STUDY OF SMOKE PROTECTION MEASURES WITHIN HIGH RISE APARTMENTS

Mitchell Pike

Bachelor of Engineering
Mechanical Engineering

Department of Mechanical Engineering
Macquarie University

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Supervisor: Dr Ann Lee

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STATEMENT OF CANDIDATE

I, Mitchell Pike, declare that this report, submitted as part of the requirement for the award of Bachelor of Engineering in the Department of Mechanical Engineering, Macquarie University, is entirely my own work unless otherwise referenced or acknowledged. This document has not been submitted for qualification or assessment an any academic institution.

Student's Name: Mitchell Pike

Student's Signature:

Mitchell Pike

Date: 06/11/2017

ABSTRACT

This thesis intends to develop an understanding of stair pressurisation systems in high-rise residential buildings, to provide information regarding the performance of such systems in a credible evacuation scenario. Stair pressurisation systems are designed to create a smoke-proof barrier, preventing the ingress of smoke into staircases within buildings over 25m tall. Currently, all stair pressurisation systems are designed with the same commissioning requirements in mind, regardless of other factors such as height or evacuation strategies. In tall buildings, evacuation strategies can utilize phased or simultaneous evaluation of numerous stories at once. Given that the number of doors open into a stair in a credible evacuation of the building exceeds the number required to be open during system commissioning, it is possible that such a system may not perform as intended when it is required the most. This report examines the performance of a stair pressurisation with a differing number of doors open into the shaft in order to determine performance as the number of doors open at once increases. Simulations using FDS have shown that a system that would pass commissioning requirements allows smoke in the shaft if there are more than 4 doors open simultaneously, signifying the evacuation of three stories simultaneously. Past this limit, the amount of smoke which leaks into the staircases continues to increase as more doors open. Overall, the simulations conducted show a disconnect between the Australian legislation for the commissioning of smoke control systems and the evacuation methodology used in taller building, signifying a necessity to create an interface between the commissioning of systems and credible scenarios in an emergency.

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Chapter 1

Introduction

1.1 Project Overview

As high-rise buildings continue to grow in height, the evacuation of occupants in emergency situations is becoming more and more difficult, especially in emergencies related to fire where smoke can very quickly reduce visibility along egress paths. The current provisions mandated in the National Construction Code (NCC) and the Building Code of Australia (BCA) for smoke control and detection remains unchanged for all buildings over 25m in height, with no consideration of the superstructures of the future.

Smoke control systems are relied upon for safe egress in high rise buildings, in particular stair pressurisation systems. If smoke is allowed to pass into stairs occupants could be prevented from using them to escape, effectively trapping them. Even small amounts of smoke could deter occupants on higher floor from entering a staircase to exit the building.

Stair pressurisation has been in use for decades as a measure for protection fire-isolated construction but as buildings continue to grow in height it is important to consider if this is still adequate, especially when zone type smoke control systems are required in other categories of buildings, including retail and office spaces.

Given that the smoke control systems provided to buildings are the sole line of defence against untenable visibility limits, it is important that Australian building codes and design standards mandate appropriate systems and continue to adapt as the culture of construction adapts.

1.2 Project Rationale

Australia has currently experienced a massive influx in residential apartment blocks being approved and constructed, with residential apartments expected to grow in price by 21% by 2021 [7]. Due to the higher population densities being found in major cities around Australia and the minimal space available for development there has been a recent trend towards higher buildings, not just in Australia but around the world. Due to this increasing height, life safety is becoming an increasingly important concern, since high rise buildings present unique challenges with respect to fire brigade intervention and occupant egress.

Recently, the usefulness of stair pressurisation systems in these high-rise buildings has been questioned due to their 'one size fits all' design rationale. Stair pressurisation systems are flawed in that they do nothing to prevent the flow and build-up of smoke in residential common corridors, and only function to prevent the flow of smoke into fire-isolated staircases. In smaller buildings, this is adequate because occupants must only travel small vertical distances and may receive earlier notification of threats allowing everyone to leave prior to the onset of untenable conditions in the corridors. There is a relatively new smoke control system which has been introduced overseas that has been used to provide higher levels of life safety in residential apartments by providing individual smoke exhaust in each corridor, helping to prevent the build-up of smoke and heat, allowing occupants considerably more time before the onset of untenable conditions.

The purpose of this thesis is to assess the ability for currently designed stair pressurisation systems to maintain tenable conditions for occupants in tall buildings, where evacuations are time consuming and require significant travel through stair shafts. Currently, a one size fits all approach is adopted by the Australian code, with no consideration for evacuation strategy or overall height of a building above 25m in height.

This thesis could identify shortfalls in the current Australian requirements for smoke control in high rise residential applications. This could significantly improve life safety in buildings where people are sleeping and most vulnerable. Investigation into other types of smoke control systems used worldwide may also uncover alternative methods of ensuring that occupants are given the best chance of escaping an emergency unharmed.

Ensuring tenable conditions in the stair shafts for longer periods of time could also have additional benefits, such as forming the basis for performance solutions for increased travel distance, floor volume and other non-compliances. This could for example allow an increase of travel distance from a residential apartment to a staircase. The configurations currently required by Australian Building Codes can be found in the guide to the BCA, with a maximum travel distance of only 6m when a single exit is provided and up to 20m when travel in two alternate directions is available.

The final aim of this thesis would be to provide recommendations as to whether the prescriptive requirements of the BCA should be updated to include more complex smoke control systems in buildings over a given height rather than a standard requirement for all buildings over 25m, as well as identifying the point at which stair pressurisation systems begin to fail.

Chapter 2

Background and Related Work

2.1 Introduction

In the 20th Century several severe fire emergencies prompted numerous international authorities to develop safety initiatives to save both human life and property from the adverse effects of fire.

This has led to safety developments seen in everyday life, such as sprinklers and fire rated construction [7]. Today more than a third of the Australian Building Code (BCA) provides provision specifically relating the fire and life safety and the industry must continue to evolve to keep up with the rapidly changing construction requirements of 21st century Australians.

The biggest risk to occupant safety in a fire emergency is not necessarily the fire itself, but the by-products, including heat and the release of toxic smoke. In fact, current statistics show that over 75% of fire deaths are the cause of smoke inhalation, rather than heat exposure, demonstrating that smoke is extremely dangerous [8].

Apartment complexes present unique fire and life safety concerns not found in other types of buildings. These issues include the provision of multiple ignition sources within a relatively small space, high concentration of electrical equipment such as cables or heaters, the possibility of occupants smoking and the generally difficult to classify fuel load within each individual apartment, due to differing occupants storage requirements. Thus the fuel load within the entire building can vary greatly, making blanket solutions difficult to formulate.

Furthermore, there is an increased chance the occupants of apartment blocks will be asleep during a fire emergency, decreasing their time to react. Due to this decreased reaction time, by the time occupants are alerted to the threat, the total amount of smoke present can have increased dramatically, significantly increasing their risk of injuries related to smoke inhalation and providing generally worsened conditions upon eventual egress from a unit.

The above issues are only made worse in high rise apartments where egress may require travelling large vertical distance before an occupant is safely outside, taking a considerable amount of time. The protection of occupants in high rise buildings should therefore be made a primary concern and all occupants should be afforded a tenable pathway from their unit to their eventual escape route for the longest period possible.

Currently buildings over 25m are provided with a stair pressurisation System, compliant with the relevant BCA clauses and AS1668.1 [9] [10]. As per the guide to the BCA, the intent of this system is to keep the fire-isolated staircases free from smoke for the duration of evacuation. However recently the effectiveness of such systems has been called into question, especially as buildings continue to grow in height [11] [12] [13] [14]. Is it possible that the current provisions are not sufficient to protect occupants, given the ever increasing height of constructions?

2.2 Physical Effects

The major physical effect which impacts both systems is the stack effect. The stack effect occurs due to differences between air densities in the inside and outside of buildings, typically caused by heating or cooling systems resulting from a temperature differential [13]. This effect is especially prominent during winter, where occupants use heating systems to increase temperatures within their apartments, causing air to rise up through shafts [15]. This means the stack effect is a positive feature in a mechanical system and is a negative factor in stair pressurisation systems as it can significantly increase the amount of force required to open doors.

It is not currently required in Australia to account for the stack effect in Smoke Control systems, which are currently designed to be commissioned based on their functioning on the day of testing. This does not consider the varying performance of the system in a variety of temperatures.

2.3 Historical Fire Scenarios

In 1994, the New York City Fire Brigade responded to a fire located in a low-rise apartment building. When they arrived on scene it did not appear as though the fire had developed in such a way that it would threaten safety to attack it directly. The Brigade made their way upwards through the building by way of the fire-isolated staircase provided and reached the door of the unit under threat without issue. Once the door to the apartment was opened, the fire grew in intensity, spurred on by large increase in oxygen provided when the door was opened because the apartments were sealed tightly to prevent air leakage for energy saving purposes.

The investigation which followed clearly showed that the nature of the corridor, created to protect the fire isolated stairway, served to pull flames into the corridor where fire fighters were located. This killed all brigade members located on that floor. Thus, there is evidence to suggest that stair pressurisation systems have the capacity to threaten brigade member life safety in relatively minor fire scenarios.

2.4 Relevant Lift Safety Systems

2.4.1 Sprinklers

In Australia, all buildings exceeding an effective height of 25m require a sprinkler system compliant with AS 2118.1-1999, with an update to the BCA in 2018 requiring compliance with AS 2118.1-2017.

The effectiveness of automatic fire sprinklers in limiting fire spread and growth is supported by statistics and studies undertaken into the effects of automatic fire sprinklers within buildings. These studies show that fire sprinkler systems operate and control fires in 81% to 99.5% of fire occurrences. The lower reliability estimates of 81.3%, as well as some of the higher values of 87.6%, do not take into accounts the differences between alternate methods of fire control systems. A number of the lower figures are results of dated studies.

It must be noted that the higher reliability of fire sprinklers reported by Marryatt [16] of 99.5% reflect fire sprinkler systems where inspections, testing and maintenance exceeded normal expectations and applies to installations specifically in Australia and New Zealand.

The statistical data from the paper titled "US Experience with Sprinklers" [17] indicate that sprinklers with appropriate maintenance are highly effective in reducing the loss of life and limiting fire spread. The research demonstrates that the proposed automatic fire sprinkler system provides a high level of reliability in operation. The sprinkler system can reasonably be expected to operate in more than 95% of occasions.

The sprinkler system is expected to prevent a severe fire from occurring and possibly eliminate the risk of exposing the occupants and fire brigade to the high temperatures and high level of toxicity within a building. The sprinkler system would be connected to the Fire Indicator Panel (FIP). The fire safety system would ensure early occupant and fire brigade notification.

An Australian review of fire experiences and fire statistics from the U.S.A was conducted [14] to study the effectiveness of various combinations of fire safety systems on reducing loss. Some key conclusions of this study are summarised in table 2.1 below;

Table 2.1: Summary of the effectiveness of activate and passive fire control systems

System	Combination of Active and Passive systems compared to the Reduction in fire loss							
Sprinklers	No	No	No	No	Yes	Yes	Yes	Yes
Detectors	No	Yes	No	Yes	No	Yes	No	Yes
Protected Construction	No	No	Yes	Yes	No	No	Yes	Yes
Reduction in fire loss	0.00	0.12	0.34	0.46	0.64	0.88	0.84	0.85

As shown in Table 2.1, the reduction in loss due to fire protected construction alone being provided is 46% compared to 64% reduction in loss by sprinkler systems alone. A combination of early detection by smoke/heat detectors and sprinkler system, statistically, provided the highest reduction in loss of up to 88% and can be considered equal to or better than the performance of any other combinations listed in Table 2.1.

Hall [18] presents data regarding the reliability of sprinkler systems based on a number of real life events. Data from the study is presented below in table 2.2;

Table 2.2: Summary of sprinkler effectiveness

Property Use	Too small	Operated	Effective operation	Combined performance
Public assembly	70 %	97 %	97 %	94 %
Educational	85 %	75 %	100 %	75 %
Health care	83 %	90 %	99 %	89 %
Apartments	61 %	96 %	99 %	96 %
Hotels	70 %	88 %	99 %	87 %
Store or office	64 %	96 %	99 %	95 %

The document titled 'Low-rise Office Construction – A Guide to Fire Safety' [19], states that by studying statistical data for apartment and residential buildings, comparison can be made to identify the relative impact on death rate against a fire safety measure. Fire statistics from office buildings were not included in this analysis due to the low death rates. The table summarizing the results has been reproduced in Table 2.3.

Table 2.3: Summary of sprinkler effectiveness in different types of occupancies

Property Use	Without Sprinklers	With Sprinklers	Reduction Percentage
Public assembly	0.8	0.0	100%
Stores and offices	1.0	0.3	74%
Industrial facilities	1.1	0.0	100%
Manufacturing facilities	2.0	0.8	60%
Storage facilities	1.0	0.0	100%

This is further supported by statistical works completed by Nystedt [20]. The relationship was further illustrated by Nystedt [21].

2.4.2 Smoke Detectors

Smoke detectors are important to consider in the design of smoke control systems as the activation of either Smoke detectors of Sprinklers is the trigger for activation of smoke control systems, occupant warning systems and triggers the activation of any other equipment and machinery which has a specific function in fire mode. As such, it is important to assess the reliability of such systems.

The effectiveness of automatic fire detectors is supported by statistics and studies undertaken into the effects of automatic fire sprinklers within buildings. These studies show that detector systems operate in 68% to 95% of fire occurrences. The lower reliability estimates of 81.3%, as well as some of the higher values of 87.6%, appear to reflect significant bias in data in terms of small number of fire incidents and the lack of differentiation between fire sprinklers and other fire suppression systems. Several of the lower figures are results of dated studies [5].

New Zealand Fire Service Commission research report Number 89, and several other papers analyses the reliability of several fire and life safety systems, including but not limited to heat and smoke detectors.

NFPA 72 [22] states the following regarding the reliability of alarm systems;

'Reliability of fire alarm systems'. Fire alarm systems located in dwelling units and having all of the following features are considered to have a functional reliability of 95%:

- Utilises a control unit.
- Has at least two independent sources of operating power.
- Monitors all initiating and notification circuits for integrity.
- Transmits alarm signals to a constantly attended, remote monitoring location.
- Is tested regularly by the home-owner, and at least every 3 years by a qualified service technician.

Table 2.4: Summary of effectiveness of smoke detectors from multiple studies [5]

Detector Type	Smoulder	Flaming	Flashover (AU)	Tokyo FD	Watanabe (JP)
Heat	0 %	89 %	95 %	94 %	89 %
Smoke	86 %	90 %	85 %	94 %	89 %
Beam	86 %	88 %	85 %	94 %	89 %
Aspirated	86 %	-	95 %	-	-

It is noted that research by Bukowski [5], shown in table 2.4, only accounts for reliability of a single detector, when AS 1668.1 mandates multiple detectors per floor, all interlinked to an indicator panel such that if even one were to trigger, all relevant systems would trigger. As a result, the reliability of the whole smoke detection system is considerably higher. Hence, it is appropriate to consider a reliability of around 95%, in accordance with NFPA guidance as it accounts for a system equal to that required by Australian law.

2.5 Smoke Control Systems

The use of pressurisation as a means of controlling smoke has been utilised for over 6 decades [15], however stair pressurisation systems have only gained widespread use among international building codes in the last 20 years. Stair pressurisation systems use doors and airflow to generate pressure differentials providing a sort of barrier which stops smoke flow into fire isolated staircases where occupants are egressing [23]. The function of stair pressurisation systems is simply to keep smoke out of the fire stair that occupants must egress via and does nothing to stop the corridor on the level of fire origin from filling with smoke. This can mean that a considerable amount of smoke is present in the corridor by the time the fire brigade arrives, which can make fighting the fire difficult due to the low visibility provided. [24]

Early stair pressurisation systems functioned via a single inlet located at the top of a building, directly supplying air into the space it was required at a given flow rate [25]. Initial tests quickly noted that the pressure differentials near doors could cause them to be exceedingly difficult to open, and a result many designers turned to the use of systems utilising multiple supply points to improve redundancy and provide better results [25].

There are several problems which can have a significant impact on the performance of a stair pressurisation system, including but not limited to: leakage within the fire stair simply due to construction; wind; and the stack effect caused by pressure and temperature differences in the inside and outside of the building. This is particularly evident during winter [26].

AS1668.1, the Standard which states how a stair pressurisation system must operate in Australia states the following:

1. 'Maintain an airflow velocity from the stair shaft, outward through the doors at not less than 1 $\frac{m}{s}$, averaged over the full area of each door opening when two doors leading from any two successive storeys and the main discharge doors are fully open simultaneously;
2. Develop a pressure differential between the shaft and the storeys such that
   (a) When all doors are closed, the pressure differential across each door does not exceed 50Pa; and

(b) The force required to open any door against the combined resistance of the air pressure differential and any automatic door-closing mechanism shall not exceed 110N at the door handle' [10]

As buildings continue to grow taller the possibility for multiple doors to be open at a time significantly increases. Any additional open doors could cause the performance of the stair pressurisation system to drop considerably, allowing smoke to breach the barrier usually created by the pressure differential. In this situation, the system is ineffectual to life safety [13]. It is further noted that there is no need to take the stack effect into account in design in many International Standards, meaning that in certain weather conditions the force required to open doors to the stairs could exceed the 110N maximum. In this scenario, the doors may be too difficult to open for some occupants, essentially trapping them.

In 2009 Miller [13] published a study focused on how pressure differentials across doorways in fire stairs change with building height, with buildings up to 30 storeys high tested. He concluded that stair pressurisation systems are adequate for protection in buildings up to and including 30m in height, provided that minimal doors are open at any one time. It is however noted that this study disregarded the amount of force required to open doors at the increased heights [13]. Ferreira [14] published a paper finding that storeys above 25 would exceed the maximum force allowances required to open doors. It was also found that the higher the building is, the more door opening impacts the performance of the system, with up to 50% reductions in 15 storey buildings [14]. Analysing this research suggests that stair pressurisation systems may become inadequate for buildings over 15 levels in height.

If an emergency is to occur, it is very possible that multiple doors into the fire-isolated-stairwell would remain open consecutively for long periods of time as people exit, holding the door open for other occupants on the level, thus significantly reducing the effectiveness of the pressurisation system [13].

Another issue with stair pressurisation systems is the existence of multiple failure modes where the failure of one component could lead to the entire system failing. If this is to occur the system will not prevent the flow of smoke into occupant egress paths and will increase smoke exposure risks. These failure possibilities include the pressure sensors, dampers or fan controllers [15].

Since the systems are so dependent on the activation of several mechanical systems, the outside weather conditions and the number of doors open at any one time, it is clear that the system cannot be guaranteed to provide an adequate level of safety in all scenarios and as a result the system is not suitable in buildings exceeding an undetermined height.

2.6 International Systems

Recently several buildings overseas, particularly in the United Kingdom have shifted away from the use of stair pressurisation systems and have instead moved to a system based on mechanically exhausting smoke from the floor of fire origin, removing the smoke out of the zone [11]. Such a system switches on upon any kind of detection, i.e. sprinkler activation, smoke detector activation, shutting off all inter-floor ventilation systems to prevent smoke spreading from one floor to another via the ventilation system [11]. Air is then supplied to the floor on one side, pushing it towards the alternate end of the corridor, flowing into a shaft at the end and upwards out of the building.

Since the system is designed to exhaust smoke from the area instead of simply using air to create a barrier, the system can reduce the total smoke inside the corridor by the time fire brigade response teams arrive on scene, increasing overall visibility, reducing toxic gases and reducing temperature. Furthermore, fire brigade members can be given control over the entire system so that they may flush individual floors as required. This means that when the brigade arrives at the floor of fire origin, the total amount of smoke is considerably reduced, making access easier. [24]

There are several cost benefits related to this system, including increasing the total area available for developers to sell. The increase in effectiveness of mechanical exhaust systems have allowed extended travel distances of up to 25m (up from 7.5m overseas) and this also increases design freedom. [11]

There is only one possible mode of failure in a mechanical ventilation system provided to a residential corridor and that is the fan operating at the inlet. The extract points will function regardless of activation due to the stack effect drawing the hot gases upwards, still providing adequate smoke exhaust.

2.7 Computation Modelling of Fire

Fire Dynamics Simulator (FDS) is a Computational Fluid Dynamic (CFD) model capable of solving the Navier-Stoke equations of heat transfer to model how heat and smoke flow throughout a defined domain. The program uses either Direct Numerical Simulation (DNS) or Large Eddy Simulation (LES) to resolve very large domains.

Large Eddy Simulations attempt to reduce the computation cost of solving Navier-Stokes equations for fluid flow by making a series of approximations, including time averaging and spatial averaging. Large Eddy simulations are particularly popular in combustion and acoustics applications.

Asimakopoulou [27] has demonstrated the ability of FDS to support the design or re-design of mechanical ventilation systems to improve indoor air quality through a comparison of experimental data and the results found using the Fire Dynamic Simulator CFD code. It was found the results from these methods corresponded sufficiently, and that therefore, results obtained from the FDS simulator are acceptable for engineering purposes. The finding that FDS is an acceptable simulator for engineering purposes is seconded by Nystedt [21].

FDS is an industry standard in fire simulation and is used throughout the world for large scale modelling of areas and can provide results for visibility, temperature and FED with ease.

The Combustion model of FDS is known as a simple chemistry model. This combustion model considers a fuel which is made up of a number of elements including nitrogen, oxygen, hydrogen and carbon that mixes with air to form a variety of products like soot and carbon monoxide. Users input the chemical makeup of the fuel they wish to utilize as well soot yield and rates of carbon monoxide generation. FDS incorporates all this information and uses it to calculate stoichiometric coefficients.

2.8 Meshing

The mesh is where all calculations for the model are undertaken and its dimensions and size have a direct correlation to the accuracy of the results. A model in FDS is broken down into many cells, typically numbering in the hundreds of thousands to millions. In each of these cells several mathematical equations are solved. The results are then moved from cell to cell to produce a final set of results which aim to closely emulate reality.

One of the most important parameters defined in FDS, and most other CFD programs is a mesh grid sizing. CFD models use these mesh cells to ensure conservation of a variety of quantities including mass, energy and others at the boundaries. The amount of error in a CFD model, assuming all geometry and other assumptions are correct, is strongly correlated to the dimensionality of mesh cells.

FDS uses 2nd order approximations for derivatives used in Navier-Stokes equations. This means that reducing a grid cell size by half will reduce error by a factor of 4 but will increase computation time up to a factor of 16. To ensure the best balance between computing time and accuracy, it is important that every model undertaken is subject to what is known as a mesh dependency study, which proves that results are independent of the sizing of mesh used.

Typically, a FDS input file should be built using a coarse mesh, and then the mesh should be reduced in size in graduations until results are no longer dependent on the dimensionality of the mesh.

The mesh is considered appropriate for use when the results no longer change substantially when the mesh sizing is further reduced, or when the computational power required to reduce the mesh further would not be feasible. The sizing of meshes required to achieve this level of accuracy is dependent on what is being simulated. With complex items like fires requiring more refined sizing.

A good way to quantify how well a mesh is refined initially, before a complete mesh dependency study is to determine the $\frac{D^*}{\delta x}$ where [28];

$$\frac{D^*}{\delta x} = \frac{\dot{Q}}{p_\infty c_p T_\infty \sqrt{g}}^{\frac{2}{5}} \tag{2.1}$$

1. D^* is the characteristic fire diameter
2. δx is the smallest size of the mesh cell
3. $\dot{Q}$ is the maximum heat release rate of the fire in kW
4. c_p is the specific heat of specific heat of air
5. p_∞ is the density of air
6. T_∞ is the ambient temperature
7. g is the acceleration due to gravity

In a mesh sensitivity study for NUREG 1824 [29], $\frac{D^*}{\delta x}$ values of between 4 and 16 were tested. When $\frac{D^*}{\delta x}$ values within this range were used, results fitted well with known experimental results. This is however noted to not mean that values between 4 and 16 are relevant for all studies.

2.9 Fire Reaction Characteristics

Determining the visibility offered in a fire scenario is highly dependent on the overall soot production of the burning objects. Visibility is defined by the distance between the object and the person, as well as the amount of obstructive smoke (i.e. soot) in between. Different materials and objects produce different amounts of soot, with wood producing very low amounts whilst plastics typically produce considerably more, ranging between 0.03 and 0.04 kg_{soot}/kg_{fuel} respectively [30]. Another factor in how much soot is produced is the amount of ventilation provided.

A study has been undertaken, comparing the results of FDS simulations against known experimental results from Peacock [1] for visibility with varying soot values. Results show that FDS modelling with soot values over 0.10 kg/kg consistently provided lower visibility than recorded during experiment, with soot values of 0.20 kg/kg providing results up to 10 times that found in experiment. For detail on their results see figure 2.1 and 2.2.

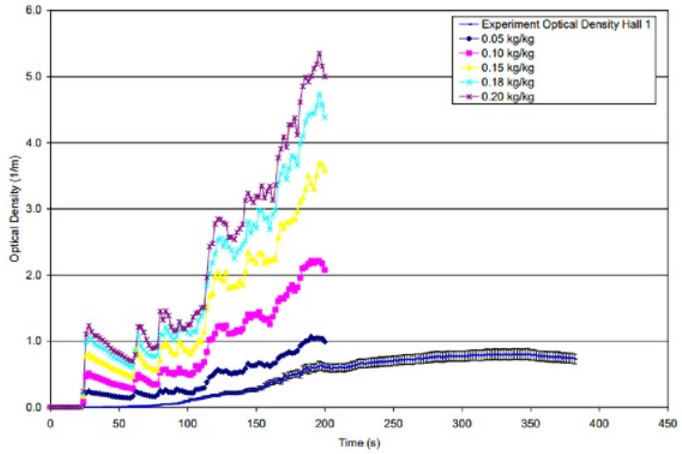


Figure 2.1: Comparison of computer simulations to recorded optical density with various soot values. [1]

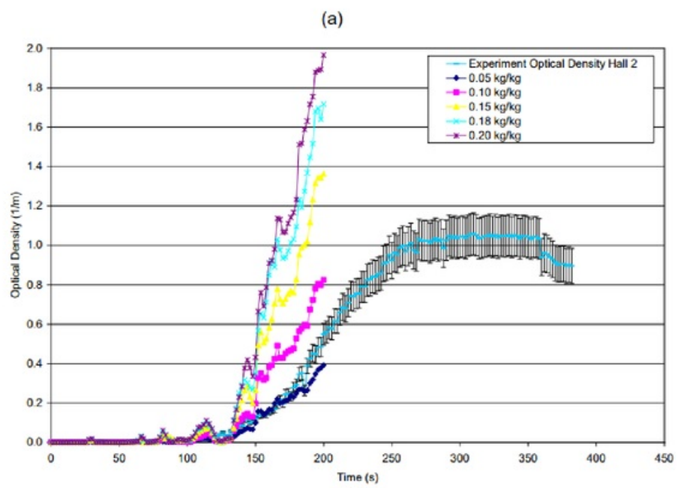


Figure 2.2: Additional comparison of computer simulations to recorded optical density with various soot values. [1]

The final recommendations from the study by Wade were that a soot value of 0.10 kg/kg would conservatively estimate the visibility within an area close to the fire, and that a value of 0.05 kg_{soot}/kg_{fuel} would conservatively estimate visibility at areas remote to the fire, i.e. corridors and other compartments.

Data regarding the soot yield values of various pieces of furniture (24 in total) was been undertaken which suggests that the 95th Percentile soot yield is 0.07 kg/kg. [1]

Further noted is that C/VM2 recommends a soot value of 0.07 kg_{soot}/kg_{fuel} be used for fire modelling in apartments, providing an accurate estimate of visibility both in the initial compartment and in the adjacent ones.

Modelling for this thesis will be undertaken with a soot value of 0.07 kg_{soot}/kg_{fuel}, to provide an appropriately conservative result, which is in line with most furniture items.

2.10 Design Fire Sizes

A design fire is a credible fire scenario which could occur in a given space. Since the number of possible scenarios within an apartment can be very large, it is important to consider a scenario that is suitably robust, such that all outcomes have been considered.

A design fire is defined by size, heat release rate and growth rate. When creating design fires, it is common to ignore the ignition phase, where heat release rate is negligible and little smoke or toxic gases are produced and then to ramp up, typically in an exponential fashion in accordance with the following formula [31].

$$Q = \alpha t^2 \tag{2.2}$$

Where the value of α is dependent on the growth rate of the fire, defined as the time it takes for the fire to reach 1.055 MW [2]. It is also common to cap the fire at a maximum heat release rate based on usage and storage type and ignore the period in which the fire would die off or decay.

There is a clear correlation between the size of the burning objects and the maximum total Heat Release Rate and thus it is important to consider the largest credible fire scenario. Multiple types of furniture have been modelled, from small armchairs to larger seating and multi-person couches as seen in figures 2.3, 2.4, 2.5 and 2.6 .

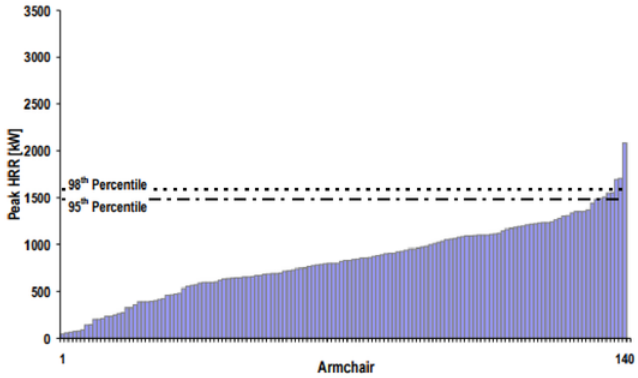


Figure 2.3: Experimental heat release rate values from Armchairs [2]

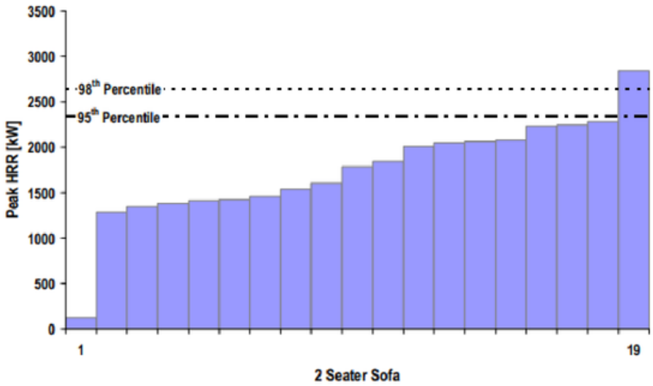


Figure 2.4: Experimental heat release rate values from 2 Seater Sofas [2]

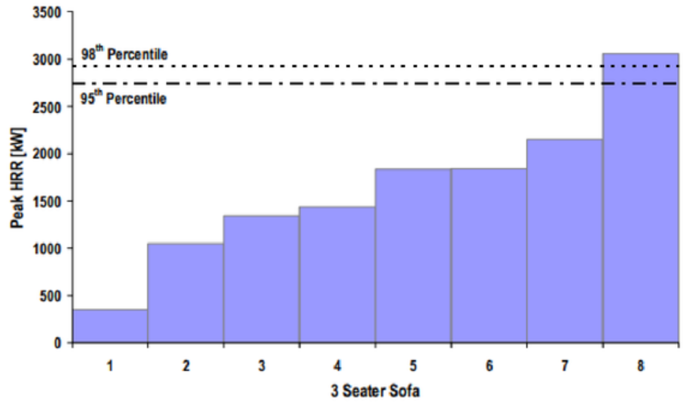


Figure 2.5: Experimental heat release rate values from 3 Seater Sofas [2]

The recommendations of Young suggest that an appropriate design fire for an apartment is quantified with a peak heat release rate of not less than 3MW and with a time to peak heat release of 150 seconds.

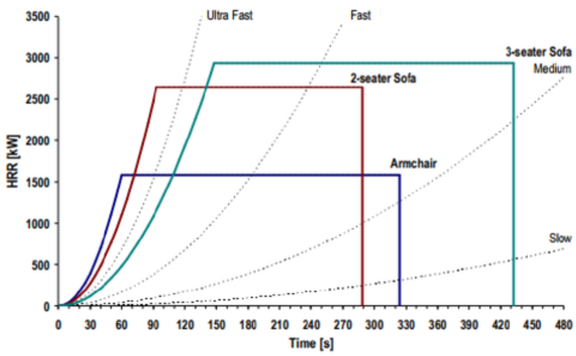


Figure 2.6: Recommended fire growth curves for various burning objects [2]

Since sprinkler failure represents the worst-case scenario within a building, it is proposed to not model the system, to ensure an appropriate robustness.

Thus, as per the above it is proposed to adopt a 3MW fast growth rate fire as the design fire, as it will encompass the worst possible couch fire, i.e. a three seater. This does not consider the beneficial effects of sprinklers which are expected to cap fire size upon their activation.

2.11 Tenability Criteria

In a fire scenario, it is important that the tenability of all required paths of travel is maintained for the length of time required for all occupants to exit the building, as well as providing safe conditions for the eventual arrival of the fire brigade. The exact criteria required to define tenability should be dependent on several factors, including the usage of the building and occupant characteristics.

In general, the most important criteria required to be maintained for safe evacuation is as follows:

- Radiant Heat Flux Exposure
- Visibility
- Toxicity
- Temperature

2.11.1 Toxicity

The level of toxicity produced in a fire is dependent mainly on the material that is burning, and the overall heat release rate of the fire. Fires produce many toxic materials, including but not limited to; Carbon Monoxide, Carbon Dioxide and Hydrogen Cyanide and a general lack of oxygen. Each of these gases can be toxic individually in high enough quantities, but are toxic at lower quantities when a combination of multiple toxins is present [3].

Work has been undertaken to quantify the chance of incapacitation for a person when exposed to combinations of the above gases. A quantity, known as Fractional Effective Dosage or FED is a time-integrated value which accounts for total equivalent exposure time within an area [32]. FED is based on the sum of the time occupants are exposed to a concentration of toxic gases and numerous experiments have been undertaken on animals.

Between a FED value of 0 and 0.3, approximately 0 to 11% of occupants will be incapacitated. Between 0.3 and 1, up to 50% of occupants will become incapacitated and upwards of these levels the gases can be deadly to almost all humans as seen in figure 2.7.

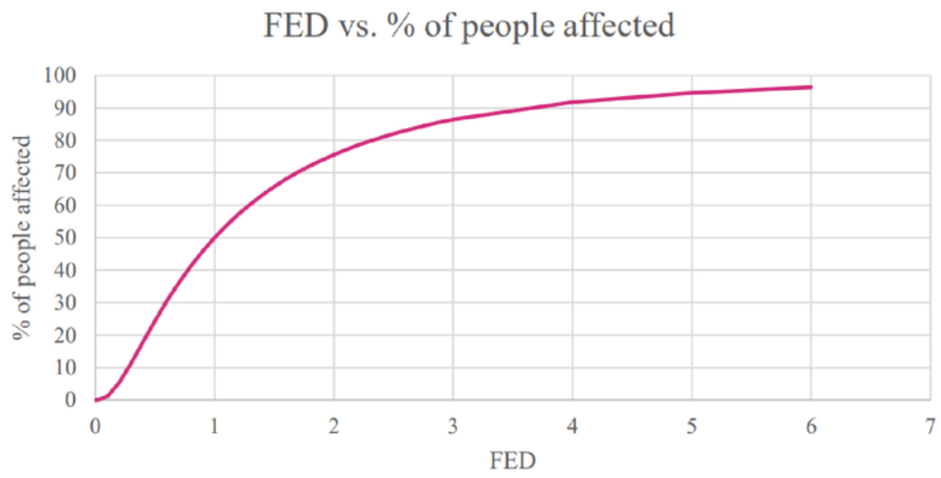


Figure 2.7: FED vs Number of occupants affected [3]

It is however noted that the fractional effective dosage method of assessing toxicity has attracted criticism, as there has been no study into how the values used to incapacitate animals translates to amounts required to incapacitate humans. However, these studies would be difficult to carry out due to the risk of injury for participants. It is also noted that the effects of temperature and heat flux are not considered with regards to the calculation of FED and it is not understood how this factor into calculating a time before incapacitation. People are not incapacitated by a single criterion, but instead a combination of multiple factors. Numerous sources have suggested that FED models incorporate the effect of all toxic byproducts of smoke at once, rather than independently [33].

Setting tenability criteria too high regarding toxicity may result in a large percentage of occupants becoming incapacitated prior to leaving the building. Thus, it is proposed to adopt a tenability criterion of 0.1 for FED. This is in line with similar guidance found in C/VM2 [34] and the SFPE handbook [35], which recommends the adoption of a 0.3 FED value as a maximum criterion. It is proposed to adopt a smaller criterion to accommodate for uncertainty regarding the translation of FED from animals to humans as well as to improve robustness.

2.11.2 Visibility

Visibility is an integral part of occupant evacuation. People inside buildings must be able to quickly and clearly identify which direction they must travel to escape, as well as identifying any hazards which may obstruct paths of travel. Research by Jin [4] has been conducted to identify how humans react when presented with smoke obscuration equivalent to that found in a fire. A 20 m long corridor was filled with smoke intended to represent the early stages of fire development and occupants were informed they would have to travel from one end of the corridor to the other. There were several illuminated and reflective exit signs along this route and subjects were to record if these were visible. The test was conducted with smoke that had irritants, and smoke devoid of irritants, to see how the type of burning material impacted tenability.

This testing found that not only did smoke prevent occupants from identifying the locations of signage until they were very close, but also that walking speed decreases as visibility decreases. Results showed that walking speed decreased considerably faster in irritant black smoke when compared to white smoke as per 2.8.

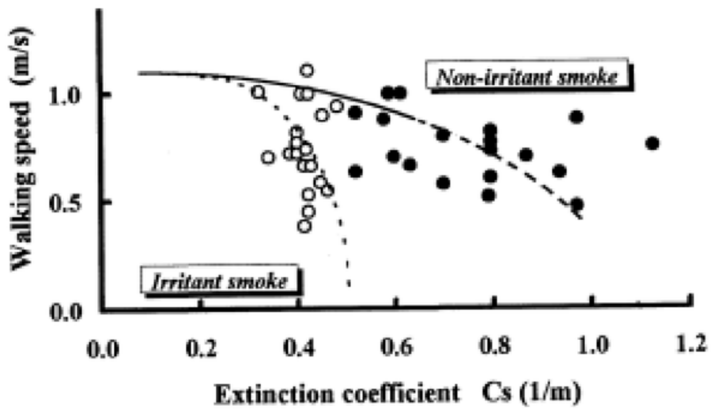


Figure 2.8: Effect of visibility on walking speed [4]

The conclusion and findings of this experiment were that occupants who were familiar with the enclosure would need only around 4m of visibility to consistently find their way to an exit, whilst those who were unfamiliar would require upwards of 13 m.

The New Zealand Building Codes C/VM2 [34] provides guidance in regard to what must be shown for tenability regarding visibility in buildings. The document states that visibility must not fall below 10m at a smoke layer height of 2 m in large rooms, and in rooms smaller than 100 m^2, where occupants may use their hands to feel their surroundings, or in queues where occupants are following those ahead of them visibility may drop to 5 m with a smoke layer height of 2 m. This guidance is taken from the International Fire Engineering Guidelines (IFEG) and the Society of Fire Protection Engineers (SFPE).

A summary of suggested limits of tenability is below in table 2.5:

Table 2.5: Visibility limits adopted by different regulatory bodies

Visibility Limit	Comment
0.8 m	N/A1
5 m	Small enclosures2,3,4,5
10 m	Large enclosures3,4,5
10 m	Large encloses2
10 m	N/A6
1 âĂŞ Barbaruskas - 1979	
2 - Buchanan - 2001	
3 - Jin - 1978	
4 - Hin and Yamada - 1990	
5 - Purser - 2002	
6 - Smith - 1998	

Due to the studies reviewed it is proposed to adopt a 10m tenability limit for visibility, as it is considered robust.

2.11.3 Radiant Heat Flux

Guidance is given in C/VM2 regarding the time taken for occupants to receive pain when exposed to varying level of radiant heat flux. The formula proposed is as follows [34]:

$$t_p = \frac{35}{\dot{q}}^{1.33} \tag{2.3}$$

Once occupants begin to receive pain they will be forced to turn back, making the area they are in untenable, even if visibility and toxicity are not exceeded. This document notes that pain begins at 2.5 kW/m^2. Several research papers and studies have been published regarding human exposure limits to varying levels of heat flux. A paper by Raj [6] has compiled these studies, which are summarised below in table 2.6;

Table 2.6: Heat flux tenability criteria adopted by a number of regulatory bodies [6]

Agency	Flux Limits (kW/m2)
NFPA	5.0
US Department of Transportation	5.0
UK Health and Safety Executive	5.0
State of NSW	4.7
Austrian Government	4.5

The paper concludes that pain is felt when skin temperature exceeds over 7 degrees above its normal temperature.

Table 2.7: Exposure time to heat flux for various levels of negative effects

Effect	Exposure time @ 5kW/m2 (s)
Blistering	35-60
Second Degree Burn	140
Third Degree Burn	125
50% Chance of Death	270

For reference, the paper also set out typical heat flux exposures for a variety of activities. Which are set out below in table 2.8:

Table 2.8: Heat flux emitted from various sources

Condition	Heat Flux (kW/m2)
Heat loss through a house wall in winter	0.009
Heat loss from a person in winter	0.0085
Sun bathing	1.135
Fireplace @ 0.6m distance	3.2
Safe limit of fire exposure	5
Heat from a lightbulb @ 10cm distance	6.4
Ignition of wood (unpiloted)	12
Human fatality	37.5

Thus, from the tables it is appropriate to use tenability criteria from radiant heat flux exposure of 5 kW/m^2 as it is supported by the largest amount of literature.

2.12 Evacuation Strategies

Research by Koo [36] in evacuation strategies for high-rise building evacuation has shown that employing phased evacuation strategies in high-rise buildings can significantly help in reducing overall evacuation time, by reducing queuing time and ensuring that the most at risk floors leave buildings at the earliest possible stage. The most at risk stories are those closest to the floor of fire origin, particularly those directly above it. A common approach to phased evacuation is to adopt what is known as a ''two up one down'' style approach, where the floor of fire origin, the two floors above and one floor below are evacuated simultaneously, with additional floors above and below evacuating at one or two minute intervals after the initial alarm. Without accounting for occupants on other floors evacuating early, the initial amount of occupants leaving already accounts for five doors open into a stair shaft, the four stories being evacuated and the ground floor doors.

The number of doors open into a shaft would continue to increase if a simultaneous approach to evacuation was to be adopted. It is then clear that the commissioning requirements of AS 1668.1 do not match real life events. Since the systems are not commissioned with a particular evacuation strategy in mind, there is no guarantee that smoke will actually be kept out of the shaft.

2.13 Conclusion

There is certainly a growing need for life safety systems that can provide enhanced life safety measures in high-rise buildings in Australia as well as internationally. By successfully providing buildings which adequate protection systems, the risk to life safety can be significantly reduced. This study aims to analyse the smoke control methods currently employed within Australia in order to identify where shortfalls occur. CFD modelling will be undertaken on stair pressurisation systems in a variety of configurations, corresponding to alternate evacuation strategies. Due to the high levels of validation offered by FDS it shall be used as the primary simulation tool in this report. Based on the research above there is a clear indication that the current prescriptive building requirements in Australia may no longer be adequate given the current building climate.

Chapter 3

Methodology

3.1 Meshing

Mesh verification is important because without it there is no way of ensuring that the accuracy of the mesh is not the primary driver of results received. It is however, important to achieve a balance between accuracy and the amount of time taken to complete a simulation.

As per the Section 2 of this report regarding mesh sizing, preliminary mesh sizing is proposed as per the following, using a proposed fire size of 3 MW which is in line with guidance provided in figure 2.6.

$$\frac{\dot{Q}}{p_{\infty} c_p T_{\infty} \sqrt{g}}^{\frac{2}{5}} \tag{3.1}$$

Meshes grid cells used will be uniform in dimension, in that x, y and z coordinates will be equal. This is because assumptions required for large eddy simulations rely on the formation of eddy's which only occurs in the largest mesh dimension of a cell and thus a cubic cell is the most efficient for simulation. [28]. The mesh resolution used will be determined by through a validation process carried out chapter 6.

3.2 Model Construction

The model is constructed as close as achievable to BCA requirements. BCA Clause D1.4 mandates that the maximum travel distance from the entrance door from an apartment to the fire stair does not exceed 6 m. BCA Clause D2.6 states that the maximum length of a corridor may be no more than 40 m and BCA Clause D1.5 states that no two exits may be located closer than 9m from one another. The height of all ceilings has been modelled as 2.75 m, as it is typical of apartment blocks constructed today to have head heights of between 2.5 and 3 m. The height of all doorways has been modelled as 2 m, as BCA clause D1.6 requires that the unobstructed height of any exit or required path of travel is at least 2m [9].

A scissor stair is provided within the model as two exits are required from any area in buildings featuring an effective height of over 25 m. A scissor stair is the most space effective way of providing multiple exits, as well as allowing design flexibility. It is noted that there is no physical connection between the two stairs within the shaft as they are separated by fire-rated construction.

Sprinkler are required in buildings over 25m in Australia as per BCA specification E1.5 but have been omitted from this simulation, as the failure of sprinklers to operate encompasses the worst-case scenario. When sprinklers do activate data shows that they will suppress a fire prior to the onset of untenable conditions in most of cases. Leakage has been modelled through all doors through holes located in the geometry, with values recommended by Gross [37].

Smoke Detectors and heat detectors have been modelled down the corridor, to accurately measure temperature for the purposes of conducting a mesh dependency study. This configuration is as close to DtS provisions are reasonable to achieve and the only differing factors between input files will be the smoke control systems provided and the number of doors open. The extent of the model can be found below in figures 3.1, 3.2, 3.3 and 3.4.

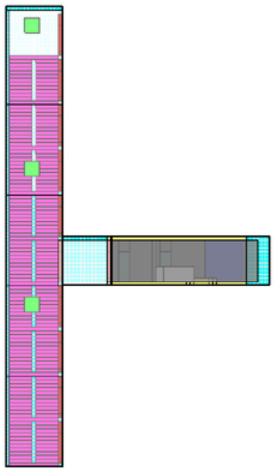


Figure 3.1: Model side view

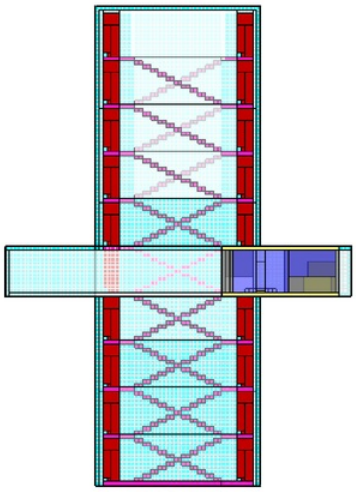


Figure 3.2: Model front view

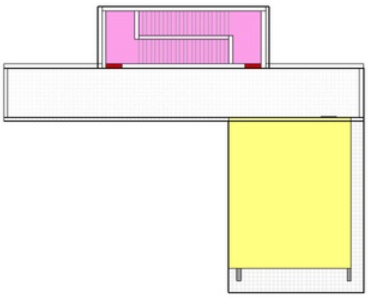


Figure 3.3: Model top view

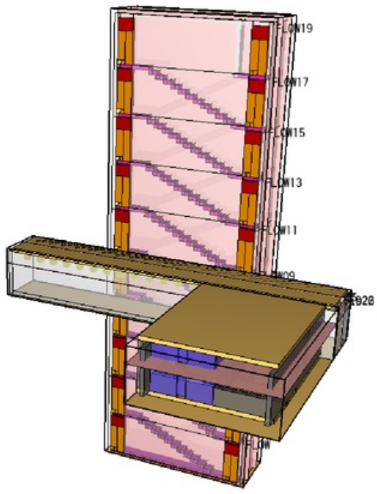


Figure 3.4: complete model extent

3.3 Measurement

For data to be recorded in FDS, items known as devices and slices must be placed into the model the quantity being recorded selected by the user and ranging dependent on user selection.

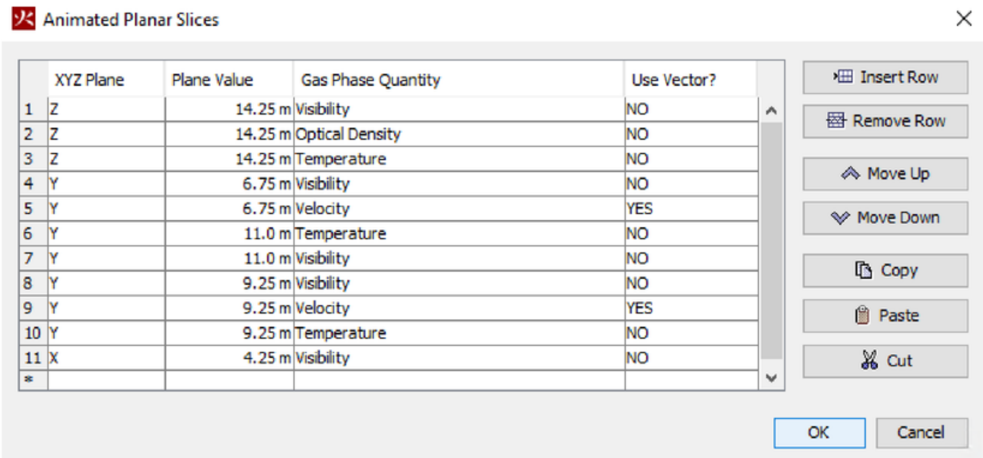
3.3.1 Slices

Slices measure data along a plane and . For the purposes of this assessment the following slices have been placed into the model.

- A slice located 2m above the floor level of the dwelling and corridor, designed to measure visibility across the space.
- A slice located 2m above the floor level of the dwelling and corridor on the z plane, designed to measure temperature across the space.
- A slice located along the x plane within the staircase, measuring visibility across both the corridor and the stair shaft.
- A slice along the y plane, halfway through the corridor, measuring velocity.
- A slice along the y plane, halfway through the stair shaft measuring velocity.

- A slice along the y plane, halfway through the corridor, measuring temperature.
- A slice along the y plane, halfway through the stair shaft measuring temperature.
- A slice along the y plane, halfway through the corridor, measuring visibility.
- A slice along the y plane, halfway through the stair shaft measuring visibility.

The slices used and their exact locations are presented below in figure 3.5



	XYZ Plane	Plane Value	Gas Phase Quantity	Use Vector?
1	Z	14.25 m	Visibility	NO
2	Z	14.25 m	Optical Density	NO
3	Z	14.25 m	Temperature	NO
4	Y	6.75 m	Visibility	NO
5	Y	6.75 m	Velocity	YES
6	Y	11.0 m	Temperature	NO
7	Y	11.0 m	Visibility	NO
8	Y	9.25 m	Visibility	NO
9	Y	9.25 m	Velocity	YES
10	Y	9.25 m	Temperature	NO
11	X	4.25 m	Visibility	NO
*				

Figure 3.5: Data recording slice locations

3.3.2 Devices

Slices measure data at a specific point and output exact quantities of measure at regular intervals throughout the simulations. This makes them favourable when compared to slices when accuracy is required, for example when undertaking grid validation studies.

- Twenty FED point measurement devices along the centreline of the corridor at a height of 2m above the finished floor level
- Twenty Temperature point measurement devices along the centreline of the corridor at a height of 2m above the finished floor level
- Twenty Visibility point measurement devices along the centreline of the corridor at a height of 2m above the finished floor level
- Two flow area measurement devices are placed on each level across the entrance doors to the fire stair, amounting to a total of twenty devices. These devices determine the average flow rate across the door at any given time.

The exact location of the devices used are shown below in figure 3.6. All devices are located at 2m above the ground floor level.

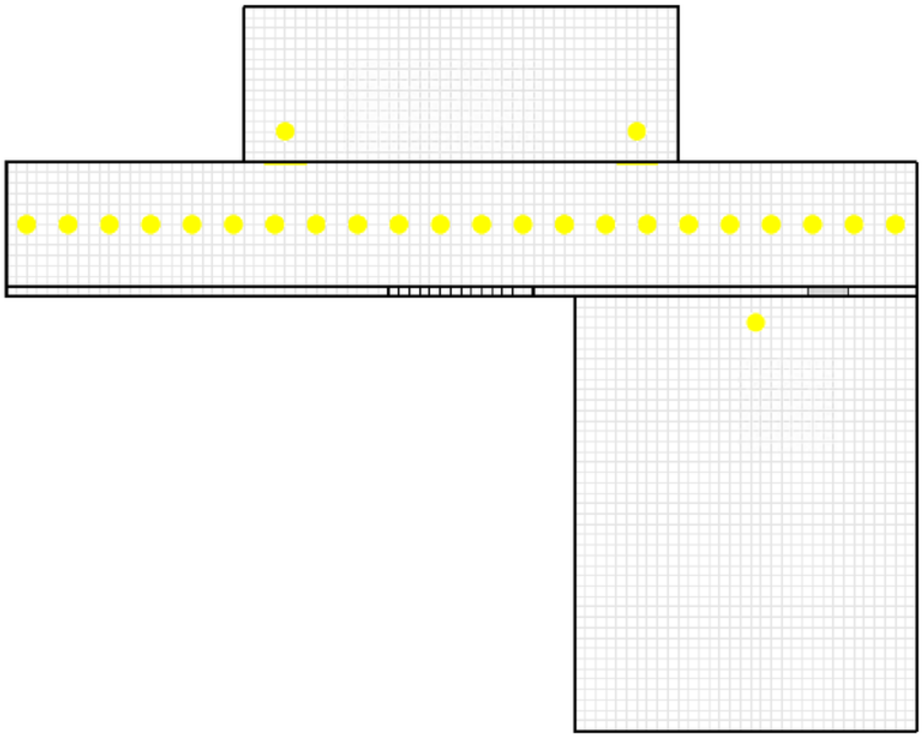


Figure 3.6: Data recording device locations

3.4 Fire and Simulation Characteristics

As discussed in section 2, the soot yield and fire size will be 0.07 kg_{soot}/kg_{fuel} and 3MW respectively, in line with guidance by Young and CVM2 [2] [34].

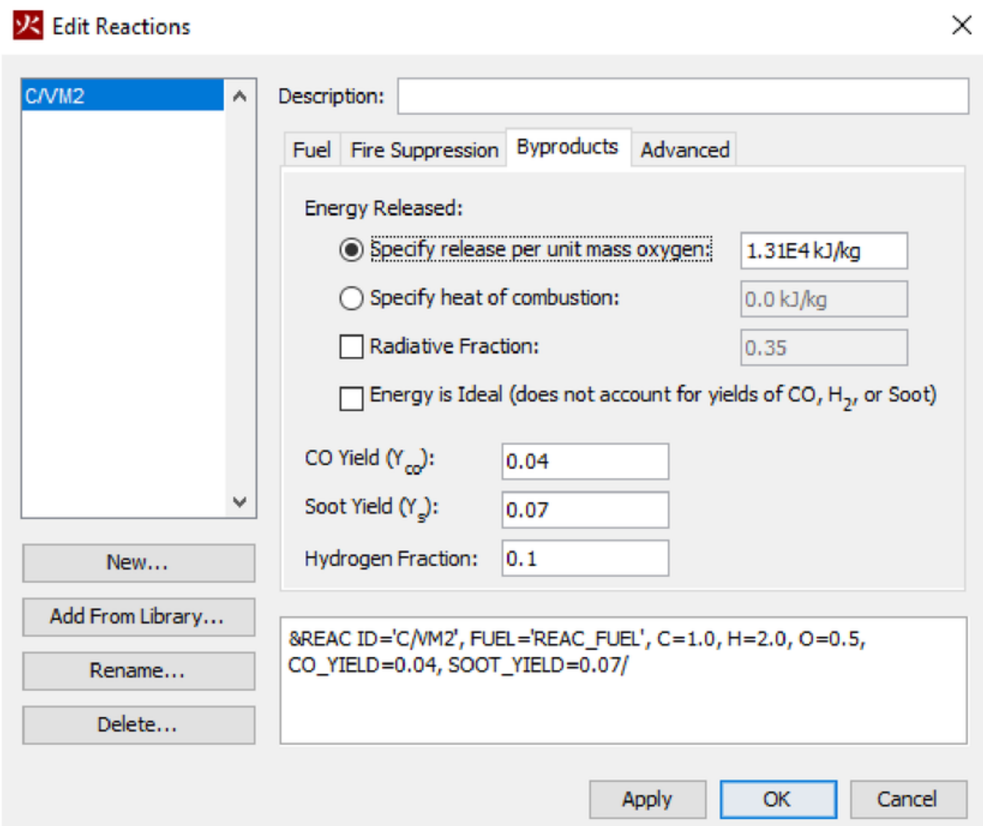


Figure 3.7: Fire characteristics as input into Pyrosim

As per section 2 of this thesis, the characteristic fire diameter D^* is given as a function of heat release rate, ambient temperature, gravity, the thermal capacity of air and density. PyroSim does not allow mesh cells which are not rectangular prisms and as such getting a perfect circle with the exact required diameter is not possible. To achieve as close to a circle as possible, a bespoke spreadsheet has been used to generate a close approximation of a circular fire, with the appropriate diameter, which each of the heat release rates of the various rings summing to provide a total fire size equal to 3 MW as per section 2. Generating a fire by this method leads to the closest an FDS fire can get to circular. The makeup of the fire used within FDS is shown below in figure 3.8.

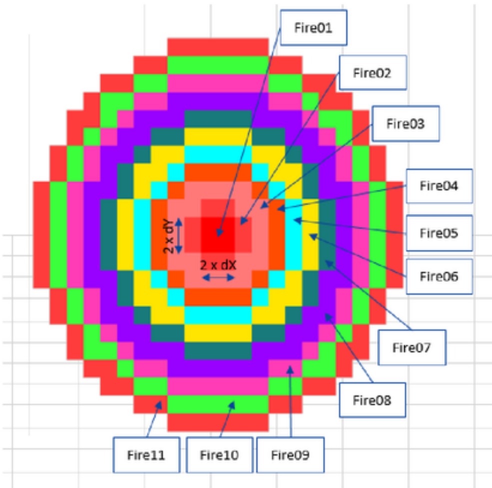


Figure 3.8: FDS fire vent make-up

The fire will grow at a fast growth rate, defined as having an α value (see 2) of 0.0469 until it reaches a peak of 3 MW, where it will remain constant for the duration of simulation. Fires typically decay after this point, or are suppressed by the sprinkler system provided but it is not proposed to model this the case in which sprinkler failure occurs is the worst-case scenario. The modelled heat release rate provided by this fire can be seen below in figure 3.9.

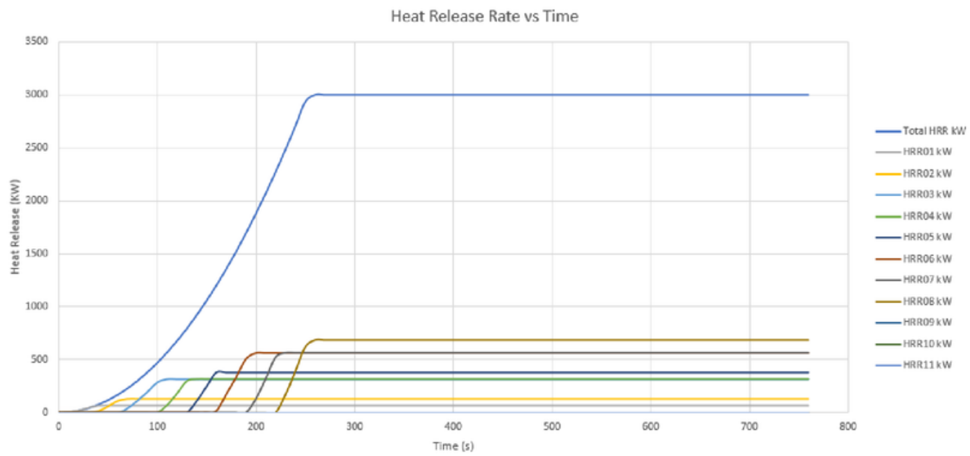


Figure 3.9: Modelled Heat Release Rate

3.5 Supply Air Quantities

To determine exact supply air requirements in each of the two scissor stairs provided some trial and error is required, as there is no one size fits all solution to achieve the required flows by AS 1668.1. Supply vents have been placed at regular intervals every three storeys at a rate of 2 $\frac{m^3}{s}$. An initial simulation will undertaken using the commissioning requirements of AS 1668.1 to show that the flow rate through the door complied with the requirements of the standard, that is that it achieves an average flow speed across the door of 1 $\frac{m}{s}$ with two doors open. The model will be run as part of a commissioning study. Since the stair would pass testing in a real-life scenario, it will be considered that this is an appropriate base case design.

The flow rates and supply vent locations will be keep constant throughout all simulations regarding stair pressurisation systems, with the only variable being the number of doors open into the shaft at any one time. Ambient temperature has been taken as 20 degrees Celsius, with gravity, outside pressure and other values being taken of those at ground level.

3.6 Simulation Characteristics

All simulations will be run for 300 seconds, a time deemed suitable to accommodate for evacuation times expected in most of cases. Conditions after occupants have left the building are not relevant from a life safety perspective, and the number of doors open into the shaft will drop back down to zero.

The flow rates and supply vent locations will be keep constant throughout all simulations regarding stair pressurisation systems, with the only variable being the number of doors open into the shaft at any one time. The event time-line for the model is as follows.

1. At time 0 s, all doors are closed and a fire initiates from an unknown source within a dwelling.
2. At time 60 s, the doors open within the tenancy, simulating the time at which occupants of that dwelling decide to leave the building.
3. At time 70 s, the doors within the scissor stairs open, indicating that occupants have made it from the exit. Furthermore, the doors to the dwelling close
4. At time 90 s, the doors to the scissor stairs close
5. At time 250 s, the doors to both the dwelling and the scissor stairs open for the duration of the simulations.

Chapter 4

Verification

4.1 Introduction

Verification is typically defined as the process of checking the accuracy of a numerical model. The aim of the verification process is to ensure that the simulations undertaken represent the intent of the user undertaking them. This typically involves the removal of as many errors as practical that may impact the accuracy of results. Verification is often confused with Validation and says nothing about how well results may compare to those found experimentally. The process of Validation is also important for analyzing results but is outside the scope of this research. The primary concern of verification work is ensuring that the mathematics being used to solve the model are appropriate.

Roache [38] has suggested that verification should be split into two complementary parts, both the verification of the underlying computational code of the program used to complete simulations and verification of the final model set-up for each individual case.

The verification of computational code is typically undertaken by the publishers of the code prior to its release for public or commercial work. A large amount of validation work has been undertaken by the NIST and is detailed in the Fire Dynamics Simulator Technical Reference Guide [28]. This work has included verification of the turbulence model, the basic flow model, boundary effects, heat transfer and a number of other important areas. Given the signification amount of work put into the validation of the underlying mathematics from a code point of view by NIST, it is considered that this part of validation has already been assessed and is outside the scope of this thesis.

Verification of a model involves reducing the amount of error to the lowest practical amount. This typically requires the use of a mesh dependency study, examining convergence and comparing results. In CFD simulations a grid is required and the resolution of this grid directly impacts accuracy as well as simulation time. For the purposes of this thesis, verification will involve a mesh dependency study, showing that results are not dependent on the resolution of grid used.

The first step in generating a fds input file is deciding on the grid sizing used. In general the finer this mesh, the better the accuracy of the equations. FDS uses 2nd order equations and therefore halving the size of a mesh will decrease error by a factor of four. Due to the fact that each grid cell is three dimensional in space and has a time dimension, halving the size of a mesh will increase the total run time of a simulation by a factor of 16 (2^4). Given time restrictions and a limited amount of computation power available it important to strike the best available balance between accurate results and reasonable simulation time. Past work in FDS, documented in Chapter 2 have shown that accurate results are typically obtained with $\frac{D^*}{\delta x}$ of between 4 and 16.

FDS is unlike other CFD codes in that the model is built within a mesh, rather than creating a mesh on an already generated model. Because of this, obstructions and objects within fds must have thickness, height and width which is a factor, multiple or equal to that of the mesh. If geometry is created that does not comply with this requirement, the piece of geometry will either by expanded to fit the mesh or be deleted. Given this, it is proposed to create the most coarse mesh with a grid size of 0.25m x 0.25m. This mesh size is used due to the proposed ceiling height of 2.75m as a mesh sizing will have to be a factor of this amount.

The model used for the mesh dependency study will feature 2 doors open per shaft, complying with the testing requirements set out in AS 1668.1. The model will also feature a fire, allowing results for temperature, visibility, fractional effective dosage and air flow to be compared with respect to grid resolution.

The grid size will then be halved until a suitably accurate mesh is uncovered. See the table 4.1 for the $\frac{D^*}{\delta x}$ of each of the proposed meshes. The mesh has to be reduced by a factor of two every run because the mesh must be kept as a factor of 2.75m.

It is noted that both the 0.25m x 0.25m mesh and the 0.125m x 0.125m mesh have $\frac{D^*}{\delta x}$ values lying between 4 and 16, complying with guidance found within the FDS technical reference [28].

Table 4.1: Proposed mesh sizes and their respective $\frac{D^*}{\delta x}$ values

δx (m)	$D^*/\delta x$
0.25	5.9369
0.125	11.8736
0.0625	23.747

Due to computational power restraints it is not feasible to generate a mesh dependency study for every single case run, however as the only change between cases is the number of doors open into the stair shaft there will not be significant change in the dynamics of the simulation in the areas of interest. This is because both the fire size and the soot release amounts are kept constant across all simulations. With additional computational power it would be favorable to conduct a separate mesh dependency study for each independent case.

4.2 Model Verification Results

4.2.1 Fractional Effective Dosage

Fractional Effective Dosage within the corridor has been compared at various mesh sizes to determine how the resolution of the grid used effects results obtained. Results of FED values for mesh sizes 0.25m x 0.25m x 0.25m and 0.125m x 0.125m x 0.125m have been plotted against time on the same axis for a direct comparison.

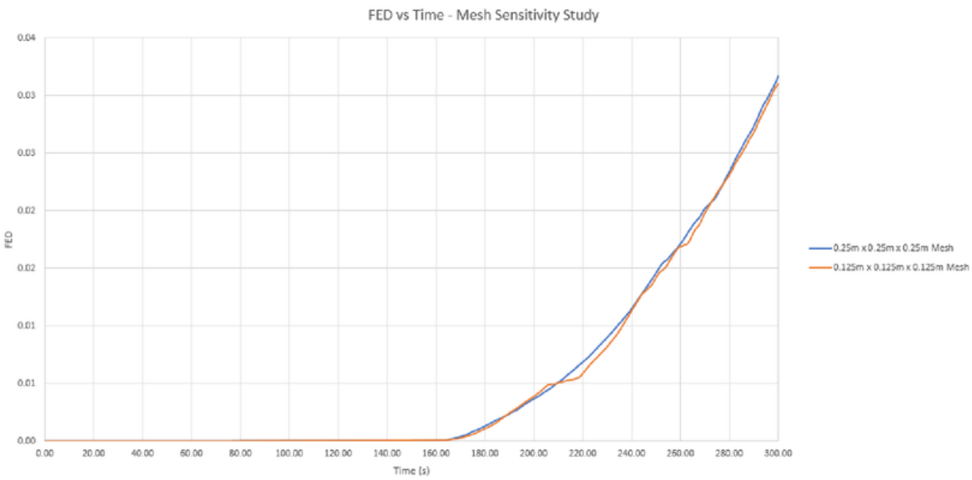


Figure 4.1: Comparison between FED results for a coarse and fine mesh.

It is clear through analysing figure 4.1 that there is slight variance between the FED values found in the coarse and tight mesh. The final results however, tend toward one another, becoming almost exactly equal by the end of the simulation. Since FED is a compounding value, the most important result is the maximum value. If the results both tend toward the same value regardless of mesh sizing, it is to be considered that mesh sizing above 0.25m x 0.25m x 0.25m does not have a significant impact on Fractional Effective Dosage.

As per figure 4.2, the results produce a fairly linear relationship, with a squared correlation

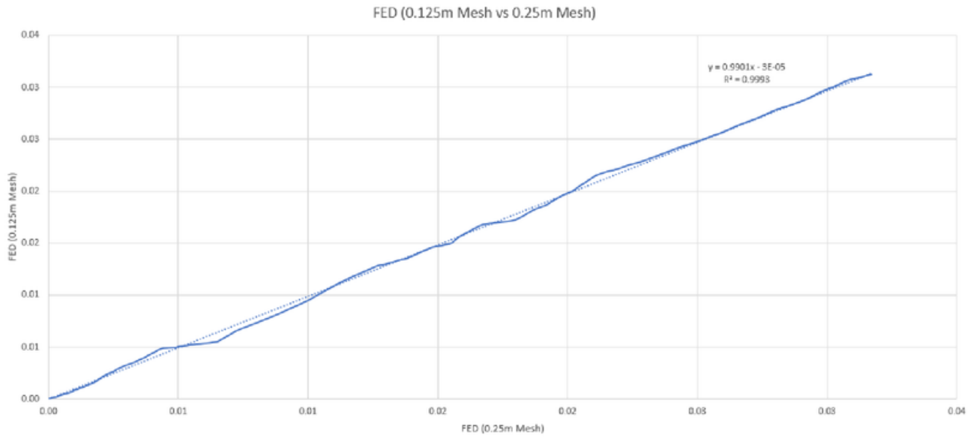


Figure 4.2: Additional FED comparison between mesh sizing.

coefficient of 0.993, indicating a very strong correlation. The high squared correlation coefficient suggests very little difference between FED results for meshes tighter than the coarse mesh.

4.2.2 Visibility

Visibility values within the compartment of fire origin at various mesh sizes have been compared to identify the relationship between the number of mesh cells and the results obtained. Results of visibility for mesh sizes 0.25 m x 0.25 m x 0.25 m and 0.125 m x 0.125 m x 0.125 m are plotted together below in figure 4.3

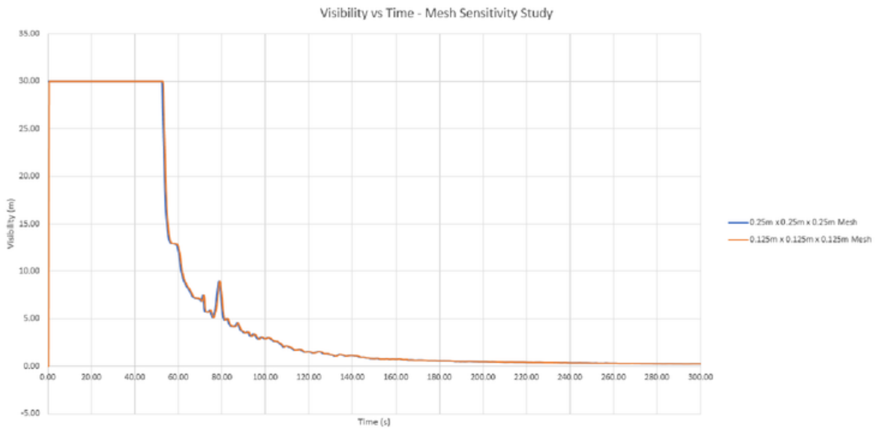


Figure 4.3: Visibility result comparison between a fine and coarse mesh.

It is clear that there is no appreciable difference between the results obtained between the two meshes where visibility is concerned. Both meshes begin to drop from 30m at the same time, and share equal results for the entirety of simulation duration. To further compare the difference between results the visibility results for both meshes have been plotted against one another below.

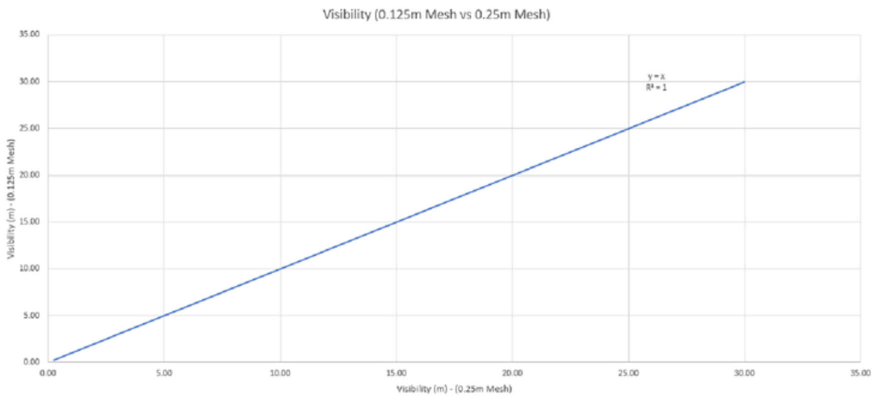


Figure 4.4: Additional visibility result comparison between a fine and coarse mesh.

As figure 4.4 above, the results produce a perfectly linear relationship. This confirms that there is no difference between visibility values as mesh resolution increases.

4.2.3 Volume Flow

Further comparison has been made between flow rate results through the openings at different mesh sizes and can be seen below in figure 4.5 and figure 4.6.

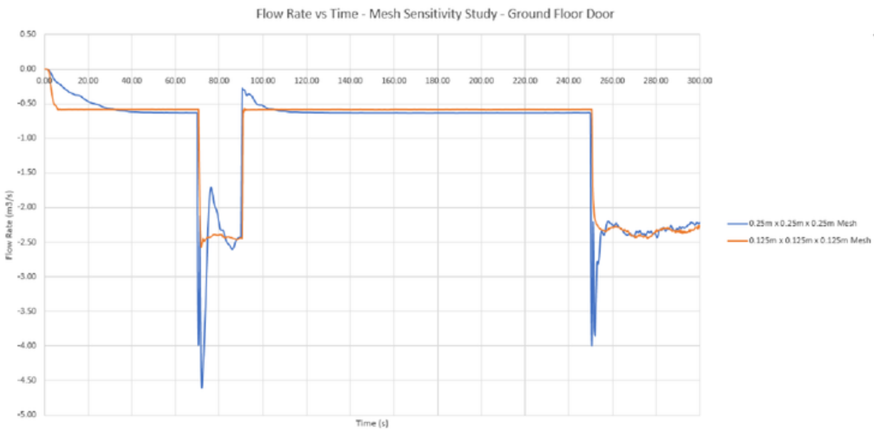


Figure 4.5: Flow rate comparison between a coarse and fine mesh at the ground floor.

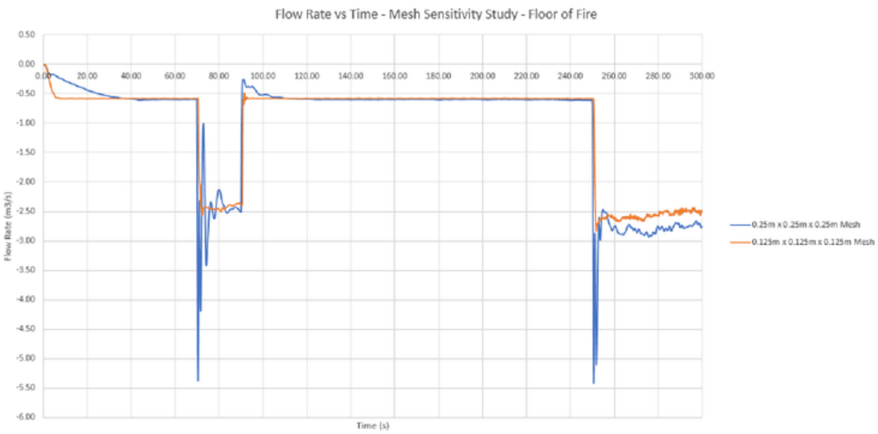


Figure 4.6: Flow rate comparison between a coarse and fine mesh at the floor of fire origin.

Looking at figure 4.5, Prior to 60 s, the flow rates through the doors due to the small leakage areas provided tend toward a the same value of 0.6 $\frac{m^3}{s}$, however the finer mesh reaches this value 35 s earlier than the coarse mesh. Once the doors initially open at 70 s, the finer mesh quickly settles at a value of 2.5 $\frac{m^3}{s}$ while the coarse mesh fluctuates for 15 s, reaching a peak of as high as 4.5 $\frac{m^3}{s}$ before settling at the same value. At time 90 s both meshes tend back toward 0.6 $\frac{m^3}{s}$ and reach the same value at equal times. At time 250 s, both meshes tend toward 2.5 $\frac{m^3}{s}$, however the finer mesh reaches it without fluctuating as higher as the coarse mesh.

Looking at figure 4.6, Prior to 60 s, the flow rates through the doors due to the small leakage areas provided tend toward a the same value of 0.6 $\frac{m^3}{s}$, however the finer mesh reaches this value 35 s earlier than the coarse mesh. Once the doors initially open at 70 s, the finer mesh quickly settles at a value of 2.5 $\frac{m^3}{s}$ while the coarse mesh fluctuates for 15 s, reaching a peak of as high as 5.5 $\frac{m^3}{s}$ before settling at the same value. At time 90 s both meshes tend back toward 0.6 $\frac{m^3}{s}$ and reach the same value at equal times. At time 250 s, the finer mesh tends toward a flow rate of 2.5 $\frac{m^3}{s}$, while the coarse mesh peaks at 4.5 $\frac{m^3}{s}$ before settling at a value of 2.8 $\frac{m^3}{s}$. The implication of these results is that the coarse mesh overestimates flow rate.

4.3 Summary

Two simulations have been completed, each with twice the mesh resolution of the last in order to compare results in a number of quantities. The purpose of this analysis is to determine the most coarse mesh which will produce results independent of the mesh sizing itself. The simulations took various amounts of time to run, with the most coarse mesh taking 6 hours, and the fine mesh taking 2 days per model. An extra fine mesh was attempted, but the simulation did not finish for over 3 weeks, making it impractical for use in this study.

While the coarse mesh, corresponding to a $\frac{D^*}{\delta x}$ of 5.9369 achieves results independent of the mesh with respect to visibility, temperature and fractional effective dosage, the results for flow rate are still dependent on mesh sizing.

Due to the fact that the main focus on this thesis is the reduction in flow rate through a stair door, it is not considered appropriate to use a mesh where results cannot be guaranteed as validated for that quantity. It is considered that the inaccuracies make it an improper for use in simulation. As a result, the fine mesh, corresponding to a $\frac{D^*}{\delta x}$ of 11.8736 will be used to ensure the most accurate measurements of flow rate.

Due to the amount of time each set of validation simulations take, particularly for the finer meshes, it is proposed to use the same fine mesh, with a $\frac{D^*}{\delta x}$ of 11.8736 throughout all simulation cases. This is because the most detailed meshes can take upwards of two weeks to finish simulating. Given additional computational power or an extended time frame, it would be preferable that each model was analysed independently. It is noted however, that there is no change in air being injected into the model, fire size, geometry or mesh configuration outside of the resolution.

Since the fire size and the amount of smoke generated is not changed in any of the simulations, it is not expected that the mesh resolution requirements would change in any subsequent models. This is support by the above equation which states that the $\frac{D^*}{x}$ quantity is dependent on only the fire size.

It is however noted, that if there was no requirement for the measurement of flow rates, for example in a building with no smoke control systems, a coarser mesh would still appear to give accurate results.

Chapter 5

Results and Discussion

This chapter examines the experimental simulations undertaken for stair pressurisation systems in a number of configurations. The testing conducted in this chapter aims to compare the performance of stair pressurisation systems with a various number of doors open into the shaft. All simulations have been undertaken for 300 seconds, with a fine mesh used in accordance with the verification study undertaken in Chapter 4. A chart of all proposed models can be found on in the figure 5.2. For the purposes of clarity, the simulation has been split into four phases, defined by the following characteristics and shown in figure 5.1;

1. Simulation begins, fire ignites and no doors are open.
2. Doors to the stairs open initially at 70 s, remaining open for 20 s.
3. Doors closed, smoke has entered the corridor.
4. Doors to the stair shaft reopen and at t = 250 s and remain so until the conclusion of the simulation.

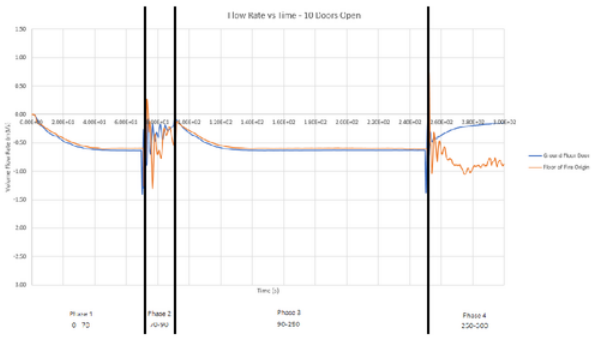


Figure 5.1: General phases of simulations

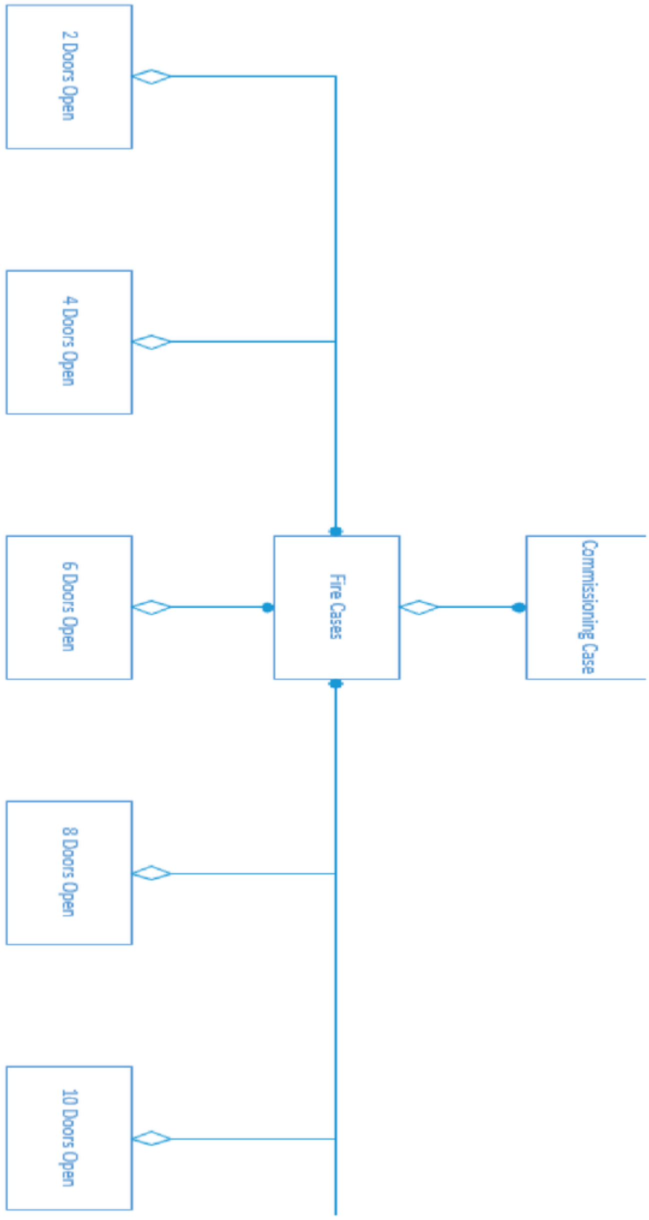


Figure 5.2: Computer simulations to be undertaken

5.1 Commissioning Case

In the commissioning case there is no fire provided. The only feature of the model is injection air provided to the stair shaft. A single door at the floor of interest and another door at the ground floor are open into the stair shaft. This configuration complies with the commissioning requirements as set out in AS 1668.1. As results show that flow speeds average through the door in the model comply with Australian legislation, the same vent configuration and supply flow rates will be used throughout all stair pressurisation models. By keeping the flow rates at the sample level it will be clear how a system which may be commissioned in a non-fire event will perform in an actual fire.

Since there is no fire in this simulation there will be no byproducts of fire produced, as a result there is no need to measure temperature, visibility or fractional effective dosage and these results have been omitted.

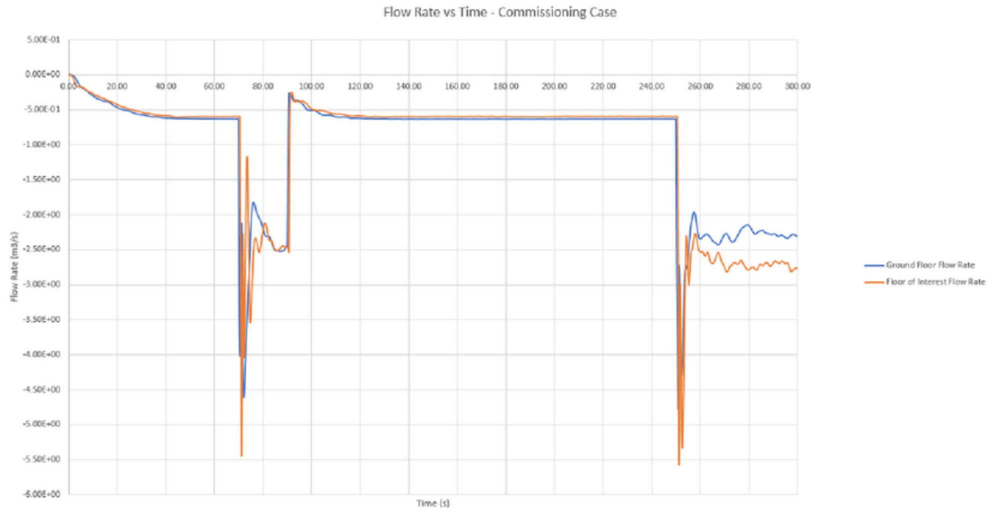


Figure 5.3: Volume flow throughout stairs of interest with 2 doors open simultaneously

Between the simulation start at time zero and the time at which the doors are opened for the first time, flow through the door tends toward 0.5 $\frac{m^3}{s}$. This is representative of the amount of air leaking through the door via the simulated cracks. The volume flow rates tend toward a constant amount during this time and reaches it at approximately 40 seconds. At time 60, when the doors open for the first time there is an initial fluctuation of flow on both floors, but these fluctuations correct themselves and the flow rates through the door appear to settle towards a flow of 2.5 $\frac{m^3}{s}$ in both doorways. It does appear that there is not enough time for the flow to reach a steady state given the amount of time the stair doors are open for. Between time 70 and time 250, where the doors have closed again results tend towards the same value of 0.5 $\frac{m^3}{s}$, as found in the beginning of the simulation and there is more than ample time available to reach this steady state. Between the time of 250 seconds until the completion of the simulation when doors open again, there is an initial fluctuation but the volume flow through both stairs settles at a relatively stable amount. Interestingly, the two stairs do not settle at an equal value. This is because the ground floor stair inlet shaft serves four stories, when the inlets above only serve three stories each, meaning there is some additional leakage from cracks on the floors above.

As per figure 5.3, flow through both the door of interest and the ground floor door achieve volume flow rates of 2.4 and 2.6 $\frac{m^3}{s}$ averaged across the entirety of the door frame respectively when the doors are both open simultaneously. Given that the door has an area of exactly 2 m^2, the flow speed through the area can be simply calculated as above 1.2 and 1.3 $\frac{m}{s}$ respectively, complying with the flow speed requirement of 1 $\frac{m}{s}$ set out within the Australian standards.

Given that the flow speeds through the shaft comply with the requirements of Australian code it is concluded that this system would pass commissioning in a real life scenario, making it suitable for used in all the following simulation cases, without adjustment.

5.2 2 Doors Open

The model used during this simulation has geometry exactly equal to that found in the commissioning case above and features identical control logic for doors, with only two doors opening into the shaft at once at any once time. In this simulation however, a fire has been placed within the centre of the modelled apartment. The fire begins at time zero and grows quadratically until reaching a peak value.

As a by-product of the fire, smoke and heat are added to the environment and spread throughout the domain. As smoke fills the corridor it will attempt to move into the stair shaft, but the stair pressurisation system provided, complying with the commissioning requirements is designed to prevent the ingress of smoke into the safe space. The volume flow rates through the doors of interest are presented below in figure 5.4;

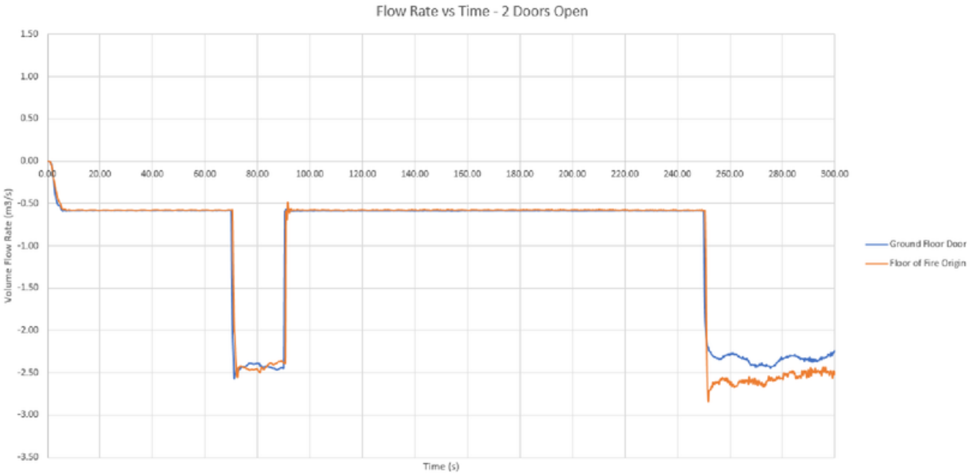


Figure 5.4: Volume flow throughout stairs of interest with 2 doors open simultaneously

An analysis of the results of flow rate simulations has been undertaken per figure 5.4;

1. At time t = 0, the simulation begins and airflow is initiated through the inlets within the stair shaft.
2. At time t = 5 s, the flow rate through the small cracks in each door has reached equilibrium and remains a constant 0.53 $\frac{m^3}{s}$ until time t = 70 s.
3. At time t = 70 s, the doors on both the floor of fire origin and the ground floor open completely at remain this way for 20 seconds. During this time air flow through both doors spikes equally to a maximum of 2.5 $\frac{m^3}{s}$ and remains at this magnitude, with minimal oscillation for the duration of time the doors remain open.

4. From time t = 90 s to t = 250 s when all doors are now closed again, the airflow through the cracks tends towards the same values as previously.

5. At time t = 250 s, the doors to both stairs reopen. By this time there is a considerable amount of smoke in the corridor adjacent the the stair shaft and the as a result the area is at a relatively high pressure. The flow through both the stair at ground floor and the floor of origin settle at 2.4 $\frac{m^3}{s}$ and 2.5 $\frac{m^3}{s}$ of flow respectively. The difference in flow between floor levels is likely caused by due to air flowing the fact that the inlet closest to ground floor serves an additional storey in comparison to the inlets above.

Comparing the results of flow out of both stair shafts while the door are open it is clear that the flow speed averaged across both doors satisfies the requirements as set out by the Australian standards, with a recorded flow speed of 1.25 $\frac{m}{s}$ on the floor of fire origin. Given this, it is expected that the system would perform as required, preventing the ingress of smoke into the shaft. This is supported by the visibility slices below in figure 5.5, which show no smoke ingress into the stair, even though the conditions in the corridor themselves have become untenable.

Figure 5.5: Visibility at time t = 300, with 2 doors open

Figure 5.6: Visibility scale for both of the above slices

As per figure 5.5, at no point in time does the visibility in the stair shaft decrease below the maximum of 30m, even while the corridor has a visibility of zero. Thus, it is concluded that a stair pressurisation will still behave as desired in the case of two openings. This is expected as this configuration is equal to the commissioning requirements of AS 1668.1.

Also of note is that the temperature within the stair does not increase about ambient, due to the ample amount of air flowing through the shaft. This is clearly shown in figure 5.7.

Figure 5.7: Temperature at 2m above floor level on the level of interest with 2 doors open.

Figure 5.8: Temperature Scale

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Toxicity within the stair never increases beyond a FED value of zero, as no smoke ever enters the stair. Since toxicity, visibility and temperature is never violated, occupants will always be safe once they access to staircase.

5.3 4 Doors Open

Like the model with 2 Doors open into the stair shaft, the geometry, fire, devices and control regimes are equivalent to the previous models simulated, with the sole difference being that now 4 doors into the stair shaft will be open at any one time. This case would represent a building operating on a one up one down phased evacuation strategy, where the floor of alarm and the floors immediately above and below are evacuated simultaneously while other floors are informed to wait. The volume flow rates through the doors of interest are presented below;

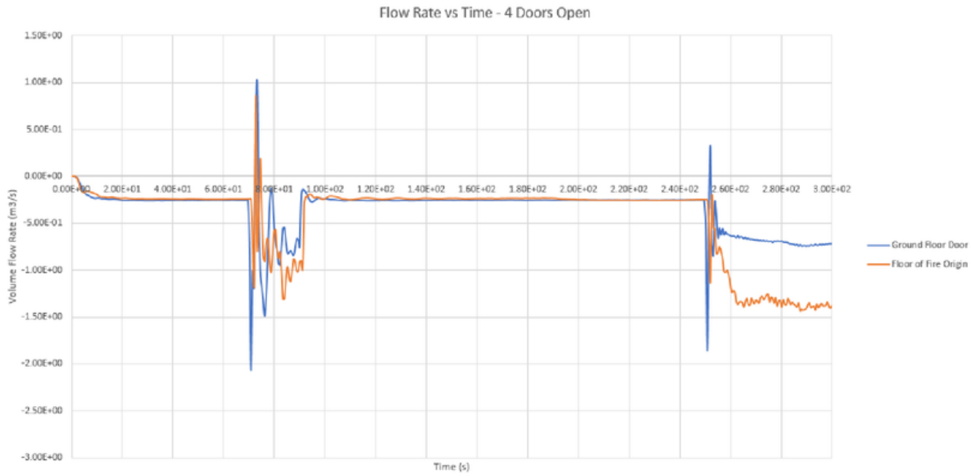

Figure 5.9: Volume flow rates through the ground floor door and floor of fire origin with 4 doors open into the shaft

An analysis of the results of flow rate simulations has been undertaken per figure 5.9;

1. At time t = 0, the simulation begins and airflow is initiated through the inlets within the stair shaft.
2. At time t = 5 s, the flow rate through the small cracks in each door has reached equilibrium and remains a constant 0.2 $\frac{m^3}{s}$ until time t = 70 s.
3. At time t = 70 s, the doors on both the floor of fire origin and the ground floor open completely at remain this way for 20 seconds. During this time air flow through both the ground floor and fire floor spike to 2.1 and 1.2 $\frac{m^3}{s}$ respectively. The flow fluctuates considerably during this period of time and does not settle on a particular value before the next phase. The flow through these doors is substantially different than found in the previous simulation, when compared to figure 5.4. The fluctuation is likely to due the stair shaft and corridor having substantially different pressure

profiles, since at this point in time the shaft is of higher pressure than the corridor as no smoke has entered.

4. From time t = 90 s to t = 250 s when all doors are now closed again, the airflow through the cracks tends towards the same values as in phase 1.

5. At time t = 250 s, the doors to all 4 stairs reopen. By this time there is a considerable amount of smoke in the corridor adjacent the the stair shaft and the as a result the area is at a high pressure. The flow through both the stair at ground floor and the floor of origin settle at 0.6 $\frac{m^3}{s}$ and 1.4 $\frac{m^3}{s}$ of flow respectively. The drop is flow rates when compared to the previous scenario is over 40%, showing that a significant drop occurs once the design scenario is exceeded. The difference in flow between floor levels is likely caused due to the additional storey served by the inlet supplying air to the ground floor, which is now open in this configuration, allowing a substantial amount of air to flow into that corridor instead of the ground floor.

Comparing the results of flow out of both stair shafts while the door are open it is clear that the flow speed averaged across both doors does not exceed the levels mandated by AS 1668.1, with a flow speed of only 0.7 $\frac{m}{s}$ in lieu of 1 $\frac{m}{s}$. Given that the results are below Australian requirements, it would be expected that there is at least some leakage into the stair shaft.

Unlike the model with 2 stairs open, there is some small amount of leakage of smoke into the stair which suggests a failure in the barrier which is supposed to be created by an effective stair pressurisation system. The amount of smoke leaking into the stair however is relatively low and visibility within the core is still maintained at a reasonable level. The visibility within the stair is still above the tenability criteria listed in chapter 3 however, suggesting that it would still be possible for occupants to way-find within the stair. The visibility within the stair is clear in figure 5.10.

Figure 5.10: Visibility at time t = 300, with 4 doors open

Figure 5.11: Visibility scale for both of the above slices

Also of note is that like the previous simulation, the temperature within the stair does not increase about ambient, due to the ample amount of air flowing through the shaft. This is demonstrated in figure 5.12

Figure 5.12: Temperature at 2m above floor level on the level of interest with 4 doors open.

Figure 5.13: Temperature Scale

Toxicity within the stair never increases beyond a FED value of zero, as no significant amount smoke ever enters the stair. Thus, the only tenability criteria in danger of being violated is visibility.

5.4 6 Doors Open

Like the model above, the geometry, fire, devices and control regimes are equivalent to the previous models simulated, with there now being at most 6 doors open at any one time. This case would represent a building operating on a two up two down phased evacuation strategy, where the floor of alarm and the two floors immediately above and below are evacuated simultaneously while other floors are informed to wait. The volume flow rates through the doors of interest are presented below in figure 5.14:

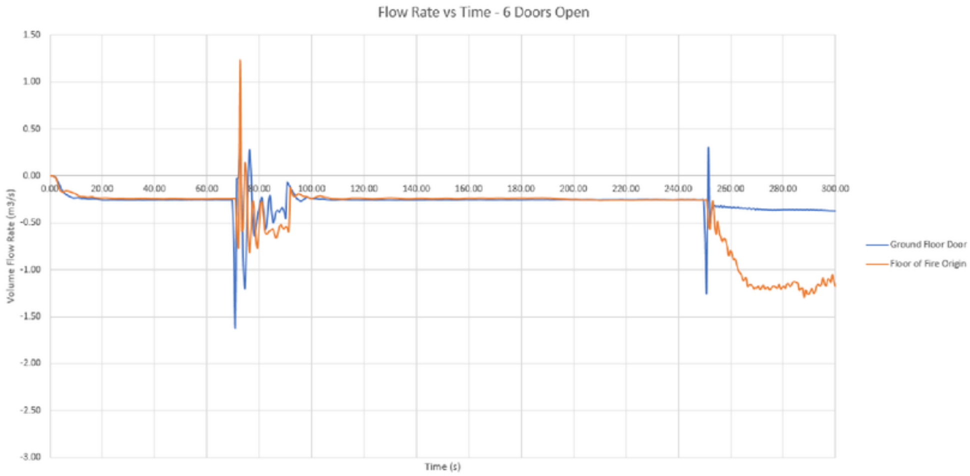

Figure 5.14: Volume flow rates through the ground floor door and floor of fire origin with 6 doors open into the shaft

An analysis of the results of flow rate simulations has been undertaken per figure 5.14;

1. At time t = 0, the simulation begins and airflow is initiated through the inlets within the stair shaft.
2. At time t = 5 s, the flow rate through the small cracks in each door has reached equilibrium and remains a constant 0.2 $\frac{m^3}{s}$ until time t = 70 seconds.
3. At time t = 70 s, the doors on both the floor of fire origin and the ground floor open completely at remain this way for 20 seconds. During this time the flow through the door on fire level peaks at a flow of 2 $\frac{m^3}{s}$ from the stair to the shaft, and 1 $\frac{m^3}{s}$ from the corridor into the shaft. This is considerably different from the previous simulations, as now air is flowing in the opposite direction on the ground floor. Like the previous simulation, the flow rates for both the floor of fire origin and the ground floor continue to oscillate for the remainder of this phase.

4. From time t = 90 s to t = 250 s when all doors are now closed again, the airflow through the cracks tends towards the same values as found in the initial phase.

5. At time t = 250 s, the doors to all 4 stairs reopen. By this time there is a considerable amount of smoke in the corridor adjacent the the stair shaft and the as a result the area is at a high pressure. The flow through both the stair at ground floor and the floor of origin fluctuate considerably before settling at 0.4 $\frac{m^3}{s}$ and 1.2 $\frac{m^3}{s}$ of flow respectively. The flow rates through both the ground floor and the floor of fire origin are considerably lower than found in the 4 door configuration, with a 33% drop in flow through the ground floor opening, and a 21% drop in flow through the floor of fire origin.

The flow rates through the floor of fire origin drops to as low as 0.6 $\frac{m}{s}$ in lieu of 1 $\frac{m^3}{s}$. This suggests that this system may not perform as designed with this many doors open. This is supported by the visibility slices below, which show significant smoke ingress into the stair.

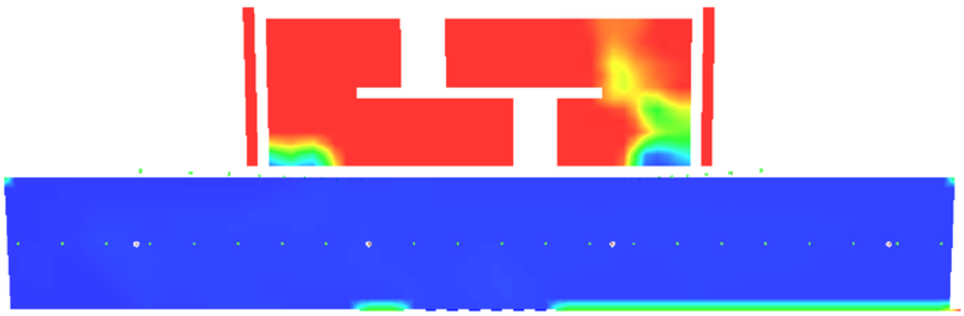

Figure 5.15: Visibility at time t = 300, with 6 doors open

Figure 5.16: Visibility scale

As per the figure 5.16, there is smoke leaking into the staircase, reducing visibility to as low as 5m within the doorway. Thus, it appears as though the stair pressurisation begins to allow large quantities of smoke within a stair once airflow through the door of fire origin drops to a speed of 0.55 $\frac{m}{s}$ or below.

Also of note is that the temperature within the stair does not increase above ambient, due to the ample amount of air flowing through the shaft. The temperatures at 2m above floor level can be found in figure 5.17 below.

Figure 5.17: Temperature at 2m above floor level on the level of interest with 6 doors open.

Figure 5.18: Temperature Scale

Toxicity does increase past zero, to the highest amount of all simulations but the results are nowhere near exceeding the FED tenability limit of 0.3, with a maximum recorded value of 0.0002. FED values only begin increase at 250 seconds, corresponding to the point when smoke initially enters the stair as per figure 5.19.

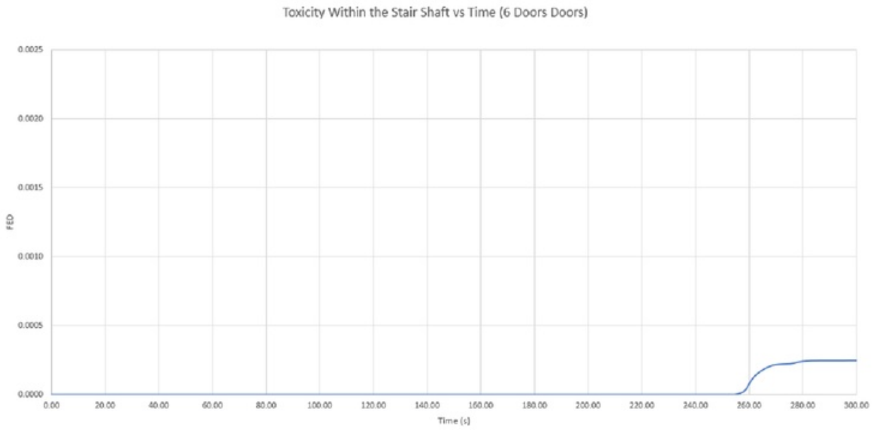

Figure 5.19: Toxicity within the stair shaft

5.5 8 Doors Open

The model used for the simulation is the same model used for all of the above simulations, the only change to which is the number of open doors at any one time which has been increased to 8. The flow rate through the door of fire origin and ground floor are plotted below in figure 5.22.

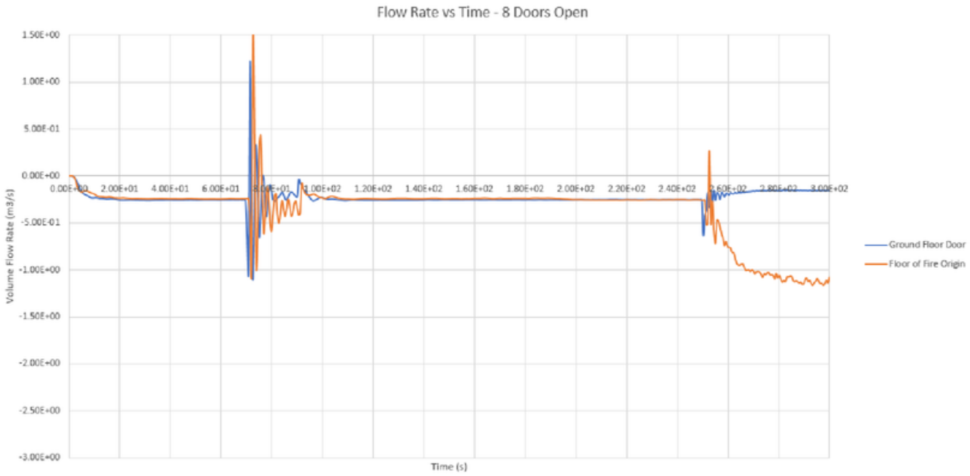

Figure 5.20: Volume flow across doors with 8 doors open

An analysis of the results of flow rate simulations has been undertaken per figure 5.22;

1. At time t = 0, the simulation begins and airflow is initiated through the inlets within the stair shaft.

2. At time t = 5 s, the flow rate through the small cracks in each door has reached equilibrium and remains a constant 0.2 $\frac{m^3}{s}$ until time t = 70 s.

3. At time t = 70 s, the doors on both the floor of fire origin and the ground floor open completely at remain this way for 20 seconds. During this time the flow through the door on fire level peaks at a flow of 1 $\frac{m^3}{s}$ from the stair to the shaft, and 1.5 $\frac{m^3}{s}$ from the corridor into the shaft. This is similar to the simulation where 6 doors are open, but the peak flow on the ground floor are higher. This is likely due to air flowing into the stair from an additional 2 floors, and leakage from all inlet points into the other stories prior to the air making it to the floor it is required.

4. From time t = 90 s to t = 250 s when all doors are now closed again, the airflow through the cracks tends towards the same values as the beginning of the simulation.

5. At time t = 250 s, the doors to all 4 stairs reopen. By this time there is a considerable amount of smoke in the corridor adjacent the the stair shaft and the as a result the area is at a high pressure. The flow through both the stair at ground floor and the floor of origin settle at 0.1 $\frac{m^3}{s}$ and 1.1 $\frac{m^3}{s}$ of flow respectively. The change from the previous simulation, seen in figure 5.14 with four doors open is small, with less than a 5% deviance in flow through both doors of interest.

Neither the flow through the ground floor stair or the flow through the stair at fire origin comply with the flow requirements set out by the Australian code, with a speed through the door of 0.55 $\frac{m}{s}$ in lieu of 1 $\frac{m}{s}$ and as expected, smoke leaks into the stair due to the inadequate barrier created. This leakage can be seen in figure 5.21.

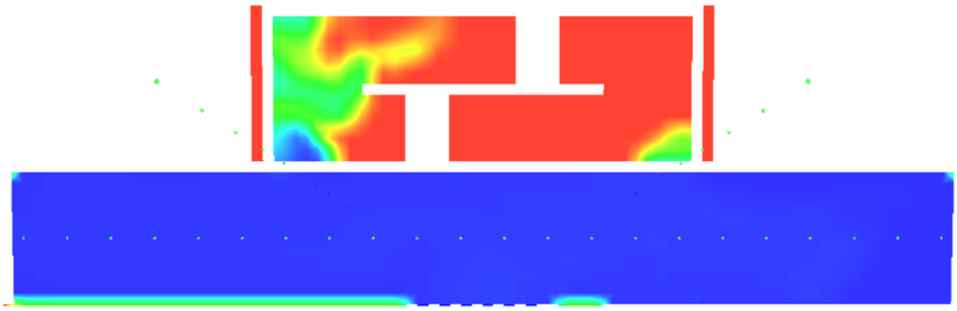

Figure 5.21: Visibility at time t = 300, with 8 doors open

Figure 5.22: Visibility scale for both of the above slices

Figure 5.21 clearly shows significant leakage into the stair shaft. The visibility within the stair is the lowest of all simulations up to this point, suggesting a continued trend between a decrease in flow through the stair of fire origin, and visibility in the stair shaft.

Also of note is that the temperature within the stair does not increase about ambient, due to the ample amount of air flowing through the shaft. This is apparent in figure 5.23.

Figure 5.23: Temperature at 2m above floor level on the level of interest with 8 doors open.

Figure 5.24: Temperature Scale

Toxicity does increase past zero, to the highest amount of all simulations but the results are nowhere near exceeding the FED tenability limit of 0.3, with a maximum recorded value of 0.0003. FED values only begin increase at 250 seconds, corresponding to the point when smoke initially enters the stair as per figure 5.25.

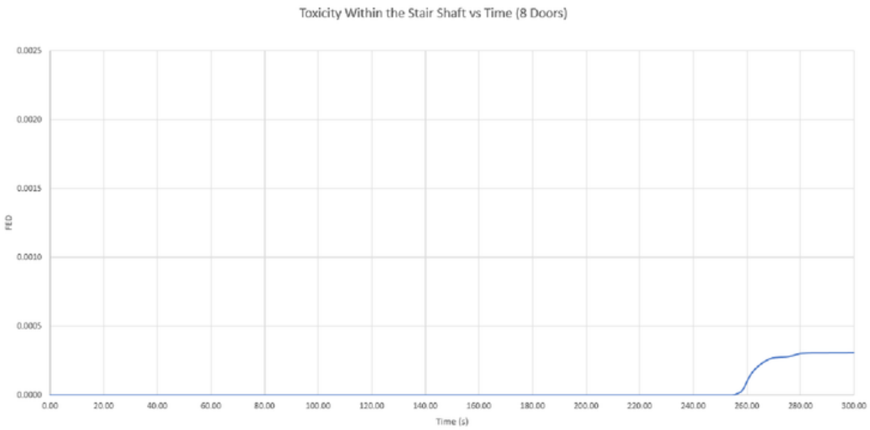

Figure 5.25: Toxicity within the stair shaft

5.6 10 Doors Open

A model has been constructed which features all doors within the model open at a single time. This would be indicative of a building using a simultaneous approach to evacuation. Flow rates through the door are noted in figure 5.26 below.

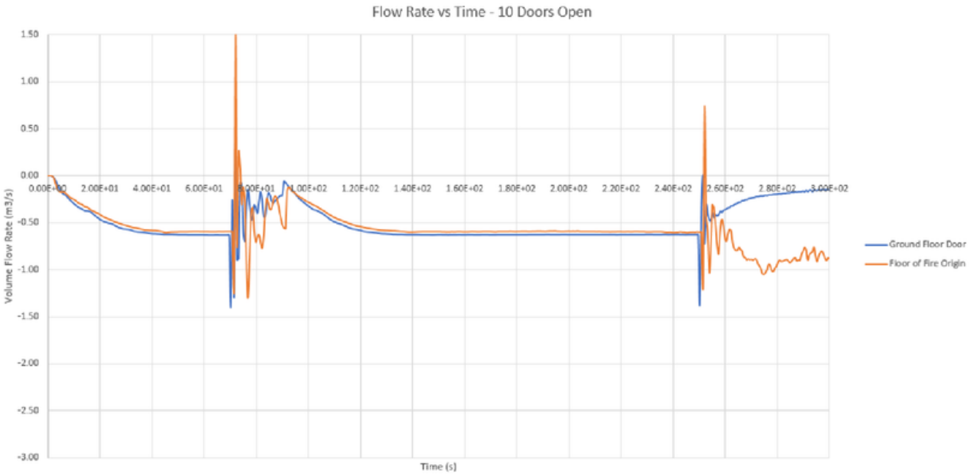

Figure 5.26: Volume flow rates through the ground floor door and floor of fire origin with 10 doors open into the shaft

1. At time t = 0, the simulation begins and airflow is initiated through the inlets within the stair shaft.
2. At time t = 5 s, the flow rate through the small cracks in each door has reached equilibrium and remains a constant 0.5 $\frac{m^3}{s}$ until time t = 70 s. The flow rate through each of the cracks is higher than any of the previous simulations undertaken. It is not apparent why the flow rate through the cracks tends toward a higher value in this simulation, as prior to the doors opening, there is no difference in this simulation to others undertaken.
3. At time t = 70 s, the doors on both the floor of fire origin and the ground floor open completely at remain this way for 20 seconds. During this time the flow through the door on fire level peaks at a flow of 1.25 $\frac{m^3}{s}$ from the stair to the shaft, and 1.5 $\frac{m^3}{s}$ from the corridor into the shaft. This is similar to the simulation where 8 doors are open. Like the other simulations undertaken, there is consistent oscillations throughout this phase and a constant value is never reached.
4. From time t = 90 s to t = 250 s when all doors are now closed again, the airflow through the cracks tends towards the same 0.5 $\frac{m^3}{s}$ value.

5. At time t = 250 s, the doors to all 10 floors reopen. By this time there is a considerable amount of smoke in the corridor adjacent the the stair shaft and the as a result the area is at a high pressure. The flow through both the stair at ground floor and the floor of origin settle at 0.1 $\frac{m^3}{s}$ and 0.9$\frac{m^3}{s}$ of flow respectively. As expected these flow rates are the lowest recorded through all simulations.

The effectiveness of the stair pressurisation system to prevent smoke ingress with all doors open is shown below by a visibility slice in figure 5.27.

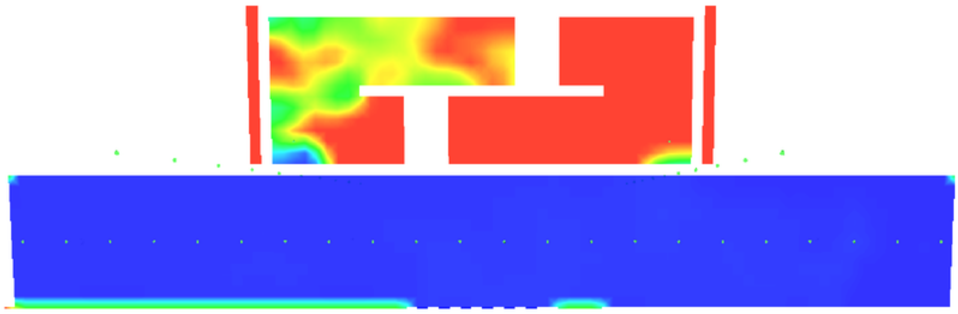

Figure 5.27: Visibility at 2m above floor level on the floor of fire origin at 300 seconds.

Figure 5.28: Visibility scale for both of the above slices

Figure 5.27 clearly shows significant leakage of smoke from the corridor into the stair shaft, with visibility dropping down below 15m in the left-most shaft. This is expected as flow within the shaft drops below 0.45 $\frac{m}{s}$ in lieu of the 1 $\frac{m^3}{s}$ required. Visibility is still higher than listed in table 2.5 but occupants entering the stairs from the floor above may be deterred by smoke in the stair, assuming that the area is compromised.

Like the previous simulations, the temperature within the stair does not change past ambient as a result of the cool air being pumped into to the shaft consistently. This can be seen in figure 5.29

Figure 5.29: Temperature at 2m above floor level on the floor of fire origin at 300 seconds.

Figure 5.30: Temperature scale for the of the above slice

Toxicity does increase past zero, to the highest amount of all simulations but the results are nowhere near exceeding the FED tenability limit of 0.3, with a maximum recorded value of 0.0012. FED values only begin increase at 250 seconds, corresponding to the point when smoke initially enters the stair as per figure 5.31.

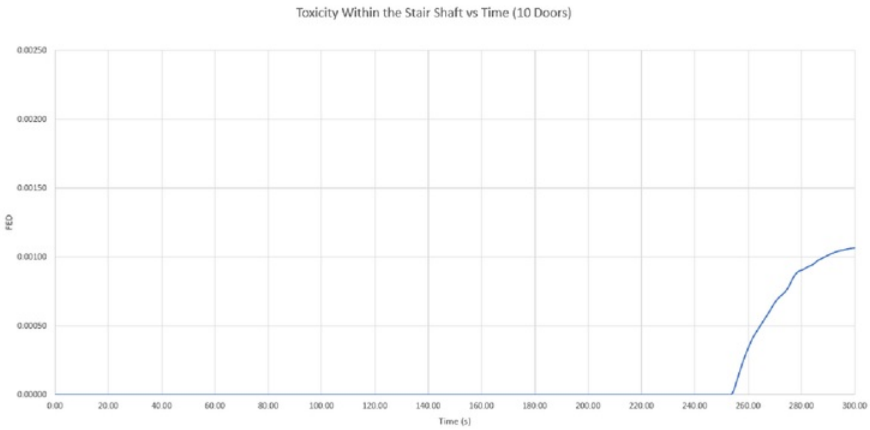

Figure 5.31: Toxicity within the stair shaft

5.7 Result Conclusions

Figure 5.32 summaries the general trend of flow rates through the two doors of interest as the number of doors into the shaft increases. The results for all simulations undertaken about show a clear trend in a reduction in flow rate as the number of doors into the shaft increases. The most significant drop in flow rate occurs between the situation of 2 doors open into a shaft and 4 doors open into the shaft, with a drop in flow rate of over 40%. This significant change is likely down to the fact that the injection points of air are only located every three levels and as a result, once 4 doors are open into the shaft the supply air has to be split amongst additional stories, allowing air which would have previously reached the required floors to leak out onto other stories. This reduces the total amount of air which flows though each individual storey considerably. For openings into the shaft greater than 4, the changes between each individual iteration becomes minor. The reason this change is minor is because the air flowing through each door is already split between over 3 storeys, so the addition of another storey only leads to a minor reduction.

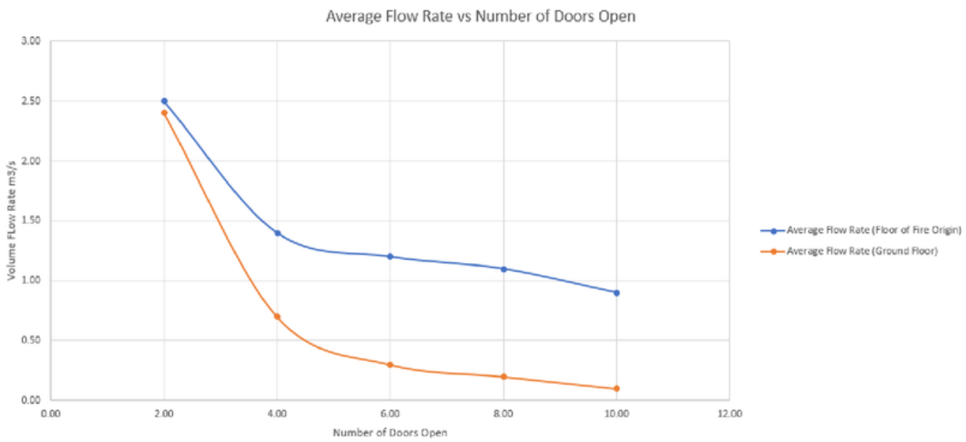

Figure 5.32: Flow rate through doors of interest as the number of doors open in the shaft increases.

As per figure 5.5, 5.10, 5.16, 5.21 and 5.27, Smoke begins to ingress into the stair shaft when 4 or more doors are open at any one time. Comparing this with the flow rates shown in figure 5.32, it is clear that the air barrier begins to fail when airflow through the shaft drops below 1.4 $\frac{m^3}{s}$, corresponding to a flow speed of a flow speed of 0.7 $\frac{m}{s}$, lower than required by Australian Standards. These results suggest that the speed requirements in the Australian Standards are suitable for prevention of smoke. The visibility the stair shaft in each configuration is presented below in figure 5.33.

While visibility was reduced within the stair, all simulations undertaken did not not increases in temperature within the stair shaft, or increases in toxicity to levels even close to that required to endanger human life. This implies that the criteria most likely to be violated during occupant egress is that of visibility.

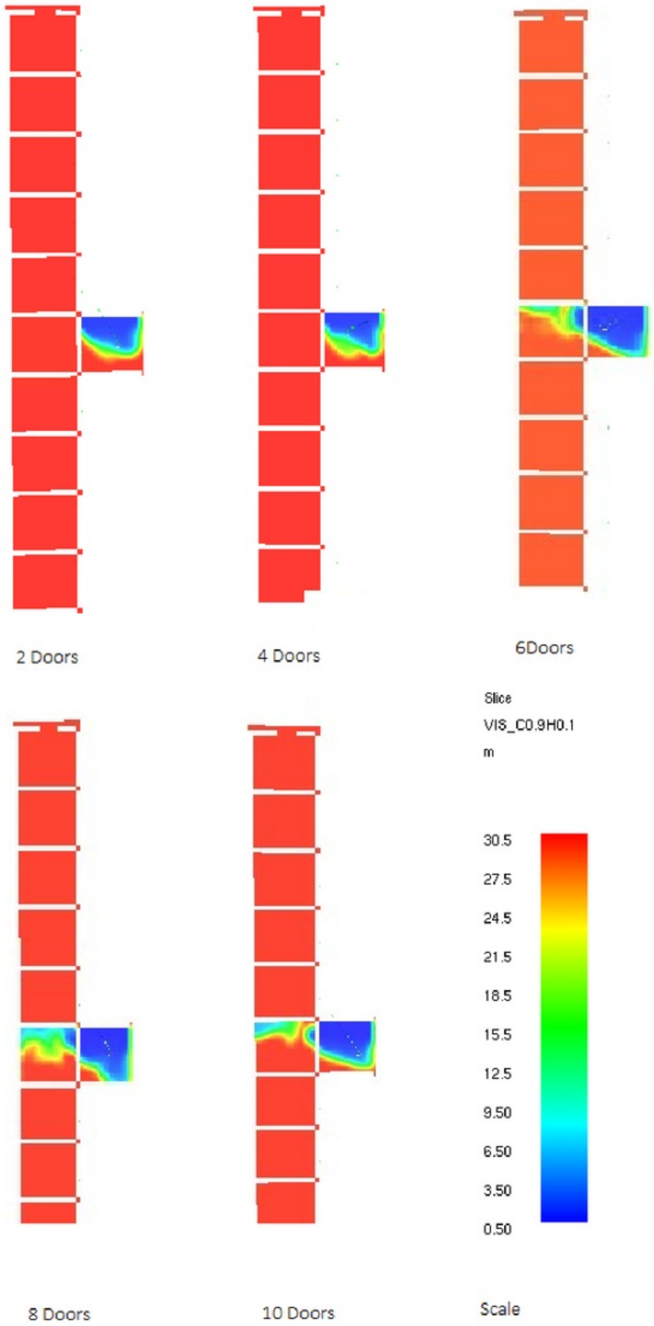

Figure 5.33: Visibility within stair shafts through each of the simulations undertaken

Chapter 6

Conclusions

This thesis aimed to assess differences in possible methods for smoke control in high rise residential buildings. Smoke control is one of the most important factors in ensuring occupants leave a building safely in a fire scenario.

A review of literature surrounding smoke control has been undertaken and suggests that current methods possess inherent issues in tall buildings, often not performing how they were originally intended, or are unreliable. The review also found that smoke inhalation and poisoning was the number one cause of death in fire scenarios, suggesting that maintaining tenable conditions in a building will have a large impact in the number of deaths experienced. The new dilution or common corridor system seeing a small amount of usage worldwide aims appears to be able to improve tenability in buildings while also having inbuilt redundancies and providing space savings.

The review of literature has also uncovered a fundamental gap between the way stair pressurisation systems are commissioned and their configuration in a realistic fire scenario. This gap lies in the fact that only a two doors have to be open to a stair during commissioning, but a considerable amount more may be open as multiple floors of people leave their units. The notion of only having two stairs open at a time is designed to simulate fire brigade members entering the building on the ground floor, and opening a single door to the floor that is originally on fire. This leads to a scenario in which the system is not designed in a way which matches realistic scenarios and requirements of the standards have not changed as the heights of buildings has increased. The code has not changed its commissioning requirements since its inception, while building height restrictions are now as high at 310m, up from the 46m restriction in place in 1957.

A possible finding of the background research undertaken is that there are a number of internationally used smoke control systems employed, aimed at both preventing ingress of smoke into stairs and to create better conditions in the corridors. These systems may allow occupants at the greatest risk additional time to evacuate the building. The additional evacuation time provided to the floor can possibility be used in a justify deviances from the DtS requirements of the BCA. Further research is needed to determine how these systems actually perform, especially from a reliability perspective.

Through research, review and simulation, a number of potential issues were raised. As simulations using a smaller mesh sized took days at a time to run, it was not feasible to run that number of simulations required a such a high resolution. As a result, a mesh dependency study was only undertaken on a single case. With additional computing power or time available, the results could be confirmed as more accurate with further grid dependency studies. However, given the results of the mesh dependency study and data from NSIT it is proposed that the results obtained are still satisfactorily accurate for the requirements of this thesis.

The trends uncovered after simulation work conformed well to initial expectations, with door flow rates decreasing in each successive scenario, as the number of doors into the stair shaft increased. It was however noted that the most significant drop in flow rates occurred between the 2 door and 4 door cases, with a drop in flow rate of over 40%. This significant change is likely down to the fact that the injection points of air are only located every three levels and as a result, once 4 doors are open into the shaft the supply air has to be split amongst additional stories, allowing air which would have previously reached the required floors to leak out onto other stories.

The simulations undertaken have shown that the stair pressurisation system beings to fail when more than 4 doors are open into the shaft at any one time. This is a credible scenario for egress in tall buildings, where it is common to adopt a 'two up one down' approach for evacuation, where occupants from the fire floor, the two floors above and the floor below are all given an evacuation tone simultaneously. The amount of doors open into the shaft will also increase as occupants on other floors begin to leave, either by the alarm system cascading upwards, or fearful occupants leaving as soon as they are provided with an alert tone. The exact amount of airflow required to prevent the ingress of smoke has been deemed by this report to be above an average flow speed of 0.7 $\frac{m}{s}$. To account for the unique evacuation strategies used within each individual building, the stair pressurisation systems must be designed in order to perform adequately in an emergency event. This means that the flow speed should never drop below 0.7 $\frac{m}{s}$ in any credible scenario. Designing a system to comply with this requirements may end up costing the design team and the developer additional money, but the benefits to life safety are of the utmost importance.

The results of this thesis suggest that at the very least, the standards regarding the commissioning of stair pressurisation systems should be updated to account for realistic evacuation scenarios, based on the evacuation strategy adopted by a specific development, including how the system is set to cascade, the number of stories and the expected evacuation time. Changes to the standards would ensure that systems perform as intended in credible scenarios. This is supported by the fact that smoke begun to leak into the stair once 4 doors were open, and the largest drop in flow rate through the door was between the 2 door and 4 door open cases.

The results obtained from these simulations match findings analysed in Chapter 2 of this thesis, showing clearly that as the number of stories of open doors increases, the further the reduction in effectiveness of stair pressurisation systems. Unfortunately, given the amount of computational time required to increase the number of stories within the model, the effect in super high buildings was not able to be analysed. It is however expected that the performance of currently designed stair pressurisation systems would continue to degrade as building grow taller, as the possibility of additional doors being open increases as the number of total stories increases.

Chapter 7

Future Work

This chapter details future work relevant to this thesis. Including changes to Australian code and the possible adoption of international smoke control systems.

7.1 Amendments to Australian Codes

Given that a system complying with the Australian requirements for commissioning may not perform as expected in a real life fire scenario in a building adopting a ''two up one down'' type evacuation strategy, becoming more common in buildings exceeding 25m in effective height, it is clear that there needs to be an update to the requirements to get a system commissioned. These requirements could include the requirement for the mechanical engineer designing the system to take into account the proposed evacuation methodology to be used, i.e. if a building is to be evacuated three storeys at a time, the requirements for flow should be 1 $\frac{m}{s}$ through four doors instead of through simply two.

Another possible change could include designing the system to require a higher speed, while adopting the same commissioning style. This would be in line with the current New Zealand building code which requires achieving an average flow of 2 $\frac{m}{s}$ instead of the 1 $\frac{m}{s}$ required by Australian codes. More needs to be done in order to determine the exact commissioning requirements which would lead to highest level of life safety provisions achievable.

7.2 Additional Simulation Work

The robustness of this research could be significantly improved by the conduction of further simulation work. This report did not look at the stair opening force within stair shafts and outside of visibility, it is the second most important feature in a stair pressurisation system, as if occupants cannot open the doors to the stairs, the performance of the systems in preventing the ingress of smoke is irrelevant. Expanding the extent of the model, in order to look at the performance of systems in taller buildings, could provide additional information of possible design requirements for taller buildings.

Egress modelling on a high-rise building could provide more realistic door open and closing time within a building, allowing more accurate modelling of real life scenarios, above and beyond simply opening or closing all door simultaneously. In a real life scenario, occupants on each floor will leave at different times, opening doors at different points, making the approach taken in this thesis not necessarily the most accurate.

Creation of a full scale model for validation may be expensive, but is the only way to ensure the simulations undertaken in this study match real life scenarios. A scale model could possibly be accecptable, but research would have to be made on the accuracy of smaller scale fire models when compared to full scale models.

7.3 Analysis of Alternate Smoke Control Measures

With a disconnect discovered between the evacuation strategies currently used in high-rise buildings and the commissioning requirements of stair pressurisation systems, it is important to consider methods to create the safest possible conditions for all occupants within a building, especially when these occupants may be asleep when an emergency initially occurs. Apart from the amendments to the Australia code discussed above it is also worth considering other smoke control methods used elsewhere in the world.

In the UK, Colt has developed a unique system which exhausts air at the floor of fire origin, using vents at the top of a stair shaft to generate a sufficient barrier without relying on a mechanical system. Such a system claims to reduce failure rates since the system will still perform well purely by natural means, due to the stack effect causing hot air to rise up the exhaust shaft. The system used by Colt has the further benefit of providing better conditions in the corridor itself, as smoke is exhausted from the space consistently. This also also the fire brigade to vent smoke as they fight a fire.

Further simulation work, looking specifically at alternate methods of smoke control could allow the identification of the best possible method of achieving occupant safety.

Appendix A

Definitions, Abbreviations & Nomenclature

A.1 Overview

Appendix A features definitions for terms used throughout this thesis, as well as abbreviations and nomenclature.

A.1.1 Fire Resistance Level

A grading in minutes, typically specified by testing in accordance with AS 1530.4 against a standard fire curve which supplies a rating in three components to a material or configuration.

1. Structural adequacy - the ability for an assembly to maintain its structural capacity when exposed to fire

2. Integrity - the ability for an assembly to resist the passage of fire and smoke for a given time

3. Insulation - the ability for an assembly to resist the transfer of heat from one side to another after fire exposure for a given time

A.1.2 Fire Rated Construction

Construction featuring a fire resistance level equal to that required by Specification C1.1 of the BCA

A.1.3 National Construction Code - NCC

A document which sets of the minimum required Deemed-to-Satisfy provisions buildings must satisfy before they can be deemed compliant.

A.1.4 Deemed to Satisfy

A method of compliance with demonstrates strict compliances with the prescriptive requirements of the BCA and NCC, without the use of a Performance Solution.

A.1.5 Performance Solution

A method of compliance which demonstrates compliance with the Performance Requirements of the BCA without strict compliance with the prescriptive requirements of the BCA. Use of a Performance Solution requires approval from both a Fire Engineer, a Certifier and often the Fire Brigade.

A.1.6 Deemed to Satisfy

A method of compliance with demonstrates strict compliances with the prescriptive requirements of the BCA and NCC, without the use of a Performance Solution.

A.1.7 Building Code of Australia

See NCC

A.1.8 Fire Door

A door achieving a FRL of at least -/60/30 when tested to AS 1530.4, resisting the passage of heat, fire and smoke for a designated period.

A.1.9 Smoke Seal

An intumescent seal place above doors which swells when exposed to heat, creating a smoke tight barrier preventing a considerable amount of smoke leakage.

A.1.10 Stair pressurisation System

A system which relies on the injection of air into a fire-isolated passageway or stairway such that a pressure barrier is created between a Public Corridor and the fire-isolated area, preventing the ingress of smoke.

A.1.11 Guide to the BCA

A document released alongside the BCA which details the intent of the BCA and provides greater insight into the requirement of each individual clause

A.1.12 Fire Dynamics Simulator

A Large-Eddy-Simulation (LES) software primarily focused on the simulation of fires. This is the industry standard for the simulation of fire around the world

A.1.13 PyroSim

A CAD program which interfaces with FDS, allowing the quick building of models for simulation work, has no simulation capability externally to FDS.

A.1.14 Effective Height

"Means the height to the floor of the topmost storey (excluding the topmost storey if it contains only heating, ventilating, life or other equipment, water tanks or similar service units) from the floor of the lowest storey providing direct egress to a road or open space" [5] SOU – Sole Occupancy Unit – "means a room or other part of a building for occupation by one or joint owner, lessee, tenant, or other occupier to the exclusion of any other owner, lessee, tenant, or other occupier and includes -

1. A dwelling; or
2. A room or suite of rooms in a Class 3 building which includes sleeping facilities; or
3. A room or suite of associated rooms in a Class 5, 6, 7, 8 or 9 building; or
4. A room or suite of associated rooms in a Class 9c building, which includes sleeping facilities and any area for the exclusive use of a resident." [5].

Appendix B

Consultation Meeting Attendance Form

Consultation Meetings Attendance Form

Week	Date	Comments (if applicable)	Student's Signature	Supervisor's Signature
1	31/7	Initial meeting to Discuss timeline.		
3	10/8	Discussed modelling requirements		
5	24/8	Discussed validation vs verification		
7	21/10	Discussed verification results		
9	5/10	Discussed progress		
11	19/10	Discussed post-processing		
13	2/11	Discussed final results + format		
13	6/11	Discussed final changes.		

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