10.0, 24.0, QUANTITY = 'TEMPERATURE', ID = 'T-B15'/ 19.0M ABOVE BALCONY 1

&DEVC XYZ = 5.0, 10.0, 26.0, QUANTITY = 'TEMPERATURE', ID = 'T-B16'/ 21.0M ABOVE BALCONY 1

&DEVC XYZ = 5.0, 10.0, 27.0, QUANTITY = 'TEMPERATURE', ID = 'T-B17'/ 22.0M ABOVE BALCONY 1

&DEVC XYZ = 5.0, 10.0, 28.0, QUANTITY = 'TEMPERATURE', ID = 'T-B18'/ 23.0M ABOVE BALCONY 1

&DEVC XYZ = 5.0, 10.0, 30.0, QUANTITY = 'TEMPERATURE', ID = 'T-B19'/ 25.0M ABOVE BALCONY 1

&DEVC XYZ = 5.0, 10.0, 31.0, QUANTITY = 'TEMPERATURE', ID = 'T-B20'/ 26.0M ABOVE BALCONY 1

&DEVC XYZ = 5.0, 10.0, 32.0, QUANTITY = 'TEMPERATURE', ID = 'T-B21'/ 27.0M ABOVE BALCONY 1

/VISIBILITY SENSOR FOR COLUMN B, IMMEDIATELY OUTSIDE THE BALCONY

&DEVC XYZ = 5.0, 10.0, 6.0, QUANTITY = 'VISIBILITY', ID = 'V-B01'/ 1.0M ABOVE BALCONY 1

&DEVC XYZ = 5.0, 10.0, 7.0, QUANTITY = 'VISIBILITY', ID = 'V-B02'/ 2.0M ABOVE BALCONY 1

&DEVC XYZ = 5.0, 10.0, 8.0, QUANTITY = 'VISIBILITY', ID = 'V-B03'/ 3.0M ABOVE BALCONY 1

&DEVC XYZ = 5.0, 10.0, 10.0, QUANTITY = 'VISIBILITY', ID = 'V-B04'/ 5.0M ABOVE BALCONY 1

&DEVC XYZ = 5.0, 10.0, 11.0, QUANTITY = 'VISIBILITY', ID = 'V-B05'/ 6.0M ABOVE BALCONY 1

&DEVC XYZ = 5.0, 10.0, 12.0, QUANTITY = 'VISIBILITY', ID = 'V-B06'/ 7.0M ABOVE BALCONY 1

&DEVC XYZ = 5.0, 10.0, 14.0, QUANTITY = 'VISIBILITY', ID = 'V-B07'/ 9.0M ABOVE BALCONY 1

&DEVC XYZ = 5.0, 10.0, 15.0, QUANTITY = 'VISIBILITY', ID = 'V-B08'/ 10.0M ABOVE BALCONY 1

&DEVC XYZ = 5.0, 10.0, 16.0, QUANTITY = 'VISIBILITY', ID = 'V-B09'/ 11.0M ABOVE BALCONY 1

&DEVC XYZ = 5.0, 10.0, 18.0, QUANTITY = 'VISIBILITY', ID = 'V-B10'/ 13.0M ABOVE BALCONY 1

&DEVC XYZ = 5.0, 10.0, 19.0, QUANTITY = 'VISIBILITY', ID = 'V-B11'/ 14.0M ABOVE BALCONY 1

&DEVC XYZ = 5.0, 10.0, 20.0, QUANTITY = 'VISIBILITY', ID = 'V-B12'/ 15.0M ABOVE BALCONY 1

&DEVC XYZ = 5.0, 10.0, 22.0, QUANTITY = 'VISIBILITY', ID = 'V-B13'/ 17.0M ABOVE BALCONY 1

&DEVC XYZ = 5.0, 10.0, 23.0, QUANTITY = 'VISIBILITY', ID = 'V-B14'/ 18.0M ABOVE BALCONY 1

&DEVC XYZ = 5.0, 10.0, 24.0, QUANTITY = 'VISIBILITY', ID = 'V-B15'/ 19.0M ABOVE BALCONY 1

&DEVC XYZ = 5.0, 10.0, 26.0, QUANTITY = 'VISIBILITY', ID = 'V-B16'/ 21.0M ABOVE BALCONY 1

&DEVC XYZ = 5.0, 10.0, 27.0, QUANTITY = 'VISIBILITY', ID = 'V-B17'/ 22.0M ABOVE BALCONY 1

&DEVC XYZ = 5.0, 10.0, 28.0, QUANTITY = 'VISIBILITY', ID = 'V-B18'/ 23.0M ABOVE BALCONY 1

&DEVC XYZ = 5.0, 10.0, 30.0, QUANTITY = 'VISIBILITY', ID = 'V-B19'/ 25.0M ABOVE BALCONY 1

&DEVC XYZ = 5.0, 10.0, 31.0, QUANTITY = 'VISIBILITY', ID = 'V-B20'/ 26.0M ABOVE BALCONY 1

&DEVC XYZ = 5.0, 10.0, 32.0, QUANTITY = 'VISIBILITY', ID = 'V-B21'/ 27.0M ABOVE BALCONY 1

/TEMPERATURE SENSOR FOR COLUMN C, INSIDE THE BALCONY

&DEVC XYZ = 0.5, 10.0, 7.0, QUANTITY = 'TEMPERATURE', ID = 'T-C1O'/ 2.0M ABOVE BALCONY 1

&DEVC XYZ = 2.5, 10.0, 7.0, QUANTITY = 'TEMPERATURE', ID = 'T-C1I'/ 2.0M ABOVE BALCONY 1

&DEVC XYZ = 0.5, 10.0, 11.0, QUANTITY = 'TEMPERATURE', ID = 'T-C2O'/ 2.0M ABOVE BALCONY 2

&DEVC XYZ = 2.5, 10.0, 11.0, QUANTITY = 'TEMPERATURE', ID = 'T-C2I'/ 2.0M ABOVE BALCONY 2

&DEVC XYZ = 0.5, 10.0, 15.0, QUANTITY = 'TEMPERATURE', ID = 'T-C3O'/ 2.0M ABOVE BALCONY 3

&DEVC XYZ = 2.5, 10.0, 15.0, QUANTITY = 'TEMPERATURE', ID = 'T-C3I'/ 2.0M ABOVE BALCONY 3

&DEVC XYZ = 0.5, 10.0, 19.0, QUANTITY = 'TEMPERATURE', ID = 'T-C4O'/ 2.0M ABOVE BALCONY 4

&DEVC XYZ = 2.5, 10.0, 19.0, QUANTITY = 'TEMPERATURE', ID = 'T-C4I'/ 2.0M ABOVE BALCONY 4

&DEVC XYZ = 0.5, 10.0, 23.0, QUANTITY = 'TEMPERATURE', ID = 'T-C5O'/ 2.0M ABOVE BALCONY 5

&DEVC XYZ = 2.5, 10.0, 23.0, QUANTITY = 'TEMPERATURE', ID = 'T-C5I'/ 2.0M ABOVE BALCONY 5

&DEVC XYZ = 0.5, 10.0, 27.0, QUANTITY = 'TEMPERATURE', ID = 'T-C6O'/ 2.0M ABOVE BALCONY 6

&DEVC XYZ = 2.5, 10.0, 27.0, QUANTITY = 'TEMPERATURE', ID = 'T-C6I'/ 2.0M ABOVE BALCONY 6

&DEVC XYZ = 0.5, 10.0, 31.0, QUANTITY = 'TEMPERATURE', ID = 'T-C7O'/ 2.0M ABOVE BALCONY 7

&DEVC XYZ = 2.5, 10.0, 31.0, QUANTITY = 'TEMPERATURE', ID = 'T-C7I'/ 2.0M ABOVE BALCONY 7

/VISIBILITY SENSOR FOR COLUMN C, INSIDE THE BALCONY

```
&DEVC XYZ = 0.5, 10.0, 7.0, QUANTITY = 'VISIBILITY', ID = 'V-C1O'/ 2.0M ABOVE BALCONY 1

&DEVC XYZ = 2.5, 10.0, 7.0, QUANTITY = 'VISIBILITY', ID = 'V-C1I'/ 2.0M ABOVE BALCONY 1

&DEVC XYZ = 0.5, 10.0, 11.0, QUANTITY = 'VISIBILITY', ID = 'V-C2O'/ 2.0M ABOVE BALCONY 2

&DEVC XYZ = 2.5, 10.0, 11.0, QUANTITY = 'VISIBILITY', ID = 'V-C2I'/ 2.0M ABOVE BALCONY 2

&DEVC XYZ = 0.5, 10.0, 15.0, QUANTITY = 'VISIBILITY', ID = 'V-C3O'/ 2.0M ABOVE BALCONY 3

&DEVC XYZ = 2.5, 10.0, 15.0, QUANTITY = 'VISIBILITY', ID = 'V-C3I'/ 2.0M ABOVE BALCONY 3

&DEVC XYZ = 0.5, 10.0, 19.0, QUANTITY = 'VISIBILITY', ID = 'V-C4O'/ 2.0M ABOVE BALCONY 4

&DEVC XYZ = 2.5, 10.0, 19.0, QUANTITY = 'VISIBILITY', ID = 'V-C4I'/ 2.0M ABOVE BALCONY 4

&DEVC XYZ = 0.5, 10.0, 23.0, QUANTITY = 'VISIBILITY', ID = 'V-C5O'/ 2.0M ABOVE BALCONY 5

&DEVC XYZ = 2.5, 10.0, 23.0, QUANTITY = 'VISIBILITY', ID = 'V-C5I'/ 2.0M ABOVE BALCONY 5

&DEVC XYZ = 0.5, 10.0, 27.0, QUANTITY = 'VISIBILITY', ID = 'V-C6O'/ 2.0M ABOVE BALCONY 6

&DEVC XYZ = 2.5, 10.0, 27.0, QUANTITY = 'VISIBILITY', ID = 'V-C6I'/ 2.0M ABOVE BALCONY 6

&DEVC XYZ = 0.5, 10.0, 31.0, QUANTITY = 'VISIBILITY', ID = 'V-C7O'/ 2.0M ABOVE BALCONY 7

&DEVC XYZ = 2.5, 10.0, 31.0, QUANTITY = 'VISIBILITY', ID = 'V-C7I'/ 2.0M ABOVE BALCONY 7


/FED SENSOR, INSIDE THE BALCONY

&DEVC XYZ = 2.5, 10.0, 7.0, QUANTITY = 'FED', ID = 'FED-1'/ 2.0M ABOVE BALCONY 1

&DEVC XYZ = 2.5, 10.0, 11.0, QUANTITY = 'FED', ID = 'FED-2'/ 2.0M ABOVE BALCONY 2

&DEVC XYZ = 2.5, 10.0, 15.0, QUANTITY = 'FED', ID = 'FED-3'/ 2.0M ABOVE BALCONY 3

&DEVC XYZ = 2.5, 10.0, 19.0, QUANTITY = 'FED', ID = 'FED-4'/ 2.0M ABOVE BALCONY 4

&DEVC XYZ = 2.5, 10.0, 23.0, QUANTITY = 'FED', ID = 'FED-5'/ 2.0M ABOVE BALCONY 5

&DEVC XYZ = 2.5, 10.0, 27.0, QUANTITY = 'FED', ID = 'FED-6'/ 2.0M ABOVE BALCONY 6

&DEVC XYZ = 2.5, 10.0, 31.0, QUANTITY = 'FED', ID = 'FED-7'/ 2.0M ABOVE BALCONY 7


&TAIL /
```