# Analysis and optimization of ventilation systems for smoke control through computational fluid dynamics (CFD) modelling.

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# ANALYSIS AND OPTIMIZATION OF VENTILATION SYSTEMS FOR SMOKE CONTROL THROUGH COMPUTATIONAL FLUID DYNAMICS (CFD) MODELLING

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# Abstract

This thesis promotes the responsible use of CFD technology through the development of the simulation based design strategy applicable to the design of the fire engineered smoke control ventilation systems. The correct representations of the problem of interest and measures that may be adopted to ensure the accuracy of the simulated solution are two key aspects of this promotion.

The development process presents the application of the proposed procedure through three industrial challenges that have subsequently been approved by the relevant fire authorities. The challenges consist of the design of fire engineered systems for residential high rise buildings and covered car parks which in turn demonstrate the robustness of the proposed procedure. The proposed procedure consists of four key stages namely:

- Qualitative Design Review (QDR);
- Quantitative Analysis (QA);
- Assessment; and
- Fire Services' comments

QDR identifies the ventilation strategy, the potential fire scenario and the appropriate assessment approach applicable to the problem of interest. QA uses the chosen fire analytical approach to evaluate parameters identified in the QDR. The assessment stage is where outputs from the analysis are assessed based on the assessment criteria defined in the QDR. Fire Services' comments are there to account for any additional requirements the fire officer responsible might had have as he/she has the final say on whether the fire engineered system is approved for installation.

A review of the current legislative literature i.e. building code, prescriptive and performance based codes is presented. Furthermore, the criteria applicable for the assessment of simulation based design solution are also discussed.

The concept of smoke control is discussed in detail which includes an overview of the mechanism of smoke movement and the provisions available to limit smoke spread. A survey of the current Computational Fluid Dynamics (CFD) software packages suitable for the assessment of smoke movement is also included.

## Declaration and statements

This work has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any degree.

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STATEMENT 1

This thesis is the results of my own investigations, except where otherwise stated. Where correction services have been used, the extent and nature of the correction is clearly marked in a footnote(s).

Other sources are acknowledged by footnotes giving explicit references. A bibliography is appended.

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# Contents

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# List of tables



# List of illustrations

# Chapter 1 Aims and objectives

The main objective of this thesis is to develop an industry specific simulation based design strategy/procedure applicable to ventilation systems for smoke control purposes. The proposed approach provides a systematic framework for the design and assessment of fire engineered smoke control systems, an area which has yet to be thoroughly explored as recent studies emphasised on simulation validation works such as those carried out by Chow et al [1-5], Lougheed et al [6, 7] and Gobeau et al [8].

Chow et al [1-5] and Lougheed et al [6, 7] have evaluated the feasibility of using analytical tools as means of predicting the fire environment, smoke movement and the effects of smoke and heat on occupants. Gobeau et al [8] on the other hand, provides a guide for the appropriate use and assessment of the outputs of analytical solution.

Smoke control systems are ventilation systems designed specifically to restrict the spread of smoke throughout a building. These systems provide protection to the escape routes to enable occupants to escape from a burning building in a relatively safe environment. Fire engineered smoke control systems are solutions which are not listed in prescriptive codes (Code of Practice). In this thesis, non prescriptive codes solutions are also referred to as non code compliant.

It has been fully documented that during an outbreak of fire, the primary hazard is the hot smoke produced [9-14] not the fire itself. This is due to the heat emitted and the presence of the toxic carbon monoxide and other gaseous combustion products, which is fatal to occupants if inhaled in large quantities. To make matters worse, hot smoke which fills the fire enclosure and any potential escape routes impedes occupants escape by reducing the visibility in such routes. The hesitation of the escaping occupants [15] in passing through smoke filled routes increases the time of exposure to the toxic hot smoke and thus puts lives at greater risk. This risk is even more significant when considering the potential chaotic situations while factoring multiple occupants escaping at the same time. Such scenarios can often be found in highly populated buildings or buildings where people congregate, e.g. high rise apartments, office blocks, shopping centres, airports and underground train stations, where many occupants may need to escape at any one time.

Smoke control systems are therefore invaluable in minimizing the possibility of serious contamination of the escape routes (e.g. common corridors and stairwells) by smoke and allows for the passage of escaping occupants in relative safety. Hot smoke is removed from the protected space via dedicated exhaust path, which reduces the concentration of the contaminant while at the same time, improves the visibility within the protected space. The possibility of hot smoke spreading throughout the whole building can either be minimized or prevented depending on the ventilation strategy. Smoke control systems can also aid fire fighters in performing their duties.

The movement of the smoke plume, otherwise known as the gaseous combustion products of a flaming fire, is essentially driven by the physics of the thermo-fluid flow. Thermo-fluid flows can be fully captured by means of Computational Fluid Dynamics (CFD) methods and represents an excellent tool by which to study the behaviour of such flows particularly when influenced by a smoke control system. This therefore makes simulation based upon CFD technology suitable for the design and analysis of smoke control systems.

The branch of fire engineering which adopts CFD technology is known as Field Modelling [16]. Field modelling divides the fire enclosure into small volumes called 'Control Volumes or 'Cells' and solves for the fundamental equations of fluid dynamics and fire dynamics within each cell. The small control volumes therefore provide detailed solution of the fire enclosure.

Another method of analysing the spread of smoke is Zone Modelling [17]. Zone modelling divides the enclosure into layers of uniform properties, typically hot and cold layers, and solves the empirical correlation between the layers. The hot layer represents the hot smoke produced by the fire while cold layer represents the low level ambient air.

Zone modelling is the current industry standard in the design and assessment of smoke control systems. However, current trends indicate that field modelling is overtaking zone modelling as the preferred investigative tool. Reasons for such a rise are due to field model's ability to analyse problems with complex geometry and to capture the detailed solution of the fire enclosure. Detailed discussion of both CFD and zonal models is provided in a subsequent chapter. This thesis further supports the move away from zone model to field model as an investigative tool.

In addition, this thesis intends to be

- **Informative** – It presents a general guidance on the use of CFD as an analytical tool in the design and assessment of smoke control systems. This is to benefit fire engineers and fire authorities alike who may have limited knowledge of CFD technology. Included in this thesis is an introduction of the computational models applicable to the design of smoke control systems e.g. zone and field models; a summary of the fire dynamics and smoke movement principles; a survey of suitable CFD software packages with an introduction to CFD technology and its sub-models relevant to fire and smoke modelling; and a summary of the assessment methods in the use of field models as a design tool.

  Questions to be addressed include:
    - What is CFD?
    - Why CFD as a design and assessment tool?
    - What are sub-models? What do they represent and why are they important?

- **Methodical** – It presents the simulation based design procedure for the design of smoke control systems and its application to industry. Included in the discussions are the design processes, from receiving client's drawings through to the approval of design by fire authorities; setting up computational model while identifying boundary conditions; identifying the design objective, the design fire scenario, and assessment methodology.

Questions to be addressed include:

- o Computational model, what needs to be considered and why?
- o What are the design assumptions and their justification?
- o Extract rates, how does it relate to choosing the correct fan?

- **Assessment** – Discuss the assessment methods and its respective merit in evaluating the performance of the smoke control system. The assessment will be in two parts: Part 1 is the numerical assessment of the CFD results e.g. the accuracy of the results; Part 2 relates to the performance of the smoke control systems i.e. whether the intended design objectives are achieved.

  Questions to be addressed include:

  - o What measures are available to ensure that the CFD simulation is valid?
  - o What is the measure of the accuracy of CFD simulation?
  - o Has the design objectives been met?

Through the process of developing the simulation based design strategy and addressing the questions above, the other key objectives of this thesis are:

- To provide an understanding of CFD technology and its application in field models.
- To promote responsible use of field modelling approach in the design and assessment of smoke control systems. In particular, the measure of the accuracy of the numerical simulations.
- To promote a general framework for the design and assessment of smoke control systems using field modelling fire analytical tool.
- Successful implementation of the framework for the design and assessment of fire engineered solutions as well as obtaining the final approval for the installation of the fire engineered systems.

# Chapter 2 Industrial context for smoke control

This chapter presents a literature review of current building code and codes of practice for the design of smoke control systems. The functional objectives of smoke control systems are also presented along with current design procedure when using prescriptive codes.

Included in the review of prescriptive codes are examples of smoke control systems whose designs are code compliant. The means of ventilation in these examples presented are by natural means and mechanically powered (e.g. pressurization and depressurization).

In addition, the review of performance based codes focuses on the role they play in the design of smoke control systems, their benefits and disadvantages and their connection with the use of fire analytical tools in order to achieve code compliance. Acceptable assessment methodologies are also presented to compliment the review as this is the critical criteria to obtaining code compliance.

## 2.1 Aims of smoke control systems

UK fire statistics [9-14] recognized that smoke is the main cause of death during fire hazards. This emphasised the need to provide an adequate yet efficient control mechanism to minimise the spread of smoke in buildings particularly in high rise buildings. The functional objectives of smoke control systems are [18]:

**Life safety** – To maintain tenable conditions within the protected spaces for occupants escape for as long as required. Environment for occupants escape is safeguarded by the removal of hot smoke from the protected space. This will allow for an increase in the visibility of the space and reduction in the amount of exposure of hot toxic fume to occupants.

**Assist fire fighting operations** – To facilitate effective fire fighting operations and to maintain relatively smoke free access route intended to be a safe bridgehead for fire fighters to prepare themselves without the use of breathing apparatus prior to the engaging of the burning accommodation. Once fire is suppressed, the systems can aid in the clearance of smoke within the protected space.

**Property protection** – Damages to properties are minimized by reducing the exposure of hot smoke and removal of any accumulated smoke from the protected space. Extensive losses can also be limited to rooms which house valuable electronic equipment that are particular sensitive to smoke damage by benefiting from these systems.

## 2.2 Current practices

Current industry practice in the design of smoke control systems for high rise buildings, considering their popularity and variety of uses e.g. flats, offices and shopping centres still relies heavily on prescriptive codes even with the introduction of performance based codes. The reasons for such a trend are that prescriptive codes are relatively straightforward and simple to use, embody past experience and that solutions, if followed to the letter are accepted by fire authorities without the need for further justification.

Another factor is the cost. The allocated budget for the design and installation of smoke control systems for a typical development is only a small fraction of the total cost. Therefore, prescriptive codes which are simple to implement and with less red tape (e.g. possible delays) are the ideal choice for designers for they will cost little.

The flowchart in Figure 2.1 shows a typical decision making process of a fire engineer when designing smoke control systems. The first step after receiving a client's drawing is to review the drawing against building codes. For example, Approved Document B [19] is the primarily reference for the design of buildings other than dwelling houses. This code states the conditions at which smoke control provisions are required and is discussed in further detail in subsequent subsection.

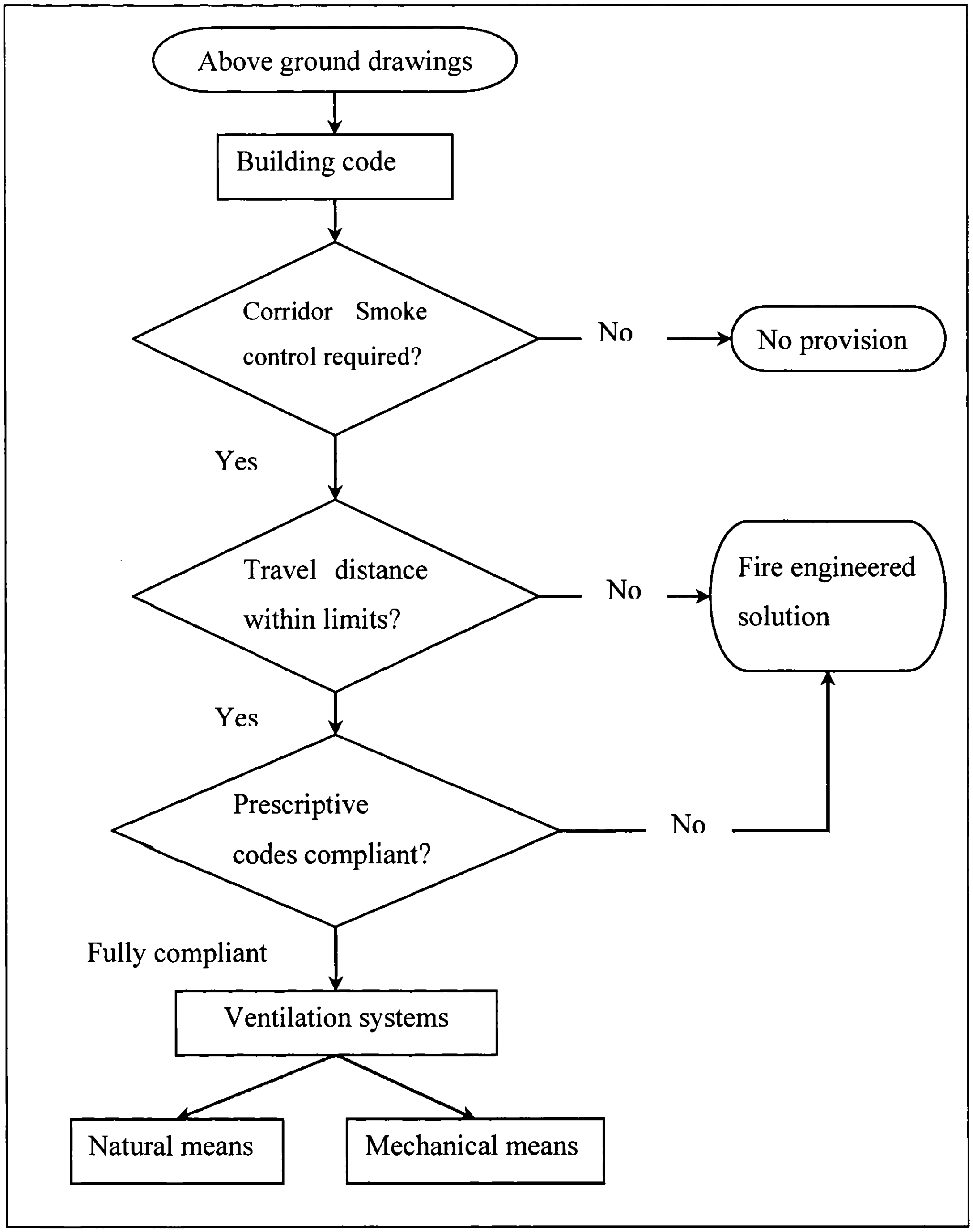



Figure 2.1 – Decision making process for above ground smoke control systems.

Once the requirement for smoke control provisions is established, the maximum travel distance (i.e. maximum distance of travel from the entrance of the furthest accommodation to the stair door) as indicated in the client's drawing is determined. For common lobbies/corridors whose maximum travel distance complies with the building code, the smoke control systems can be designed in accordance to prescriptive codes: BS9999:2008 [20] for ventilation by natural means and BS

EN12101 part 6:2005 [18] for ventilation by pressure differential, on condition that all requirements stated in the respective prescriptive codes are met. An example for each of the systems is discussed in section 2.2.2.

For common lobbies/corridors whose maximum travel distance exceeds the prescribed value or when requirements of prescriptive codes cannot be achieved in full, smoke control systems can only be designed by means of fire engineered solution which is beyond the scope of prescriptive codes.

Fire engineered solution is made possible by the introduction of performance based codes. Fire engineered smoke control systems are solutions whose performance are evaluated against a set of acceptance criteria or objectives [21]. Acceptance criteria are defined by the chosen assessment approaches that set out the requirements at which the performance of the fire engineered solutions when met are deemed acceptable for installation.

These points toward the need for an investigative tool in order to analyse the performance of such a fire engineered solution which can then be compared against the acceptance criteria. Zone and field models are such tools. The merit of such systems needs further approval from fire authorities namely the local fire brigade and local building council [21]. It is the intention of this thesis to present the procedure for the application of a CFD based fire analytical tool in the smoke control industry.

### 2.2.1 Building codes

Building codes define the conditions on the extent to which a building requires smoke control provisions. Using high rise residential building as an example, the need for provisions of smoke control, with reference to Building Regulation 2000 Approved Document B [19], is dependent on three main criteria which are:

- Height of the building;
- Maximum distance of travel from the entrance of the furthest accommodation to the stair door (referred to as maximum travel distance here after); and
- Number of common escape routes (for multi-storeys buildings, this also refers to the number of stairwells).

Small single stair buildings

Small single stair buildings are buildings which have only one direction of escape. As stated in Approved Document B 2000 [19], small single stair buildings are defined as

- Top floor of the building exceeds 4.5m but no more than 11m above ground level;
- No more than three storeys above ground level storey;
- Stair does not connect to a covered car park; and
- Maximum travel distance of 4.5m.

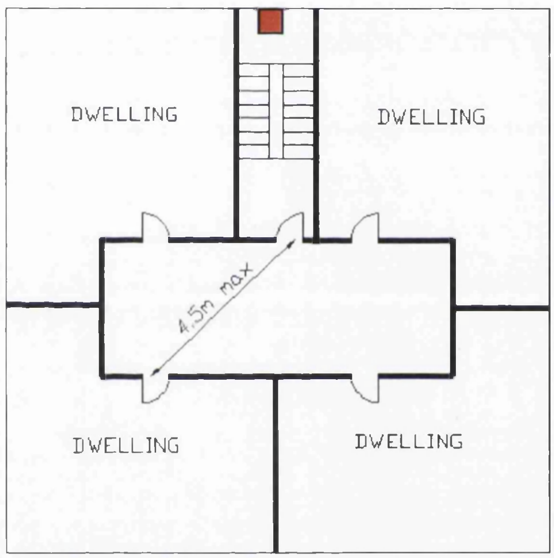



Figure 2.2 – Small single stair building with maximum travel distance of 4.5m.

Provision for smoke control is not required for the common lobby/corridor which serves the accommodations and stairwell. Instead, smoke control provision only needs to be provided for the stairwell. The protection offered to the stairwell can be in the form of either a high level vent at each floor level or a single openable vent at the head of stair, shown in red in Figure 2.2, which can be remotely activated from the fire and rescue service access level.

The maximum travel distance can be increased to 7.5m on the condition that smoke control provisions are provided to protect the common lobby/corridor.

Single direction of escape

For single stair buildings other than those classified as small single stair [19] (e.g. buildings where the top floor exceeds 11m in height), smoke control provisions need to be provided to the common lobby/corridor serving the stairwell in addition to those provided in the stairwell.

Similar to small single stair buildings, these buildings have only one common direction of escape. With the requirement of smoke control provisions, the common corridor has a maximum travel distance of 7.5m. Examples of such arrangements are given in Figure 2.3 and Figure 2.4.

Figure 2.3 shows that the common lobby which serves the stair needs to be ventilated. This is so that some degree of protection is offered to the stairwell which will allow occupants living above the fire floor to escape, when requested, in a relatively safe environment via the stairs.

Common corridors on both sides of the common lobby do not require smoke control provisions as they do not serve the stair directly.

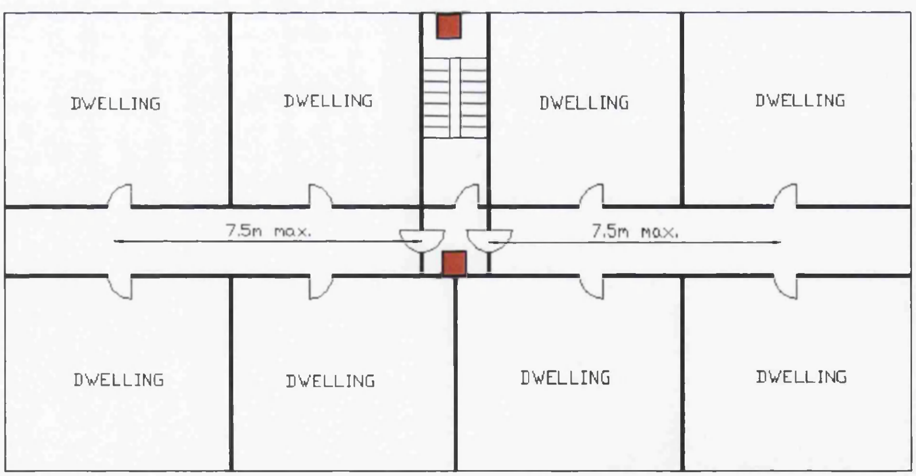



Figure 2.3 – Maximum travel distance for common corridor.

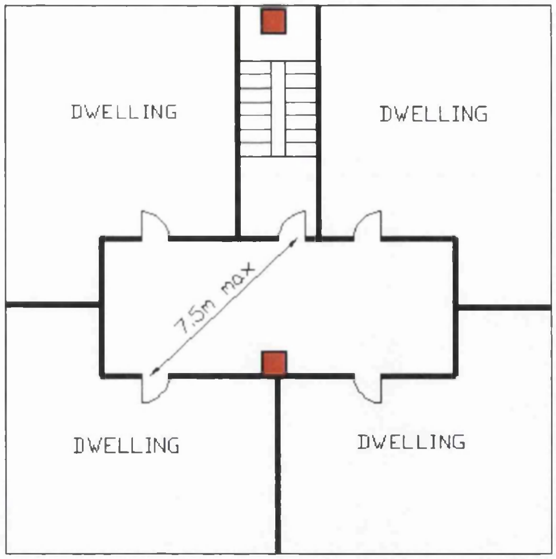



Figure 2.4 – Maximum travel distance for common lobby.

Two or more directions of escape

Buildings which have two or more stairwells generally have either one or two directions of escape. Figure 2.5 is a good example where dwellings in the dead end of the common corridors to the left and right of the layout have only one direction of escape whilst dwellings in between the two stairs have two directions of escape (i.e. occupants can escape in the opposite direction).

The dead end common corridors have a maximum travel distance of 7.5m while the common corridors with two direction of escape have a maximum travel distance of 30m. Smoke control provisions need to be provided for the common corridors that serve the stairwell directly.

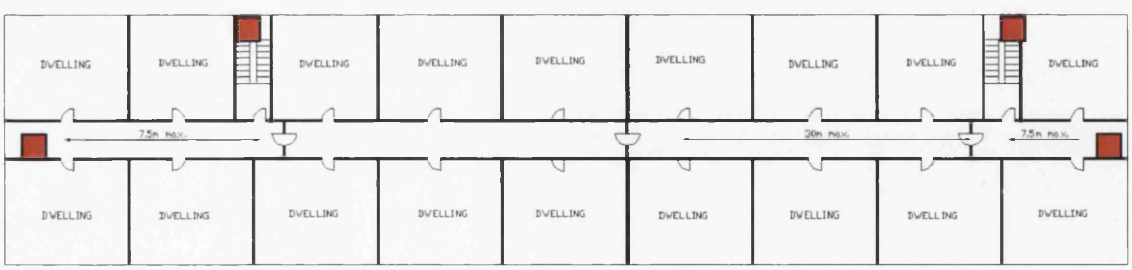



Figure 2.5 – Layout with two stairs.

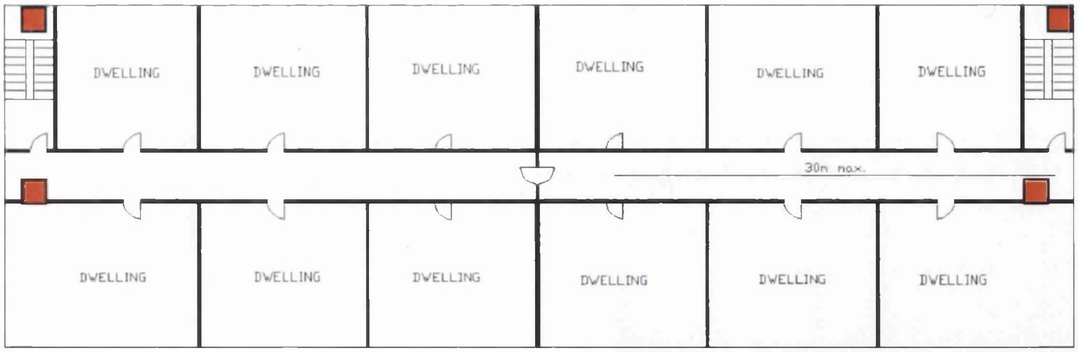



Figure 2.6 – Example of 30m corridor serving the stairwell directly.

Means of escape provisions

Provisions for means of escapes for flats are based on the assumptions stated in Clause 2.3 [19]:

- fire is generally in a flat;
- there is no reliance on external rescue (e.g. by a portable ladder);
- High degree of compartmentation – low probability of fire spread beyond the flat of origin and that simultaneous evacuation of the building is unlikely to be necessary;
- Although fires may occur in the common parts of the building, the materials and construction used there should prevent the fabric from being involved beyond the immediate vicinity.

Hot smoke which filters into a communal area (e.g. common lobby/corridor) from the flat on fire will fill the communal area and in turn impede occupants' escape. The ability and tendency of occupants to escape through smoke filled communal area drops drastically. Hence, smoke control systems are crucial in providing a safe environment for both occupants to escape and fire fighters to work in.

Fire fighting provisions

In buildings other than low rise buildings, provisions for additional fire fighting facilities are required by fire fighters to minimise delays in reaching the fire and to provide a safe environment in which to operate. This requirement is stated in Clause 17.1 [19] as:

> "In low rise buildings without deep basements fire and rescue services personnel access requirements will be met by a combination of the normal

> means of escape and the measures for vehicle access in Section 16, which facilitate ladder access to upper storeys. In other buildings, the problems of reaching the fire and working inside near fire necessitate the provision of additional facilities to avoid delay and to provide a sufficiently secure operating base to allow effective action to be taken."

The additional fire fighting facilities consist of a fire fighting lift, fire fighting stair and fire fighting lobby, the combination of which is known as the fire fighting shaft. These facilities serve all intermediate storeys between the highest and lowest storey that they are designed to serve.

In most residential buildings the need for fire fighting lobbies, which serves the fire fighting stairs and fire fighting lifts, may be omitted and be replaced by the protected communal area designed for means of escape purposes. This is clearly documented in Clause 17.14 [19] which states:

> "Where the design of means of escape in flats has followed the guidance in Section 3 and 9, the addition of a fire fighting lobby between the fire fighting stair(s) and the protected corridor or lobby provided for means of escape purposes is not necessary. Similarly, the fire fighting lift can open directly into such protected corridor or lobby, but the fire fighting lift landing doors should not be more than 7.5m from the door to the fire fighting stairs."

Fire fighting strategy

During the evacuation process of residential high rise buildings, it is common practice that only the occupants of the flat which is on fire are evacuated while occupants of other flats seek refuge in their respective apartments. This is possible due to the high compartmentalisation between flats which keep occupants of other flats in a relative safe environment. Occupants in other flats will only be evacuated if instructed to do so by fire fighters.

Protection for common escape routes

All walls and floors except for external walls of a building are of compartmental construction and fire rated to a minimum of 60 minutes. This is to ensure that the structural integrity of the buildings is not compromised throughout the fire event therefore allowing occupants to escape while providing access for fire fighter to reach the fire scene.

### 2.2.2 Prescriptive codes

There are currently three types of ventilation systems in the UK market that are associated with smoke control, all of which are specified in prescriptive codes. The systems, with their respective codes are:

- Natural means, design specified in BS9999:2008 [20];
- Pressure differential systems (pressurization), design specified in BS EN 12101 part 6:2005 [18]; and
- Depressurization system, again specified in BS EN 12101 part 6:2005 [18].

As the name suggests, smoke control by natural means exploits the buoyancy of the hot smoke and an opened window located in the protected space. The opened window provides a path for the hot smoke to flow out of the protected space while at the same time allows cool external air to enter the protected space. With sufficient free area, the open window allows for the efficient removal of hot smoke therefore preventing its accumulation in the protected space. Hence, this enables occupants to escape in relative safety.

The effectiveness of the natural systems is highly influenced by wind, stack effect (known as the bulk movement of air within buildings due to internal and external temperature differences), buoyancy of smoke, effective free area of the opening, the dimensions of the opening and the position of the opening. Wind, stack effect and smoke buoyancy influence the movement of smoke through small pressure differences that each mechanism produces. Combinations of these small pressure differences are capable of spreading smoke throughout a high rise building if a smoke control system is not provided or is inadequate.

Effective free area of the opening, its dimension and its position affects the ventilation efficiency of the hot smoke. The efficiency of an opening of 1.5m$^2$ positioned at high level as close as practical to the ceiling is much more effective in ventilating smoke than an opening of the same size positioned at low level. Detailed discussion of this point is provided in Section 3.4.2.

Pressure differential systems [22] use mechanical fans to introduce external air into the stairwell or protected space or both. This creates a pressure difference between the protected space and stairwell or between the accommodation on fire and the protected space. This pressure difference discourages hot smoke from flowing into the pressurized space ensuring a smoke free environment for occupants to escape.

The risk of failure of the pressure differential systems in operation when required is medium compared to natural systems which is low [23]. This is due to the increase in the number of components required when installing pressure differential systems. The design pressure difference not being achieved may also be a factor to the increased risk as natural systems have not such concerns.

That being said, pressure differential systems, when in full working order, are a more effective means of protecting the protected space compared to ventilation by natural means. This is because small pressure differences due to factors that influence smoke movements are overwhelmed by the pressure difference produced by the pressure differential systems. The advantage of pressure differential systems is further confirmed by BRE Report no. 79204 [24] which states:

> "Pressure differential systems have specific advantages in providing a higher standard of protection in specific buildings, particularly those operating a means of escape strategy based on phased evacuation. They can also provide a greater level of protection to the fire-fighting lobby itself than any of the natural ventilation systems discussed herein".

The opposite of introducing external air, depressurization systems use mechanical fans to extract hot smoke within the protected space at a high level. These mechanical fans need to be fire rated as they are in direct contact with hot smoke. In these systems a source of inlet air is crucial and needs to be provided as a replacement for the hot smoke removed.

Smoke control by natural means and pressure differential are often chosen as the preferred methods of protecting the common escape routes in high rise buildings. Depressurization systems, however, are often used in protecting buildings with large open spaces such as atria, typically, shopping centres and covered car parks. An example for each of these systems is discussed later.

Examples of smoke control systems by natural means in accordance to BS 9999:2008 [20]

As mentioned previously, smoke control by natural means take advantage of the buoyancy possessed by hot smoke in order to remove it via an opening which leads to open air. The arrangement of the opening can be either one of two ways and are associated with the layout of the protected space. They are:

- Openable windows (vertical orientation) and roof vents (horizontal orientation) are suitable for buildings whose protected space has an external wall leaf or ceiling which connects the roof. (An example given in Figure 2.7)

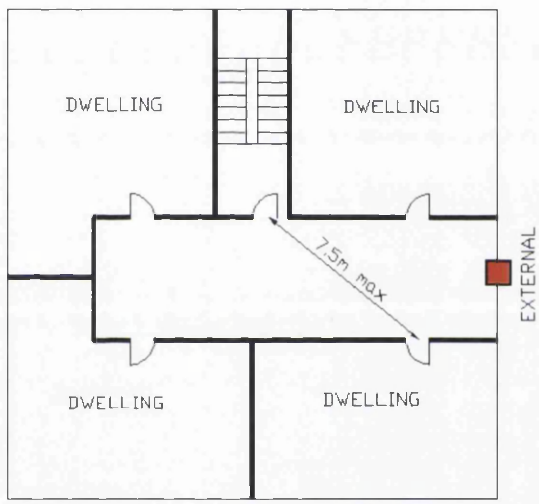



Figure 2.7 – Common lobby with external wall.

- Lobby ventilators (vertical orientation) which opens into a smoke shaft that rises the entire length of the building are suitable for buildings whose protected space is enclosed by accommodations (An example for such an internal protected space is given in Figure 2.4).

*Openable windows/vents*

Openable windows/vents used as smoke control provisions for common lobbies/corridors are required to have a geometric free area of not less than $1.5m^2$ and be open to external air. The openable windows/vents can either be manually operated or automatically actuated upon detection of smoke in the protected space and be positioned as near to the ceiling as practically possible or at least as high as the top of doors serving the stair. The 1.5m$^2$ free area is also applicable to roof vents. The geometric free area is acceptable for both means of escape and fire fighting operations.

The flow scheme often found across these types of vents, shown in Figure 2.8(a) is that hot smoke flows out to open air through the top half of the opening while cool external air flows into the protected space via the bottom half of the opening. A natural plane where no net flow occurs is often seen at the middle of the opening.

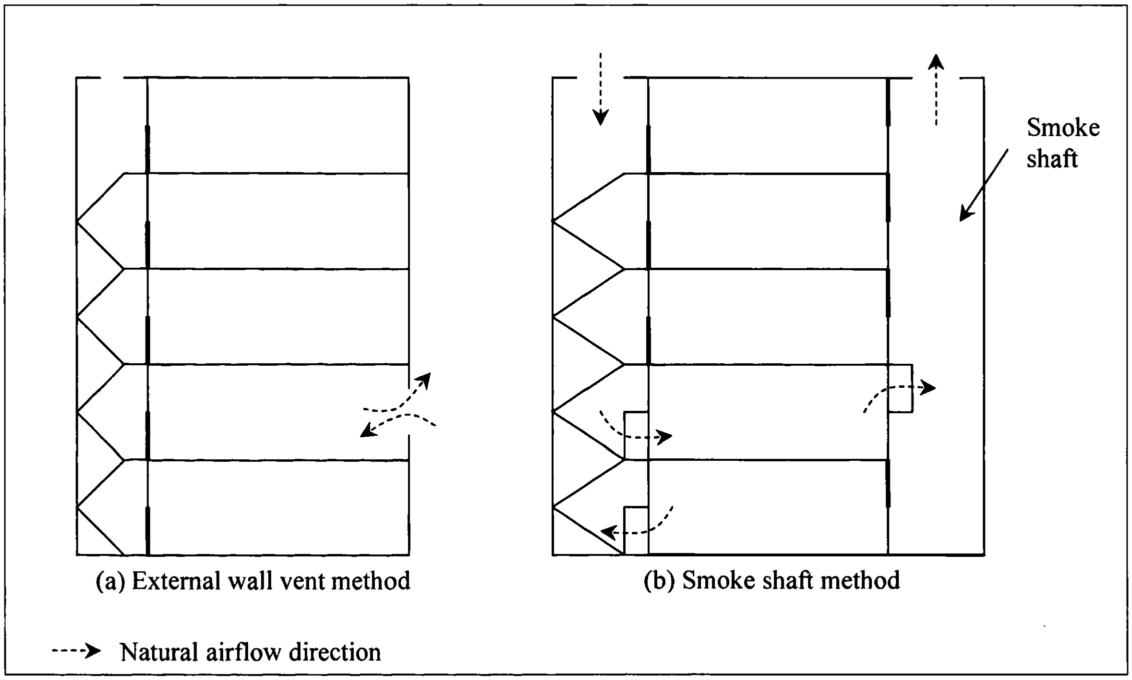



Figure 2.8 – Natural ventilation method

*Smoke shafts*

Smoke control provisions for internal common lobbies/corridors can be provided via a lobby ventilator on each floor opening into a common smoke shaft rising the length of the building that needs protection. For example, consider a typical 5 storeys building where the common corridors/lobbies on the ground and first floors are ventilated by means of an openable window while the second to fourth floors common corridors/lobbies are land-lock and are ventilated by a smoke shaft. The smoke shaft can then be constructed on the second floor rising to the fourth floor of the building and in this case, be closed at the bottom. The smoke shaft can either be:

- Open at top and bottom with minimum cross sectional area of $3.0m^2$ in accordance to BS 9999:2008 [20]; or
- Open at top and closed at bottom with minimum cross sectional area of $1.5m^2$ for residential high rise buildings and $3.0m^2$ for commercial high rise buildings in accordance to BRE Report no. 79204 [24].

Hot smoke flows into the smoke shaft via the lobby ventilator and out through a head of shaft vent at the top as shown in Figure 2.8 (b). Replacement air can be provided either by the ground floor entrance via the ground floor stair door or the head of stair vent when it is not used to vent smoke which has flowed into the stair.

The lobby ventilators are required to have a geometric free area of not less than $1.5m^2$ and be automatically actuated. The lobby ventilators are installed with the top of vent positioned as close to the ceiling as practically feasible and at least as high as the top of door serving the stair.

Smoke shafts must be of fire resistance construction and can either be made of builder's work (brick, block works and etc) or ductwork. The top of smoke shafts should be located in regions with a negative wind pressure coefficient to further encourage smoke exhausts. Positive wind pressure coefficient will severely hinder the performance of smoke shafts for obvious reasons.

*Stairwells*

Stairwells with external walls serving a top floor of less than 30m in height are to be provided with an openable vent with geometric free area of $1.0m^2$ either at each storey with manual operation or at head of stair with remote operation procedure.

Internal stairwells serving a top floor of less than 30m are to be provided with an openable vent with geometric free area of $1.0m^2$ operated either remotely or automatically.

*Vents opening mechanisms*

All openable vents (in stairs, lobbies, and shafts) provided for smoke control should adhere to the following

- Be outward opening;
- Not to be top hung;
- Open a minimum of 30° except for head of stair vent; and
- Head of stair vent to open 120°.

Vents which are remotely openable should be provided with a remote control located adjacent to the fire services access doorway. The remote control is required to have a capability of opening and closing the vent.

An automatic opening vent is designed to open upon the detection of hot smoke within the protected spaces. Upon activation, only the automatic vent in the protected space of the fire floor where smoke is detected is opened, all other vents remained closed.

<u>Example of smoke control by pressure differential in accordance to BS EN 12101 part 6 [18]</u>

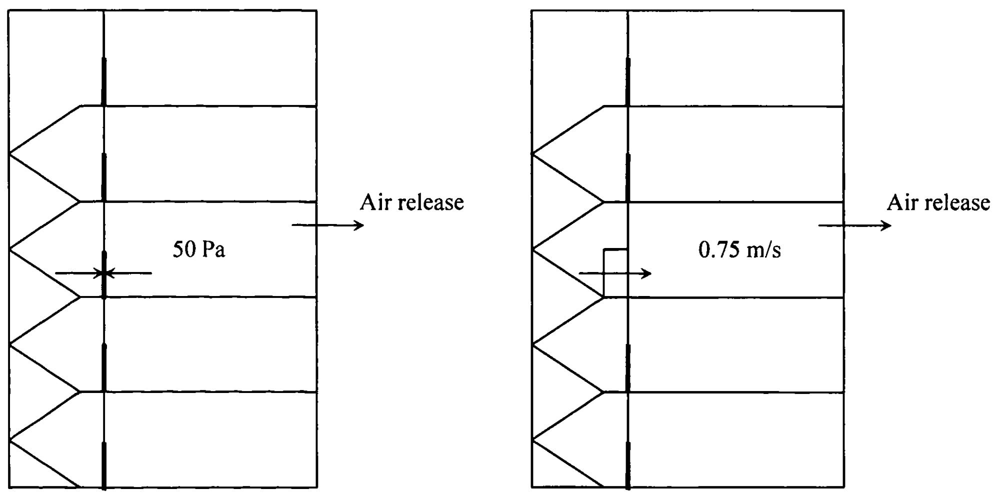
Pressure differential systems are systems that raise the pressure of a protected space intended to be kept free of smoke e.g. common stair and sometimes common corridors depending on the fire safety objectives identified. The difference in pressure between the protected space and adjacent spaces prohibits hot smoke to flow into the protected space. This system is used typically in high rise buildings with internal protected space.

Class A and Class B pressurization systems are discussed. The former system is designed for means of escape i.e. the time at which occupants escape whereas the latter is designed for both means of escape and fire fighting. These systems are compliant in accordance with EN 12101-6:2005 [18].

*Class A pressurization system for means of escape*

As the name suggested, these system are designed primarily for means of escape and are based upon the assumption that occupants of the building will not be evacuated unless directly threatened by fire or told otherwise by fire officers. Provisions for the level of compartmentation are such that occupants will be in relative safety while remaining in the building. Therefore, no more than one door serving the protected space will open simultaneously.

The closed door pressure difference across the pressurized stair and the lobby/corridor is not less than 50Pa ± 10%. Air release within the lobby/corridor is assumed to be opened.




(a) Pressure difference

(b) Airflow criterion

Figure 2.9 – Class A systems design conditions [18]

When all doors serving the stairwell are closed except for the fire floor, the air flowing through the doorway between the pressurized stair and the lobby/corridor is not less than 0.75m/s. Air release within the lobby /corridor on the fire floor is again assumed to be opened.

*Class B pressurization systems for fire fighting*

The systems are designed to minimise the exposure of fire fighting shafts (i.e. a combination of fire fighting stair, fire fighting lobby and fire fighting lift shaft if provided), to smoke during both means of escape and fire fighting process.

As such, the doors between fire fighting lobby and accommodation on fire will be opened to allow for fighting access. In some cases, the door serving the stair will need to be opened in order to connect water hoses to the fire mains on the floor below.

The air supply shall be sufficient to maintain a minimum pressure differential of 50pa across lift well and accommodation area and across stair and accommodation area, whilst the minimum pressure differential across closed doors between each lobby and accommodation area is to be kept at 45pa, provided that all doors to the lift, stair and lobby and the final exit doors are closed and the air release path from the accommodation area is open.

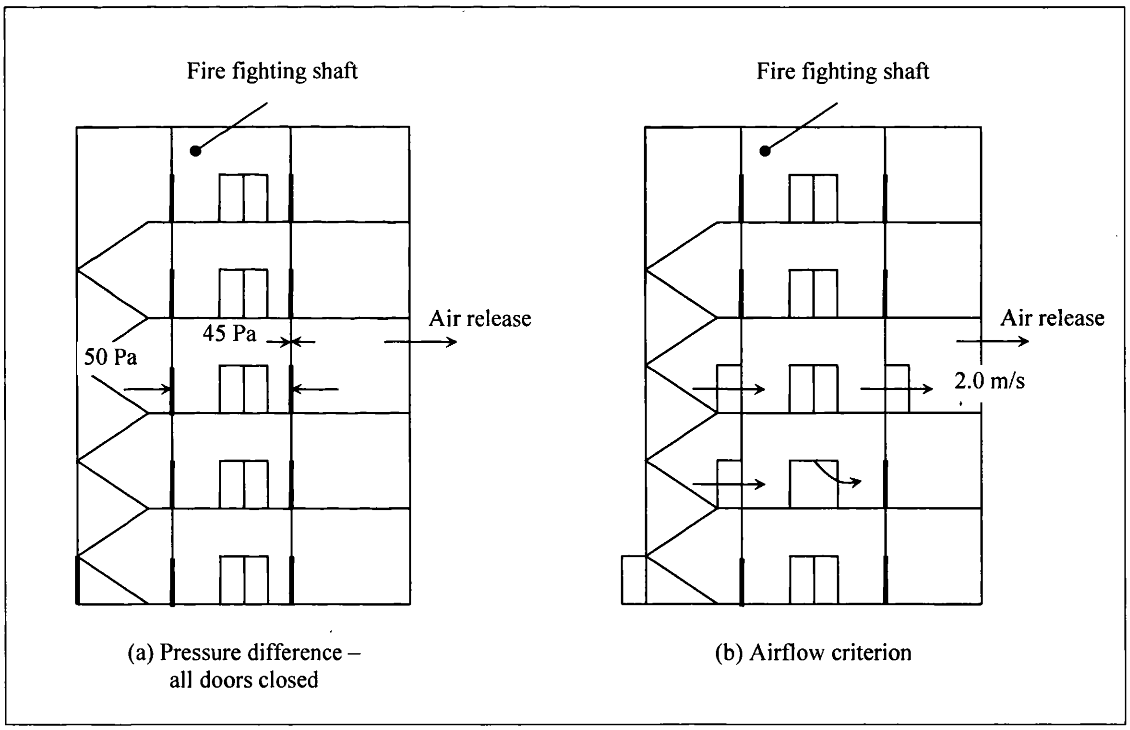



Figure 2.10 – Class B systems design conditions [18]

Air supply is required to maintain a minimum air velocity of 2 m/s through the open door between the lobby and the accommodation at the fire affected storey with all the following doors open between

- the stair and the lobby on the fire affected storey;
- the stair and the lobby on an adjacent storey;
- the fire fighting lift shaft and the lobby on the adjacent storey ;

- the stair and the external air at the fire service access level; and
- the release path on the fire floor is to be opened.

*Air release*

The difference in pressure encourages air to leak into unpressurized space through small gaps and cracks along with open doors. Provisions for air release to flow to open air in the unpressurized space are essential to ensure a continuous air movement which therefore maintains the required pressure difference and open door airflow velocity between the two spaces. This air movement also stops smoke from flowing into the pressurized space.

Provisions for air release as per Clause 5.3.2.2 [18] can be provided via

- Provision of special vents at the building periphery. Where the building is sealed special vents may need to be provided on all sides of the building.
- Vertical shafts. If venting the pressurizing air by building leakage or peripheral vents is not possible, vertical shafts may be used for this purpose.
- Mechanical extraction. The release of the pressurizing air by mechanical extraction is a satisfactory method. The mechanical extraction would be required to operate only during the period prior to window breakage.

*Over pressure relief*

Over pressure relief vent is provided to ensure that the closed door pressure build up does not exceed the design pressure. This indirectly ensures that the opening the door into pressurized space does not require extensive efforts. These vents should discharge directly to open air or through appropriate ductwork.

*Air supply*

Air supply provisions for pressurization systems are provided in accordance to Clause 5.2.2. [18]. Each vertical escape (i.e. stairwell and fire fighting shaft) is provided with its own dedicated pressurization system.

Stairwells for buildings less than 11m in height can be pressurized via a single air supply. Buildings that are 11m or more in height require that supply points be evenly distributed throughout the height of the pressurized stairwell where the maximum distance between air supply points not exceeding three storeys. Pressurized common lobbies/corridors at each level suffice with a single supply point.

*Door opening force*

The door opening force is designed so that the force on the handle of the door does not exceed 100 N. This is to allow for occupants (young and elderly) to escape readily when systems are activated.

Examples of depressurization systems application

*Atrium*

Atria may either be naturally or mechanically ventilated at a high level (roof) to ensure that the hot smoke layer does not fall below head height [25]. Head height refers to the average height of an adult in a standing position typically taken as 1.8m. For mechanically ventilated atria which have been designed for smoke clearance, the required extract duty is 10 air changes per hour. Air changes per hour are the frequency at which the air volume in the space has been replaced in an hour. Smoke clearance systems are designed to remove smoke from a space after the fire has been controlled or extinguished [20]. Secondary benefits are to ease the conditions to which fire fighters are exposed, at their discretion, while fighting the fire [20].

The venting process can be aided with smoke curtains which drop down creating a smoke reservoir. Smoke curtains which drop down covering the balcony of the top floor prevents smoke from flowing into the commercial accommodation destroying goods.

Replacement air is often provided at low level (e.g. ground floor of the atria). A typical flow pattern of atria ventilation is shown in Figure 2.11.

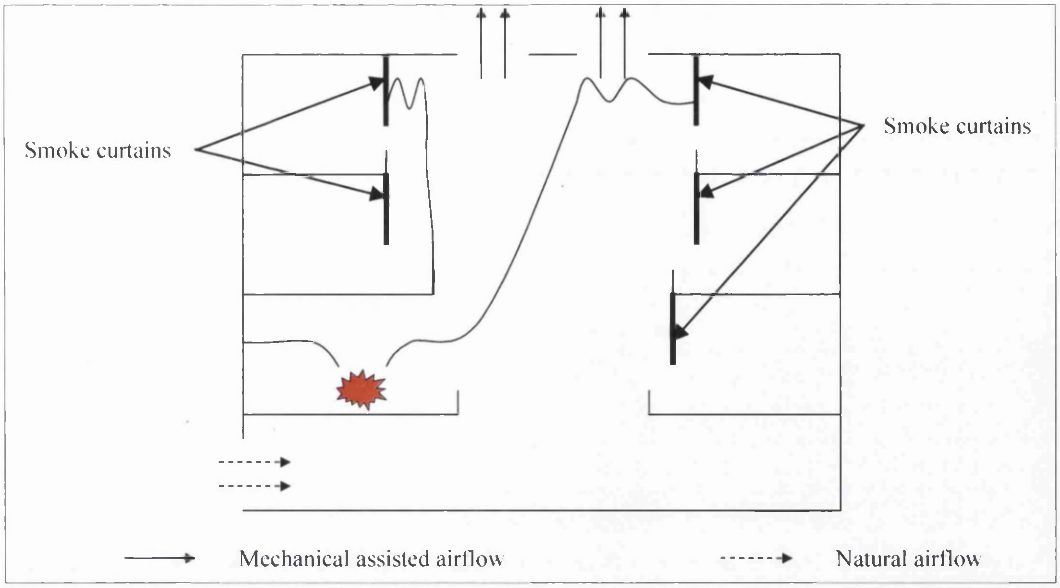



Figure 2.11 – Typical flow profile for atria smoke control

*Covered car park*

Covered or underground car parks are ventilated by means of main extract fans concurrently with ducted supply points at both high and low level. The main extract fans are commonly housed in purpose built plant rooms. Inlet replacement air is provided via natural openings to the surrounding or by means of mechanical supply.

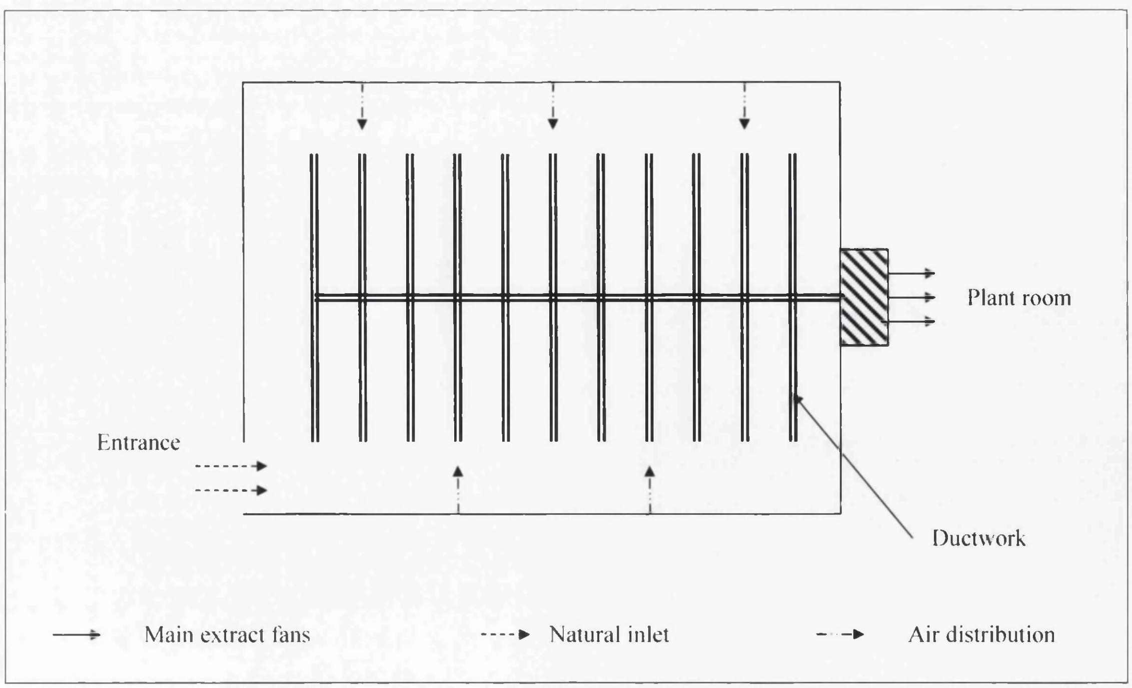



Figure 2.12 – Ducted underground car park ventilation strategy [26]

Figure 2.12 shows a general means of ventilating an underground car park with the use of mechanical extract fans and ducted supply points. The main extract fans, designed for smoke clearance, require an extract duty of 10 air changes per hour.

### 2.2.3 Performance based codes

Unlike prescriptive codes which explicitly states what to do in a given situation, performance based codes, in the words of Hadjisophocleous et al [27],

> "Express the desired objective to be accomplished and allow the designer to use any acceptable approach to achieve the required results".

The main driver of performance based codes in the United Kingdom is BS 7974:2001 [21] and is supplemented by a series of publish documents [28-34].

The move towards performance approach is due to the advantages that performance based fire safety design can offer over prescriptive design. These advantages can be summarised as follow [35]:

- establishing clear fire safety goals and leaving the means of achieving those goals to the designer;
- permitting innovative design solutions that meet the established performance requirements;
- eliminating technical barriers to trade for a smooth flow of industrial products;
- allowing international harmonization of regulation systems;
- permitting the use of new knowledge as it becomes available;
- allowing cost-effectiveness and flexibility in design;
- enabling the prompt introduction of new technologies to the marketplace; and
- eliminating the complexity of the existing prescriptive regulations.

In addition to the advantages of performance based approach, there are several disadvantages that need to be noted. These are as follows [28]:

- suitably qualified and experienced personnel are required to carry out and assess Fire Safety Engineering studies;
- might involve increased design time and costs;

- lack of data in some fields; and
- might be restrictive unless future flexibility of use is explicitly considered as a design objective.

The biggest challenge to performance based codes is to define the criteria to meet the code compliance and the necessary tools to quantify them [27]. This is where decision making tools based on analytical and computational methods (i.e. fire modelling techniques), supported by engineering correlations can be of value.

Engineering correlations are input properties which define the scenario to be analysed by means of fire modelling. The results of which, based on rational assessment methodologies, are then used as justification to satisfy the fire safety objectives. The engineering correlations specific to the analysis of smoke control is presented in Chapter 3. Methodologies that provide a valid assessment are discussed in a subsequent section.

Contrary to popular beliefs that a performance based approach be applied to all aspects of a project, the approach can also be used to fill gaps that are not covered by prescriptive design or are not fully code compliant. This flexibility is stated as [28]:

> "The most common use of Fire Safety Engineering (FSE) is to justify one or two specific departures from prescriptive codes. There is generally no need to apply FSE to all aspects of a project if it is otherwise code-compliant".

This is particularly true in the design of smoke control systems where the flexibility of performance based approach is either used to compliment a code compliant building or to provide solutions to building that is entirely non code compliant.

Design of ventilation systems for smoke control (not to be confused by smoke clearance) by means of impulse fans for covered or underground car park is an ideal representation of the innovation and maturity of performance based approach. The ventilation system, with the aid of impulse fans, benefits from the use of fire modelling tools to assess its merit of maintaining a visibility of 10m to the seat of the fire [26]. The performance has been well documented [26] and is acknowledged by both fire engineers and fire authorities. The use of impulse fans to assist in the air movement within the car park has rendered the use of ducted network obsolete. This is because impulse fans take up much less space and are cheaper to install compared to ducted network. Smoke control system is designed for the purpose of controlling the movement of smoky gases within a building in order to assist fire fighting operations [26]. Smoke clearance is only intended to clear the smoky gases once fire is under controlled or extinguished [26].

Use of a performance based approach in the design for above ground (storeys used for flats, offices and etc except car parks) smoke control systems have recently gained in popularity and this has lead to design of buildings which allow for protected escape routes (common lobbies/corridors), in one direction of escape, to have a maximum travel distance up to three times that of prescriptive codes, a distance not compliant to building codes.

For buildings which are compliant to building codes, the approach may be used to offer fire engineered smoke control solutions when prescriptive solutions cannot be met in full. An example for a fire engineered solution is presented in Chapter 5.

General design procedure

Published documents [28] present a general procedure for fire engineered design and is as shown in Figure 2.13. This generic procedure forms the basis of the framework presented in this thesis and is specifically tailored for the design of fire engineered smoke control systems. The three main stages of the procedure are identified as Qualitative Design Review, Quantitative Analysis of Design and Assessment against Criteria.

*Qualitative Design Review (QDR)*

Qualitative Design Review (QDR), first stage of the design process, identifies and reviews all relevant aspect of fire safety design i.e. objectives and performance criteria, proposed design of fire safety solutions, method statements, relevant assessment methodologies and criteria. Relevant engineering correlations which enable quantitative analysis to be carried out are also identified.

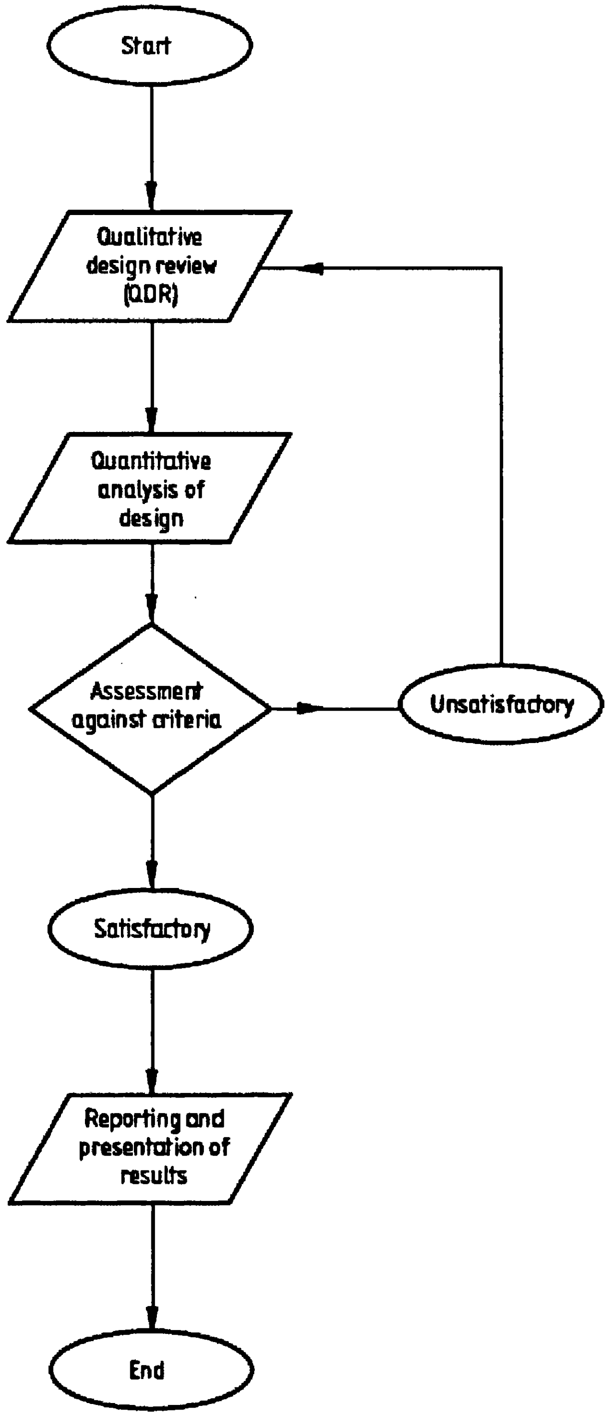



Figure 2.13 – Fire safety engineering design process [28]

*Quantitative Analysis*

This stage incorporates the evaluation of the proposed design solution identified in the QDR through the use of engineering methods. Use of field modelling as a key engineering method is discussed in this thesis. The analysis can take the form of either time-based analysis which reflects on the impact of fire on people and property at different stages of the fire development or steady state and limit state analysis.

*Assessment Criteria*

This is the stage where the output of the quantitative analysis is evaluated against the acceptance criteria identified in the QDR with the used of the appropriate assessment methodology. It is also the stage where a decision on the acceptability of the proposed design is made. If none of the trial designs satisfies the specified acceptance criteria, the QDR and quantification process should be repeated until a fire safety strategy has been found that satisfies the design criteria.

## 2.3 Assessment methods

The methodologies that can be used to assess the acceptability of a proposed fire engineered solution are [28]:

- comparative;
- deterministic;
- probabilistic.

One or more of these approaches may be used as part of the analytical study and which ever approach used should satisfy the identified fire safety objectives.

<u>Comparative criteria</u>

A comparative method is relatively straight forward, where the proposed fire engineered solution is required to demonstrate a level of safety equal to or better than a solution that complies with recognised prescriptive codes.

In addition, comparative assessment can be made on the basis of either the deterministic or probabilistic approaches or a combination of both approaches. An example of this method is provided in Section 5.2.2.2.

The advantages of comparative methods are [28]:

- relatively quick;
- consistent with established prescriptive codes;
- not usually dependent on initial assumptions;
- may be used where definitive design data is not available;
- explicit safety factors not required;
- allows the use of probabilistic risk assessment;
- without the need for absolute acceptance criteria.

The disadvantages are [28]:

- generally only suitable for one or two significant departures or several minor deviations from prescriptive codes;
- might incorporate the weakness of the prescriptive code.

Deterministic criteria

This method shows that a define set of conditions (i.e. objectives) has been met under assumptions that often represents the worst case scenario. The conditions (objectives) may be

- smoke layer will not fall below head height; or
- maintain tenable conditions.

Examples on the use of deterministic criteria are given in Section 5.2.2.1. A measure of tenable conditions can be taken as temperature, visibility and toxicity of the smoke produced by the flaming fire.

The advantages of deterministic methods are [28]:

- considerable data available;
- wide range of well validated calculation procedures available;
- widely used for life safety evaluation;
- provides a simple yes/no result.

The disadvantages are [28]:

- very dependent on initial assumptions;
- provides no measure of costs and benefits;

- limited benefit for loss control purposes.

Probabilistic criteria

This assessment criteria defines that the probability of a given event occurring is acceptably low. This probability is associated with risk and often expressed in terms of annual probability of the unwanted event occurring.

Some advantages of probabilistic methods are [28]:

- provide comparison between dissimilar fire protection systems;
- provides a numerical value of risk;
- can quantify the probability of unlikely events with severe consequences;
- can quantify the risk associated with failure of one or more fire-protection systems;
- provides data for cost-benefit analysis.

The disadvantages are [28]:

- limited statistical data;
- time consuming analysis.

In the design of smoke control systems, probabilistic approach is not adopted as the possibility that systems fail to operate has been accounted for by the failsafe measures which aim to contain and minimise the spread of smoke to the region of fire origin. This method is presented for the sake of completeness and will not be further discussed as it is not used in this thesis.

### 2.3.1 Industry practice

It is common industrial practice that smoke control solutions compliant to prescription codes provide a sufficient level of safety that are acceptable without further justification. On the other hand, justification needs to be sought for fire engineered solutions prior to any systems being accepted for installation.

Justification of fire engineered smoke control solutions is often by means of either comparative or deterministic in nature. Comparative means often compare the performance of the proposed engineered solution against the code compliant naturally ventilated system. The proposed system is accepted on condition that its performance is equal to or better than the code compliant solution.

Deterministic methods may specify that the proposed fire engineered solution be designed to maintain a tenable limit within the protected space. This method can also be used to specify the equipment used (e.g. choice of extract fans with appropriate fire rating can be determined by temperature that the fans are exposed to).

### 2.3.2 Tenable conditions

Tenable conditions are the conditions that can be tolerated by an individual when exposed to a fire hazard. The duration an individual can be exposed to is highly influenced by the conditions e.g. temperature and toxic potency of smoke produced by the combusting material.

Heat exposure

It is suggested that the tenable limit of unprotected human skin by means of convective heat is 120°C whereas exposure by means of radiant heat corresponds to 2.5 $kW/m^2$ [36]. Exposure to convective heat at this level and above causes skin pain followed by burns in a matter of minutes whereas exposure due to radiant heat causes the same burns within a few seconds.

| Mode of heat transfer | Intensity | Tolerance time |
|---|---|---|
| Radiation | Less than 2.5$kW/m^2$ | Greater than 5 min |
| | 2.5$KW/m^2$ | 30 seconds |
| | Greater than 2.5$kW/m^2$ | 5 seconds |
| Convection | 100°C at less than 10% $H_2O$ (humidity) | 12 min |
| | 120°C at less than 10% $H_2O$ | 7 min |
| | 140°C at less than 10% $H_2O$ | 4 min |

| | | |
|---|---|---|
| | 160°C at less than 10% $H_2O$ | 2 min |
| | 180°C at less than 10% $H_2O$ | 1 min |

Table 2.1 – Limiting condition due to heat (Copyright BRE Ltd.) [36]

These conditions are applicable to the early stages of fire development where occupants escaping from the fire hazard have no protection against the heat possessed by the hot smoke.

In the later stages of fire, these conditions are not significant as fire fighters are equipped with protective clothing and breathing apparatus while engaging the fire. In terms of occupants' safety, those who are unable to escape initially would have been either incapacitated or died at this stage due to the exposure to intense heat.

Visibility

Another measure of tenability condition is the visibility of smoke. Unlike exposure to heat, visibility causes incapacitation or death indirectly. The loss of visibility impedes occupants escape while at the same time increases the duration of which occupants are exposed to toxic gases and heat.

The suggested tenability limit for visibility for buildings with small enclosure and short travel distance is 5m (optical density OD/m = 0.2) whereas large enclosure and long travel distance has a suggested visibility of 10m (OD/m = 0.08) [34].

The use of visibility in this work will be further discussed in Section 5.1.2.1 under Qualitative Design Review (QDR), order of events.

Toxicity

Untenable toxic gas conditions can be determined using the product of transient gas concentrations and exposure duration (dose). The Fractional Effective Dose (FED) concept describes the potency of toxic gases and is defined as the product of toxic gas concentration at small time intervals of exposure during the fire divided by the product of toxic gas concentration dose causing the toxic effect as shown in equation (2.1) [36]. The fraction effective dose for each toxic gas if applicable is then summed for the duration of exposure. When this reaches unity, the toxic effect is predicted to occur,

$$FED = \frac{\textit{Dose received at time t}}{\textit{Effective dose to cause incapacitation or death}} \tag{2.1}$$

This is presented for the sake of completeness and will not be discussed further as this criterion is not used in this work. Furthermore, in the case studies in Chapter 6, hot smoke temperature, the extent of smoke spread and visibility are used as means of acceptance for fire authorities to make an informed decision.

## 2.4 Concluding remarks

Legislative documents have prescribed a means to identify the need for, design and assessment (applicable only to fire engineered solutions) of smoke control systems. These legislative documents are then used to provide a platform for fire engineers to decide on the appropriate smoke control methods to be used for the building of interest. The typical decision making process of a fire engineer is discussed in Section 5.1.1. The criteria that influence the decision making process are:

- Height of the building;
- Maximum travel distance; and
- Compliance to prescriptive codes.

In addition to the decision making process, the legislative literature prescribed the assessment approaches that may be used to assess the performance of the fire engineered solutions. The respective merits of the assessment approaches and their applications are further discussed in Chapter 5 and Chapter 6.

# Chapter 3 Fire Modelling and Engineering Correlations

This chapter describes the representation of a fire by means of a temperature time curve (heat release rate time curve). Introductions on zone and field models are also presented. In addition, this chapter presents the available smoke control concepts as well as engineering correlations in support of the use of fire engineering tools.

## 3.1 Temperature time curve

Temperature-time curves define the history of the fire development in an enclosure and are often an indicative of the rate of heat release of the fire against time. Temperature-time curves and indeed the rate of heat release against time curves are used to characterise the design fire in time when using fire engineering design tools [37]. The generalised temperature-time curve, as see in Figure 3.1, shows that fire undergoes several phases of development namely [38]:

- Incipient phase;
- Growth phase;
- Flashover phase;
- Fully developed phase;
- Decay phase; and
- Extinction phase.

The incipient phase is the start of fire development where the heating of potential fuel takes place. The combustion process maybe smouldering or radiant where products of the combustion may be minimal, effects on the surrounding environment may be difficult to observe (only some smoke with no detectable flame), and that the amount of heat generated will be insignificant to the surrounding area. This phase may last for a few moments (i.e. combustible liquid is ignited by external heat source) or even hours (i.e. smouldering material which is ignited with the introduction of easily combustible fuel and/or sufficient ventilation).

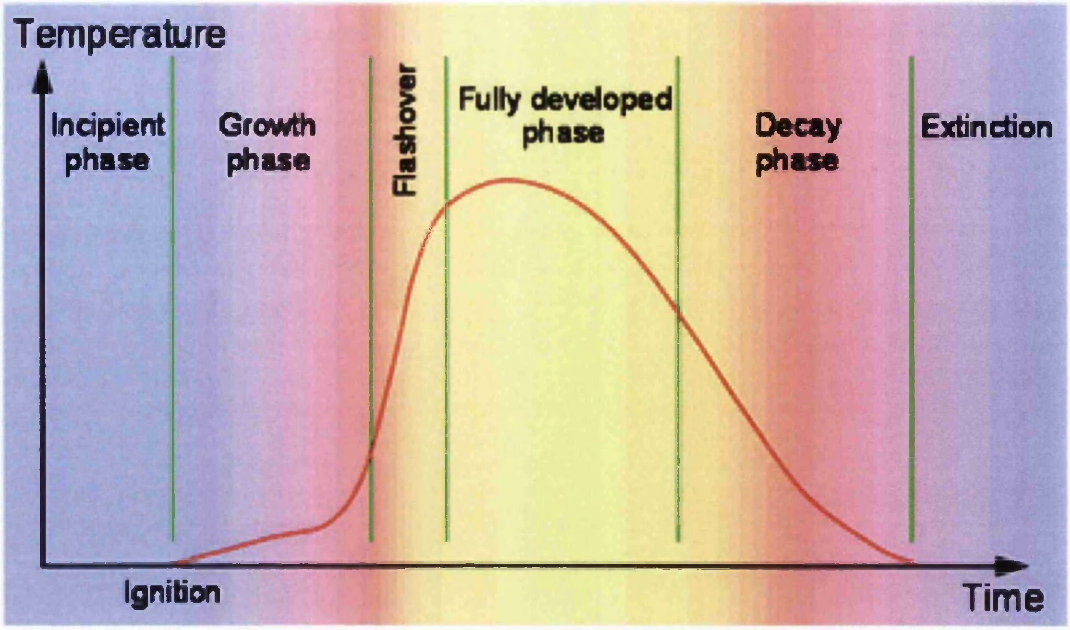


Figure 3.1 – General temperature time curve [38]

Ignition is the beginning of flaming combustion which also signals the start of the fire growth i.e. growth phase and often referred to as the pre-flashover phase. At the initial growth phase, the fire is normally small and localised within an enclosure. Smoke or combustion products will accumulate beneath the ceiling and gradually form a hot upper layer in the enclosure, with a relatively cool and clear layer at the bottom. The fire will progressively grow larger and releases more hot gases into the smoke layer if left alone with sufficient fuel and oxygen. As time passes, the hot smoke layer increases in thickness, descends and eventually fills the enclosure. Figure 3.2 shows an arrangement of such a system.

The growth phase of the fire also coincides with the means of escape phase where occupants in the enclosure make their escape from the fire scene. The escape route may either be contaminated by smoke prior to occupants escape (due to leakages around closed door) or be contaminated while occupants make their escape (opened door allows large quantities of smoke to spill into the escape route). The contaminated escape route impedes the escape of other occupants that may have been left behind. This emphasises the need for smoke control systems to provide a safe environment for occupant escape. The rate of smoke production can be assumed to increase proportionally to the rate of heat release [39].

The continuous growth of fire, with sufficient fuel and oxygen, will eventually lead to the onset of flashover. Flashover is where all unburned combustible materials, in both solid and gaseous form, in the enclosure are instantly ignited due to radiation from the burning flame and the hot smoke layer which feeds the fuel. The whole enclosure will be engulfed in fire and smoke.

Flashover leads to the fully developed or post-flashover stage where fire is at its peak, the heat release rate is at its maximum and is substantially steady. The fire may be ventilation or fuel controlled. This also represents the most critical stage where structural damage and fire spread often occurs.

Fully developed fire often coincides with fire fighting activities as previous fire phases may have past before fire fighters arrive at the scene. Smoke control systems, when required, can be designed to facilitate fire fighting operation by providing a safe bridgehead near the fire floor for fire fighters to prepare themselves without the need for breathing apparatus before engaging the fire.

Decay phase is where rate of burning decreases either as the combustible materials is consumed which occurs after a period of sustained burning or by fire fighters intervention. Extinction is where the fire eventually ceased and that all combustible materials has been consumed with no more energy being released. Smoke control systems are often used to clear residual smoke from the protected space.

## 3.2 Introduction to computational models

Recent emergence of performance-based regulation and the increased complexity of building design have been the driving forces in the increased use of computer modelling of smoke and heat movement in buildings. This section provides a general discussion on the types of computer models used in fire safety engineering.

At present, there are several mathematical and computational models developed for the purpose of fire modelling. These models are known as the nominal fire (standard fire) [38], time equivalence fire [38], compartment fire [38], zone models [17] and field models (CFD models) [16].

The nominal or standard fire curves are the simplest way of representing a fire where some arbitrary temperature-time relationship is pre-defined which is independent of the boundary conditions and ventilations. Time equivalence fire curves are used to relate the severity of real fires to the temperature-time relationship of standard fires, with the boundary conditions, ventilation conditions and compartment size taken into account.

These two models were mathematically derived in the form of simple equations for easy hand calculations and are mainly for fire analysis of structures. The temperature within the domain is assumed uniform throughout. The limitations of these assumptions are such that they bear little relationship to the real fire behaviour, do not always represents the most severe fire conditions and they are only suitable for modelling post flashover fire. Pre-flashover fire is unsuitable because the growth phase of the fire will alter the conditions within the burning room [38].

Compartment fire models [38] consist of two sections which are known as parametric and localised fire models. Parametric models provide a simple method to approximate post-flashover fires where temperature in the compartment is assumed uniform throughout. Localised models consider the pre-flashover environment of the compartment. Temperature of the flame and smoke plume is not uniform and needs to be determined separately. Zone and field models are presented separately.

The three models discussed are considered simple models which require few input parameters. Zone and field models are advanced models and require very detailed input data. The complexity of the models increases from nominal fire models to field models.

### 3.2.1 Zone models

Zone models are computer models developed as means of predicting the fire environment of an enclosure. Some of these models consider only the fire room, e.g. FIRST [40], while others may extend the fire room to incorporate a series of adjoining rooms whose sizes are in the form of domestic rooms, offices or small industrial units. e.g. CFAST [41]. The later models can be used to determine smoke and heat movement through out a building. Olenick et al [42], in a recent survey, listed existing zone models that are in use around the world.

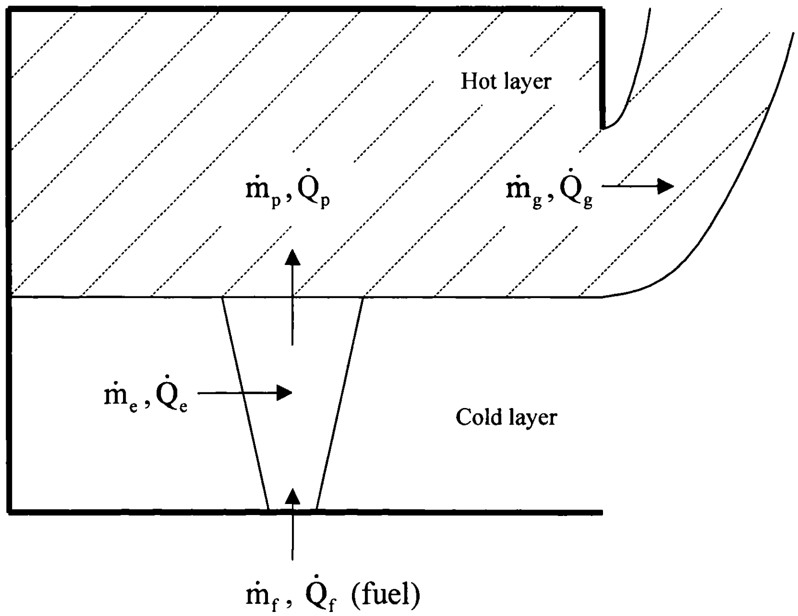



Figure 3.2 – Two-zone model of an enclosure [17].

Two-zone models [17] are the most common zone models which consider the system as two distinct homogenous gas zones (layers): an upper volume (layer) and a lower volume (layer) which results from thermal stratification due to buoyancy. The fire, typically represented as a source of energy and mass, feeds the upper zone through a plume that rises from the lower zone to the upper zone. The mechanism of which is known as entrainment.

Figure 3.2 shows the typical two-zone concept in a compartment with a fire plume and a door vent. The upper zone (layer) is the upper region of the room where hot combustion gases accumulate and overspill via the door vent. The lower zone (layer) consists of the remaining spaces and is of cool ambient air.

Solution of the system, e.g. gas temperature and height of the hot upper layer, is obtained by solving a set of ordinary differential equations (ODEs) derived from the conservative equations of mass, energy and the ideal gas law. The physical details of the gas within the zones are not considered. Mass and energy transport between zones are calculated by modelling the fire sub-processes e.g. combustions, heat transfer and fluid flow.

Momentum conservation is not explicitly applied in which the variables associated with fluid flow e.g. pressure and velocity of the gas zones are determined only at the vent boundary of the enclosure. The mechanism of flow through vents is discussed in Section 3.4.2.

The equation for the conservation of mass as expressed in Karlsson et al [17] is given by:

$$\frac{dm}{dt}+\sum_{j=1}^{n}\dot{m}_j=0 \tag{3.1}$$

This equation states that the rate of change of mass and the sum of the net mass flow rates is zero. The flow streams shown in Figure 3.2 give

$$\sum_{j=1}^{3}\dot{m}_j=\dot{m}_g-\dot{m}_e-\dot{m}_f \tag{3.2}$$

where $\dot{m}_g$ is the mass flow rate out of the door, $\dot{m}_e$ is the mass rate of entrainment into the fire plume and $\dot{m}_f$ is the mass rate of gaseous fuel supplied. $\dot{m}_p$ is the mass flow rate of the plume in the hot layer interface and is the sum of the mass rate of entrainment and the mass rate of gaseous fuel supplied ($\dot{m}_p=\dot{m}_e+\dot{m}_f$).

Likewise, conservation of energy incorporating the ideal gas law and as expressed in Karlsson et al [17] is given by:

$$Vc_p\frac{dT_g}{dt}-V\frac{dP}{dt}+c_p\sum_{j=1}^{n}\dot{m}_j\left(T_j-T_g\right)=\dot{m}_{react}\Delta H_{eff}-\dot{q}_{loss} \tag{3.3}$$

where V is the volume of the gas layer, $c_p$ is the specific heat capacity, P is the global pressure of the gas layer, $\dot{m}_{react}$ is the rate at which fuel is burn, $\Delta H_{eff}$ is the effective heat of combustion and $\dot{q}_{loss}$ is the rate of heat loss at the boundary.

Important assumptions which support the application of the conservative laws between the zones are [17]:

- The properties of the zones are spatially uniform and can vary with time i.e. the thickness/depth of the hot layer may increased or reduced depending on the ventilation strategy;
- The gas is treated as an ideal gas of constant molecular weight and specific heat capacity;
- Combustion is treated as a source of mass and energy. The combustion zone is not resolved from first principles;
- The plume reaches the ceiling instantly. No attempt is made to account for the time required to transport mass vertically or horizontally in the enclosure;
- Room contents are ignored as their mass and heat capacity is insignificant compared to the enclosure structural walls, ceiling and floor elements. Heat is therefore considered lost to the enclosure elements but not the contents;
- Mass flow into the fire plume is due to turbulent entrainment. The inflow velocity varies linearly to the vertical velocity in the plume;
- Fluid frictional effects at solid boundaries are ignored.

Applications of zone models

Chow et al [2] studied the smoke filling process in atrium due to smoke spread from a shop adjacent to the atrium. The study was conducted using a two layer zone model CL-Atrium incorporating three different balcony spill plume expressions. The results were then compared to those obtained using CFAST with favourable results observed in two of the three plume expressions.

Shi et al [43] compares the different plume correlations to that currently used in CFAST by means of a two-layer zone model approximation developed to include mechanical exhaust. The results of which are then validated by full scale fire experiments. The fire scenario is taken as in a small retail shop at 4m x 3m x 3m, a mechanical exhaust at a rate of $0.4023m^3s^{-1}$ and a natural vertical vent at low level of width 1.6m and 1.0m high. Results concluded that the two-layer model is in good agreement with experiments but for CFAST prediction of the temperature was slightly over estimated. The predicted height of the smoke layer interface is approximately the same as those observed in experimental data. The author also confirms that there is no overriding preference when choosing a better plume correlation, instead recommends that the correlations be used within their respective limits.

Chow [44] investigates the fire environment in car parks of varying volumes and ceiling heights using three fire zone models, namely CFAST, CCFM.VENT and FIRECALC. The former two are products of the Building and Fire Research Laboratory, NIST in USA while the latter is developed at the Division of Building Construction, CSIRO, Australia. The results found that the CFAST model is suitable where the average predicted hot gas temperature correlates with the volume of the car parks.

Fu et al [45] developed a fire growth and smoke movement model for a two-zone multi-compartment building. The paper presents the relevant physical models, numerical methods and verification examples for single and two-compartment fire test. The model is also validated against other comprehensive compartment fire models in CFAST and FIRST. The single compartment fire example is validated against experimental data carried out by Dempsey et al [46] where the compartment is 2.5m x 3.7m x 2.5m with a single doorway of 0.76m wide x 2.0m high, positioned at the central on one of the shorter side. Multi-compartment fire example is validated against experiments carried out by Cooper et al [47]. The comparison between the upper layer gas temperature, interface height and vent flows showed a favourable result.

Shigunov's [48] work on the analysis of fire development in multiple connected compartments based on a zone model is worth noting although it is primarily for ship hull design. This shows the extent of the scenarios at which zone models can be applied. The proposed method makes use of an improved treatment of walls between compartments and an efficient algorithm for pressure calculations.

Advantages

The main advantage of zone models is that it gives reliable and accurate prediction of the fire environment for something that is relatively simple in principle. Simple in a way that the zones (layers) are spatially uniform and that physical details within each zone are not considered [49].

Consequent to the simplicity in the makeup of zone models, little detail is required when setting up a fire scenario. The details that are required include the size of the enclosure, the design fire size, the choice of which smoke is entrained, size of vent and the mechanism of the flow regime e.g. natural or mechanically ventilated.

Another advantage which makes zone models popular is its low computational power requirements and relatively short computational time (compared to field models) needed to perform a reasonable simulation [49]. These factors lead to a relatively low running cost and make them attractive to industrial users.

Limitations

Although zone models perform admirably in a single enclosure or a series of connected enclosures whose size represent domestic rooms, office or small industrial units, they have been particularly weak when predicting smoke movement in enclosures with large length-to-width ratios or rooms with horizontal length to vertical length ratio that is very large or very small [17].

Consider a weak fire in a very large space. The weak plume due to the fire may not result in a two-zone situation as the plume is unable to drive the gases to the ceiling. A stratified layer may instead form at mid height of the enclosure and not the ceiling as would be assumed in typical two-zone models. Conditions within the enclosure when predicted will be less hazardous than what might actually occur as the models would have considered the ceiling ventilation while the actual ceiling ventilation has no influence on the smoke plume [17].

Similarly, a very large fire in an enclosure with a relatively low ceiling will not necessarily lead to a two-zone situation. This is due to the highly turbulent nature of the flow of the hot gases which disturbs the zones and may result in a well mixed situation [17].

The geometrical limitation of zone models is acknowledged by Cooper [50] who has developed a set of model equations to attempt to overcome such limitations. The model equations introduced a combined buoyancy and ventilation-driven flow of a perfect gas into a long vertical shaft. Consequently, an addition of local rate of mass into the shaft occurs along with the rate of heat transferred to the gas in the shaft (heat transfer takes place from the shaft surface to the gas) per unit volume.

Cox [49], in agreement with Yao et al [51], stated that zone models have a particular flaw concerning the employment of the correct treatment for air entrainment into fires and as a consequence the volume flow rate of smoke throughout a building. In addition, there is also a lack of consensus on the appropriate treatment for entrainment into smoke spilling over a balcony edge. In order to overcome these problems the behavioural patterns of such distinctive variation must be initially assumed and incorporated into the model. One example is the King Cross Underground Railway fire study by Cox et al [52] where a trench effect is noted. The trench effect is the behaviour of fire which occurs when a flame front spreading across flat terrain meets an incline. Such effect is well known especially to those dealing with forest fires.

Operation of sprinklers in a fire event is another factor which may affect the validity of two-zone models. Sprinkler flow will cool and mix the zones such that the two-zone analogy no longer valid [17].

Needless to say, the role of an experienced user, based on the appropriate engineering estimates, practical experience and common sense, is important to best ensure that the assumptions and limitations of zone models are applied in a fitting manner [17]. It is also the role of the experienced user to assume a priori i.e. an initial condition of how smoke is expected to spread or identification of the zone representing the hot layer, when the need to model scenarios of complex geometries.

It is also arguable that zone models are near their end in terms of further scientific development for treating smoke movement problems. As a suggestion, the primary challenge facing zone models now is the incorporation of reaction-to-fire behaviour of compartment linings and furniture which is avoided by most existing smoke model movement through prescribed fire growth [53].

### 3.2.2 Field models

Field modelling is the terminology used when CFD technology is applied in fire engineering. Keeping to CFD terminology, the volume of the enclosure and its surrounding regions of interest are divided into a very large number of sub-volumes (known as cells or control volumes). The arrangement of these control volume is known as the computational mesh. Figure 3.3 shows an example of the structured division of the volume within the enclosure and the region adjacent to the opening.

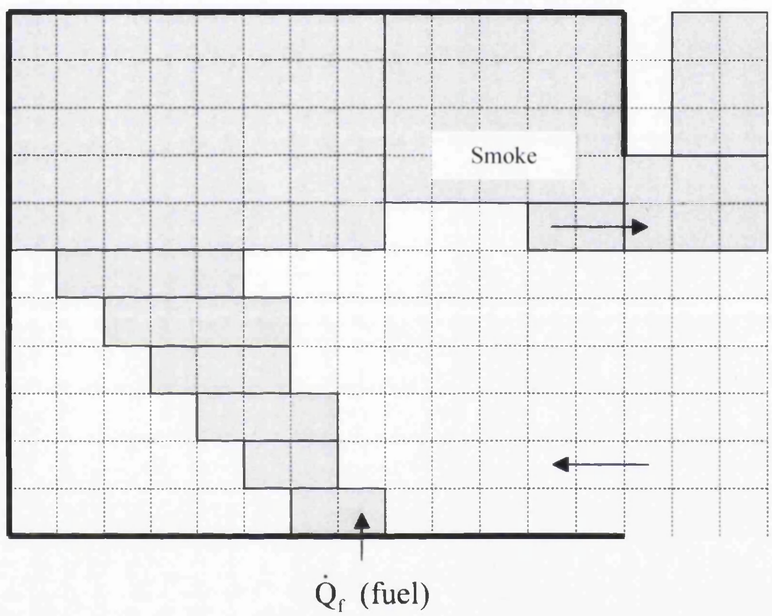



Figure 3.3 – Field model showing the spread of smoke using a structure mesh.

It is within each of these cells that the localised partial differential equation set which describes the principles of conservation of mass, momentum, energy and species, subject to the particular boundary conditions, are numerically solved. The governing conservative equation set contains further unknowns that are the viscous stress components in the fluid flow. Navier-Stoke equation refers to the substitution of these unknowns into the momentum equations and the solution of these is central to any CFD codes [17].

The equation for the conservation of mass in partial differential form is [54]:

$$\frac{\partial \rho}{\partial t} + div(\rho \underline{u}) = 0 \qquad (3.4)$$

Where $\rho$ is the density, $t$ is the time and $\underline{u}$ the velocity vector.

Similarly, the equation for the conservation of momentum in partial different form is [54]:

$$\frac{\partial(\rho u_i)}{\partial t} + div(\rho \underline{u} u_i) = -\frac{\partial P}{\partial x_i} + div(\mu_{eff}\, grad(u_i)) + S_{u_i} \qquad (3.5)$$

Where $u_i$ is the velocity in the x, y and z direction, $P$ is the pressure and $\mu_{eff}$ is the effective viscosity.

Likewise, equation for the conservation of energy is [54]:

$$\frac{\partial(\rho h)}{\partial t} + div(\rho \underline{u} h) = div\left\{\left(\frac{k}{c_p} + \frac{\rho v_t}{\sigma_T}\right) grad(h)\right\} + S_h \qquad (3.6)$$

Where $h$ is the enthalpy, $c_p$ is the specific heat capacity and $S$ the source term.

The effective viscosity variables described in the momentum conservation equation is solved with the introduction of the turbulence sub-model. The turbulence sub-model influences the viscosity of the fluid in the enclosure and encourages mixing. Other sub models which further captures or influence the behaviour of the fire environment are [17]:

- Radiation modelling – influences the temperature of the hot layer and further heat lost through enclosure boundary.
- Combustion modelling – A heat source that is characterised by the chemical composition of the fuel of interest e.g. liquid propane, wood cribs, polyurethane and etc.

The mathematical expression for these sub models is further discussed in Chapter 4.2.

Olenick [42] carried out a survey of field models that are currently available either commercially or open sourced. Of the identified CFD codes, they can be categorized as either general multipurpose CFD codes that are capable of modelling almost any scenario if the codes are correctly adjusted for the role e.g. ANSYS-CFX [55] and FLOVENT [56] or CFD codes that are specific to fire and smoke movement modelling e.g. SMARTFIRE [57] and Fire Dynamic Simulator (FDS) [58]. These codes commonly consist of a [17]

- Pre-processor – Geometry of the region of interest is defined, the grid is generated, the physical and chemical phenomena that need to be modelled are selected, fluid properties are defined and boundary conditions are specified.
- Solver – Unknown flow variables for a new time step are approximated. The approximations are discretized by substitution into the governing flow equation and the algebraic equations are solved.
- Post-processor – allows for the display of both input and output data in various forms e.g. grid display, vector plots, contour plots, etc.

Application of field models

Qin et al [59] used a FDS code to investigate the smoke filling process in a large building or atrium under different ventilation conditions. A Large Eddy simulation (LES) assumption was applied to describe the turbulence. The ventilation conditions involved were a natural smoke ventilation system, mechanical smoke extract system and under ventilated conditions. The position of the system i.e. wall mounted or ceiling/roof mounted, for both natural and mechanical extract were considered. The effect of the ceiling temperature on the smoke spread was also discussed.

Qin et al [60] discussed the numerical simulation of smoke movement and ambient airflow within a stairwell due to fire scenarios and under a LES turbulence model assumption. A typical two-storey (calculated from ground floor up i.e. three-storey building including the ground floor) confined stairwell with an open door on the top floor and a fire source on the ground floor was investigated. The effects on the width or gap that the door was being kept opened were also discussed. It was found that the heat release rate had a remarkable effect on the distributions of temperature and velocity within the stairwell.

Sinai [61] used ANSYS-CFX, a general-purpose CFD software originally developed by AEA Technology, to study the role of leakages on fire development in under-ventilated compartment fires, in line with experimental studies set out by the Home Office. The experiments involved heptane pool fires of about 10 MW unconfined output, in a leaky compartment with a volume of 600m$^3$. The building was sealed (i.e. all doors and vents are closed to create an under-ventilated compartment) for the first 5 minutes, at which point various combination of doors and vents were opened to ventilate the compartment. Preliminary predictions showed that the thermal stratification during the 'sealed' period had collapsed, which contradicted experiment observations. Subsequent sensitivity studies indicated that weak leakages can have a major effect on the fire dynamics of a large compartment fire.

Hasib et al [62] used the Steckler room experiment as the basis of their validation for the analysis of a growing fire using CFX. The simulations were run as transient with a time step size of 5 seconds. Elements used for the mesh were in the regions of 775,000 to 779,000. The predicted results suggested that it is in agreement with experiment results. A neutral plane at about the door mid height was also predicted.

Advantages

Field models strengths are reflected by zone models limitations which are [49]:

- Capability to analyse the fire environment in detailed at any point within an enclosure;
- Ability to analyse problems with complex geometry; and
- No need to assume a priori a plume structure.

The fundamentals of field models is the reason for such advantages where the solution of the transport equations in each control volumes allows for data at that control volume be read and analysed. This entails that the resolution of the control volumes i.e. structure and size, highly influence the transport and flow schemes of the enclosure.

In addition, this approach does not require the need to assume a priori which often be a problem for zone models. Instead, the movement of the plume, whether it is deflected by a door-jet or the consequence of losing its buoyancy due entrainment of air, is determined by the solution of the conservative equations subject to the particular boundary conditions (i.e. the physics) and not by prior assumption.

Disadvantages

Field models are complex computer models that require users with expert knowledge to ensure that the sub models (e.g. combustion model, radiation models and turbulent models) are correctly applied or indeed being applied at all and that the solution is valid.

Field models also require significant computational power and are time consuming compared to zone models. The cost associated with these models coupled with the need for expert users is therefore comparatively higher.

However, a growing confidence in predicting far-field conditions and the availability of increasing computer power at reducing cost has encouraged greater interest in their use for the assessment and design of smoke control systems in buildings [49].

## 3.3 Smoke control concepts

Methodologies of controlling smoke movement may be classified as either passive or active methods. Passive methods make use of physical barriers e.g. walls and doors while active methods are smoke control systems which are designed to be activated by smoke detectors that are triggered upon the presence of smoke. The most effective means of restricting smoke movement is to make use of the combination of the two methods.

### 3.3.1 Passive methods

Passive methods play an integral part in restricting smoke movement for egress from high rise buildings. This approach exploits the physical barrier that is the compartmentation [63] consisting of walls, partitions, and most importantly the closed door that leads from a room that could be on fire to other spaces such as corridor or stairs which may be used by people during everyday activities or emergencies. These barriers are of fire resistance construction that is sufficient to remain intact for a specified duration and provide a level of protection against fire and smoke spread from the location of fire origin. Regions of a building that are enclosed within fire-resisting compartmentation elements can be referred as protected spaces.

Doors are the main weakness [63] in this approach where they are only effective when closed. These doors can be made self-closing if their everyday normal uses are in the close position (which would not be a problem). Doors which are propped open in their daily used would not give any protection should a fire occur. This can be overcome by installing door holders that release the doors automatically in response to the detection of smoke, be it globally or locally, within the protection area.

Gaps around a closed door [64] is another weakness which allows smoke to leak into smoke free area. Counter measures such as smoke sealed or smoke stop doors may be used to reduce the possibility of smoke leakage. Pressure differential systems can also be used as means of preventing smoke spread through leakage.

### 3.3.2 Active control method

Active methods are ventilation systems designed specifically for the purpose of controlling smoke movement and are intended to be automatically triggered by smoke detectors on the presence of smoke. These systems are usually ventilated by either natural or mechanically assisted means. Means of mechanically assisted ventilation are [22]:

- Pressurization method
- Depressurization method
- Dilution or purged method
- Air flow method

<u>Natural means</u>

Natural systems exploit the natural buoyancy of smoke and vent the smoke to external air via openable windows or ventilators which open into a smoke shaft upon detection of smoke. The ventilation strategy is most efficient when open windows and ventilators are positioned at a high level as is prescribed by prescriptive code [20]. This approach ensures that hot buoyant smoke which makes up the upper layer be promptly removed. If the opening is at low level, the buoyant hot smoke is allowed to accumulate with the resulting smoke reservoir be ventilated once the smoke layer interface descends below the level of the top of opening. Due to the presence of the smoke reservoir, conditions within the protected space would be highly undesirable.

Head of smoke shafts which are open to external air should be positioned in regions of non adverse wind effect (positioned in area of negative wind pressure). As discussed previously, these systems are highly susceptible to wind effects.

Pressurization method

Pressurization systems mechanically blow external air into the intended region thus pressurizing the space relative to others. Positive pressure difference occurs across the door separating the space and protects the space from smoke by preventing smoke flowing through gaps around the door. These systems are commonly found in both commercial and residential high rise buildings which are highly compartmented with predominately low ceiling spaces. The common pressurized areas are the stairwells and protected corridors/lobbies. Design considerations include the leakiness of the building and the number of doors that can be simultaneously opened when the system is in operation. A design that allows for all doors to open simultaneously will always work, but it will probably add to the cost of the system.

Depressurization method

Depressurization or extract systems, as their name suggest, remove hot smoke from either in the fire compartment or far field spaces that are contaminated by smoke. Smoke ventilation systems for covered and underground car parks are examples of the former approach while smoke ventilation systems whose purpose are to ventilate protected space e.g. protected lobbies/corridors are examples of the latter approach.

By extracting the smoke contaminant, these systems are capable of reducing the concentration of the smoke layer while maintaining the height of the smoke layer interface, a criteria in the design of atrium smoke ventilation systems [65].

Note that such systems require sufficient low level inlet (or make up) air to replace the hot smoke that has been extracted out of the system and to maintain a reasonable pressure difference so that hazards due to doors being held tightly shut are avoided [66].

Dilution method

Dilution of smoke or smoke purge is another method of smoke control. Dilution refers to the process of introducing large amount of fresh air to dilute the concentration of smoke during the fire event whereas smoke purge refers to the post fire smoke clearance process. This method can also be used to maintain acceptable smoke concentrations in adjacent spaces which are subjected to smoke infiltration. This is however only effective if the rate of smoke infiltration is small compared to either the total volume of the space or the rate of purging air supplied and removed from the space.

Doubts were raised on the effectiveness of the dilution method when used to improve conditions within a space containing a fire. Klote et al [67] provides the following caution with regards to the use of dilution near a fire:

> "There is no theoretical or experimental evidence that using a building's heating, ventilation, and air conditioning (HVAC) system for smoke dilution will result in any significant improvement in tenable conditions within the fire space. HVAC systems promote a considerable degree of air mixing within the spaces they serve. Because of this and the fact that building fires can produce very large quantities of smoke, dilution of smoke by an HVAC system in the fire space will not result in any practical improvement in the tenable conditions of that space. Thus smoke purging systems intended to improve hazard conditions within a fire space or in spaces connected to a fire space by large openings should not be used."

Airflow method

An airflow method is normally used for buildings with large openings where a pressurization method is not feasible. This approach prevents smoke from migrating through the opening by means of an oppose airflow to limit the egress of smoke. Figure 3.4 shows the effective use of the method.

Care should be taken when installing such systems as smoke backflow at the uppermost portion of an opening is possible if airflow is not of sufficiently high velocity, or the temperature of the hot smoke is excessive resulting in a two way flow through the opening (as shown in Figure 3.5). Excessive airflow velocity is also not recommended as this may directly disrupt plume dynamics or interfere with smoke exhaust whilst indirectly intensifying the fire (by providing fresh air to sustain the burning fire). Both figures are extracts of Klote [68].

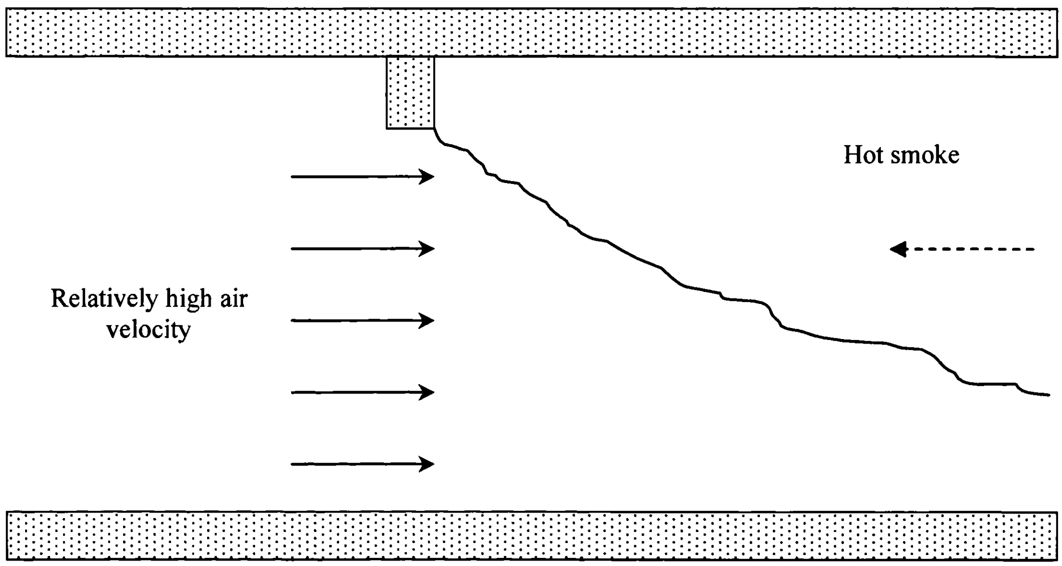



Figure 3.4 – Effective airflow method.

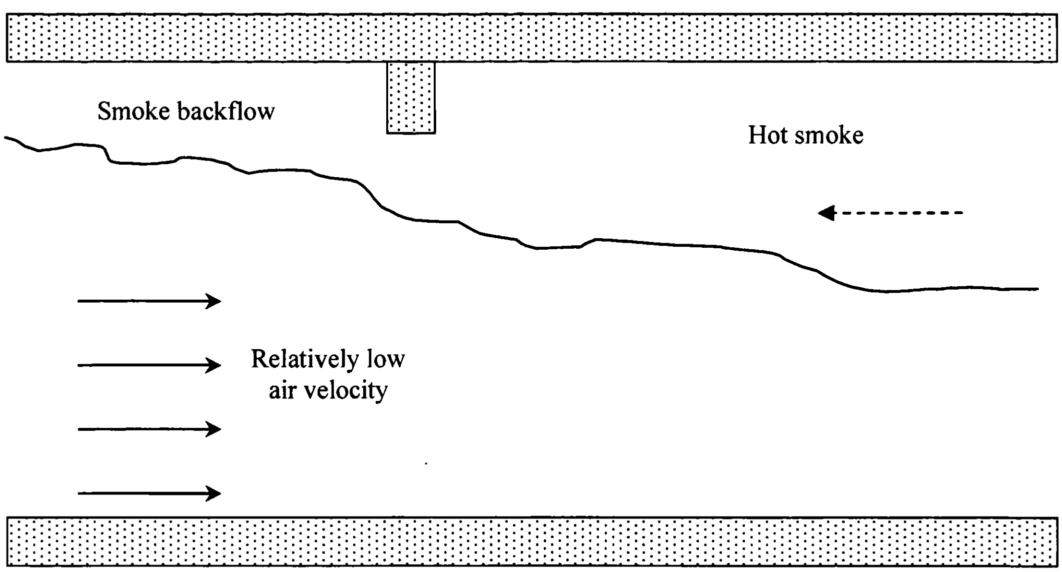



Figure 3.5 – Failed airflow method.

## 3.4 Fire and smoke properties

This section presents the properties of fire and smoke which may be used to define the fire scenario for use in fire engineering analytical tools. The mechanisms which may influence smoke movement are also presented for the sake of completeness.

Factors that defines a fire scenario and the severity of the fire are [38]:

- fire load type, density and distribution;
- combustion behaviour of fire load;
- compartment size and geometry;
- ventilation conditions of compartment; and
- thermal properties of compartment boundary.

### 3.4.1 Fire dynamics

Heat release rate

The rate of heat release is an important factor that determines the impact of fire on the surroundings namely occupants and the structure concerned. Heat release rate is referred to as the amount of energy release by the fire per unit time and is commonly measured in kW. The rate of heat release is significantly affected by the type, quantity, orientation of fuel and the enclosure where fire is burning [69].

The heat release rate is directly proportional to the mass loss rate of the fuel. Mass loss rate is the amount of mass that the fuel has lost per unit time due to the complete combustion process and is highly influenced by the type, furl orientation and the fire-induced environment. The heat release rate, $\dot{Q}_f$, can be expressed as [39]:

$$\dot{Q}_f = \chi \dot{m}'' A_f \Delta H_c \tag{3.7}$$

Where $A_f$ is the fuel surface area (m$^2$), $\Delta H_c$ the heat of combustion of fuel (kJ/g), $\chi$ the combustion efficiency with a value between zero and unity, and $\dot{m}''$ is the mass loss rate per unit surface area of the fuel.

Combustion of the fuel is not always complete which results in the heat of combustion being lower than the net heat of complete combustion. Incomplete combustion generally consists of soot particles and carbon monoxide which are unburned vapour and can normally be seen just above the visible flame. The ratio of heat of combustion to the net heat of combustion is known as the combustion efficiency $\chi$ of the material.

The fuel efficiency depends on a number of factors notably the nature of the chemical bonds between the materials, fire ventilation and entrainment of air by the material vapour. The efficiency will decrease with restricted ventilation or supply of fresh air. This reflects upon the fuel leaving the burning surface does not necessarily take part in the combustion process and that burning rate may be less than the mass loss rate of the material. Hence, two main controlled fires can be defined namely *fuel-controlled* and *ventilation-controlled* fire.

Fuel controlled fires are fire that have unrestricted supply of oxygen i.e. free burning, where the energy release rate are affected only by the burning of the fuel itself. The heating of the fuel is primarily from the flames of the burning fuel.

Ventilation controlled fires are fires that have a restricted or limited supply of oxygen i.e. in enclosed spaces, whereby the burning rate and heat release rate would be limited by this lack of oxygen supply. As such, the rate of energy release can be related to the inflow of air through openings such as doors and windows. Assuming that all oxygen is consumed by the fire, the heat release rate can be expressed by [70]

$$\dot{Q}_{f} = \dot{m}_{air}\Delta H_{c,air} \tag{3.8}$$

Where $\dot{m}_{air}$ is the rate of air flow into the enclosure, and $\Delta H_{c,air}$ is the heat of combustion in terms of air consumed.

<u>Fire growth</u>

Flaming fires often grow rapidly during the initial stages of fire development. The rate of fire growth can be estimated from a time squared correlation and expressed as [39]:

$$Q = \alpha (t - t_i)^2 \tag{3.9}$$

Where $Q$ is the heat release rate from the fire during the growth phase (kW), $t$ is the time from ignition (s), $t_i$ is the time of ignition (s) and $\alpha$ is the fire growth parameter.

This relationship has been found to be suitable for various fuel compositions but only after ignition of the fuel has been well established and has started to grow. The growth parameter $\alpha$, which describes the characteristic of the fire growth, is highly dependent on either the building contents or building type. In most cases, the building type and its uses is employed to determine the growth parameter. This is because the building contents are not readily known. Table 3.1 lists the recommended growth rate for various type of occupancy as quoted in Karlsson et al [39].

| Type of Occupancy | Growth rate $\alpha$ |
|---|---|
| Dwellings, etc | Medium |
| Hotels, nursing homes, etc | Fast |
| Schools, offices | Fast |
| Shopping centres, entertainment centres, | Ultra fast |
| Hazardous industries | Not specified |

Table 3.1 – Typical growth parameter for occupancy type

Table 3.2 lists the classification of the growth rate and $\alpha$ value given in Karlsson et al [39].

| Growth rate | $\alpha$ (kW/s$^2$) | Time to reach 1055 kW |
|---|---|---|
| Slow | 0.003 | 600 |
| Medium | 0.012 | 300 |
| Fast | 0.047 | 150 |
| Ultra fast | 0.19 | 75 |

Table 3.2 – Values of $\alpha$ for different growth rates, according to NFPA 204M.

The growth of the fire will eventually slow down and reach a steady state where either the fuel reaches a maximum burning rate or insufficient oxygen to sustain the combustion process. The magnitude and duration of this maximum heat release rate are commonly based on either the building contents or building type.

The decay phase signalled the end of the fire development. The fire reduces in time until it is eventually extinguished. In practice, the fire is often under the control of fire fighters.

Heat transfer

This section discusses the mechanism of heat transfer from a fire source and the hot plume to the surroundings limited to the conditions within the burning enclosure. The effect of heat transfer on the structure of the enclosure and its fire integrity will not be discussed. The three mechanism of heat transfer are conduction, convection and radiation.

*Conduction*

Conduction is a mode of heat transfer across a medium with a temperature difference. The amount of heat loss across the medium is highly dependent on the properties of the material. The rate of heat loss $\dot{q}$ in one direction can be expressed as

$$\dot{q} = -kA\frac{dT}{dx} \tag{3.10}$$

Where $k$ is the thermal conductivity of the medium ($W/m \cdot K$), $A$ is the surface area across which heat is transferred (m$^2$), $T$ is the temperature and $x$ is the distance normal to the surface (m). Conduction is often considered when analysing heat transfer of a structure and its fire integrity.

*Convection*

Convection is the transfer of heat energy to and from a medium involving the movement of surrounding fluid. In fire cases, convection is responsible for the transport of huge amount of energy to the surrounding by the motion of hot gases i.e. hot smoke. The empirical relationship that governs convection is expressed as

$$\dot{q} = hA\Delta T \tag{3.11}$$

Where $h$ is the convective heat is transfer coefficient and $\Delta T$ is the temperature difference.

The motion of the hot gases may be either naturally induced by the fire itself or by sources external to the fire. Based on this, convective heat transfer can be classified into natural and forced convection. Both natural and forced convection may occur simultaneously under certain conditions which would give a mixed mode of convective heat transfer. Forced convection applies to compartments where forced ventilation is provided i.e. by heating and ventilation system (HVAC systems).

*Radiation*

Radiative heat transfer, being the dominant mode of heat transfer in fire, involves energy exchange between surfaces e.g. walls, ceilings, floors etc. Radiative transfer is proportional to the emissivity, temperature, and dimension of the flames. The expression given in Rasbash [71] is expressed as

$$\dot{q}'' = -\varepsilon\sigma T^4 \tag{3.12}$$

$$\varepsilon = 1 - e^{-\alpha L} \tag{3.13}$$

Where $\alpha$ is the absorption coefficient ($m^{-1}$), $L$ is the flame thickness (m), $T$ being the temperature of flame (K) and $\sigma$ is the Stephan Boltzmann constant (5.67 x $10^{-8}$ $W/m^2K^4$). The perfect emitter has an emissivity of unity.

In addition to provide heat transfer to surrounding surfaces, radiative heat transfer plays an important role in providing radiative feedback to the fire and fuel surface. The former has implication for structural fire performances while the later influences the burning rate and fire spread within an enclosure.

Radiative feedback to the fuel surface is often provided by the hot gas layer. This radiant heat transfer depends on the soot, carbon dioxide and water vapour concentrations. The emissivity of this hot layer as discussed in Rasbash [71] is expressed as

$$\varepsilon = 1 - e\left[-(0.33 + 0.47C_s)l\right] \tag{3.14}$$

Where $l$ being the thickness of the layer and $C_s$ the smoke concentration ($g/m^3$).

### 3.4.2 Principles of smoke movement

From Section 2.2.2, the mechanisms which significantly influence the natural spread of smoke is discussed. The mechanisms are the flow through openings, the stack effects and wind effects.

Flow through openings

Internal flows between spaces of any buildings are primarily due to the building leakage and pressure distribution [70]. These flows are mainly responsible for the movement and distribution of smoke remote from the fire source within a building. Leakage paths stated here represent the gaps around doors, cracks around windows, ventilation ducts and cracks in walls and partitions. These cracks are unavoidable even in air tight buildings.

Flows through narrow openings [70] such as gaps and cracks around doors, windows and in walls are governed by the flow Reynolds number. The flow rates through narrow gaps around door edges can be obtained by the following equation for application to steady, laminar flow over a wide range of pressure differential

$$Q = AC_d\left(\Delta p\right)^n \tag{3.15}$$

where the discharge coefficient $C_d$ and the exponent $n$ is not always known. $Q$ is the volume flow rate, $A$ is the area of the gap and $\Delta p$ is the pressure difference.

Significant airflow takes place across openings of an enclosure. These openings can take the form of either vertical or horizontal openings [70]. Vertical openings [70] take the form of doors between compartments, wall mounted windows and vents. These are mainly openings that do not extend to the ceiling. It is assumed that hot gases flow out through the top part of the opening whereas cold air flows in the opposite direction into the fire room through the bottom part of the opening. The pressure drop across a vent is assumed to be a linear function of the height of the opening.

The neutral plane exists at the location where there is no net flow. This coincides to the interface between high hot smoke layer and low level ambient air. The flow rate per unit width can then be calculated by summing the product of the velocity of the strip and the height of strip per unit width.

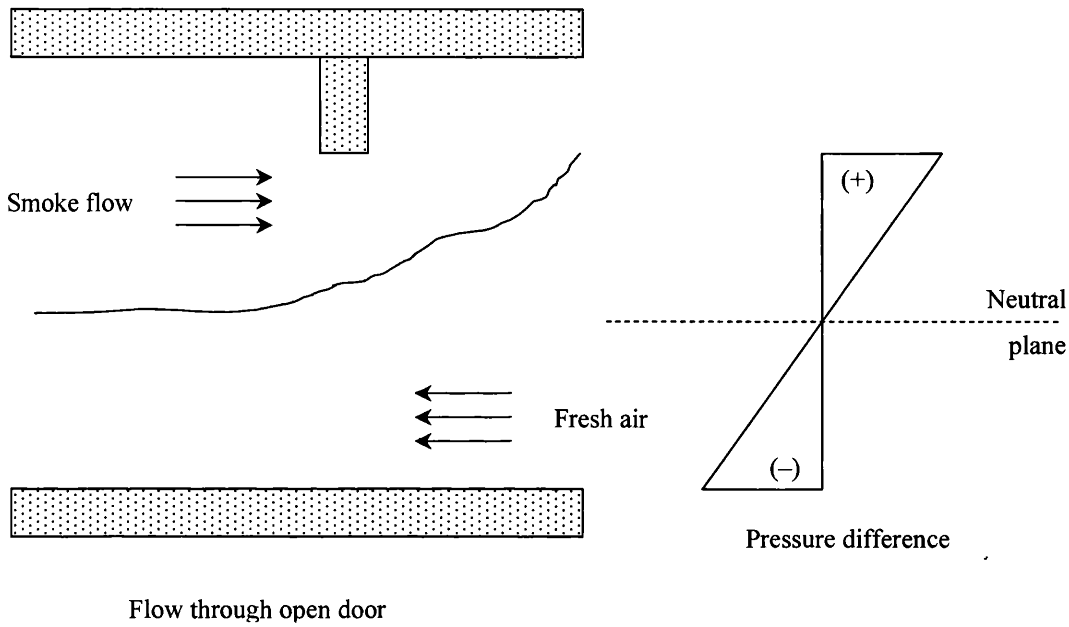



Figure 3.6 – Flow through vertical opening

Horizontal openings [70] normally take the form a roof vent. Airflow across the openings is highly complicated due to hydrodynamics instability. The main reason due to this instability in flow is the density (buoyancy) and pressure differences between the inner condition to the outer condition e.g. hot smoke layer below the openings and colder ambient air outside of the openings. Unidirectional flow exists for flow when pressure difference dominates. In contrast, bidirectional flow takes place when buoyancy dominates similar to those normally seen in vertical openings. Figure 3.7 illustrates the flow patterns that may take place through a horizontal opening.

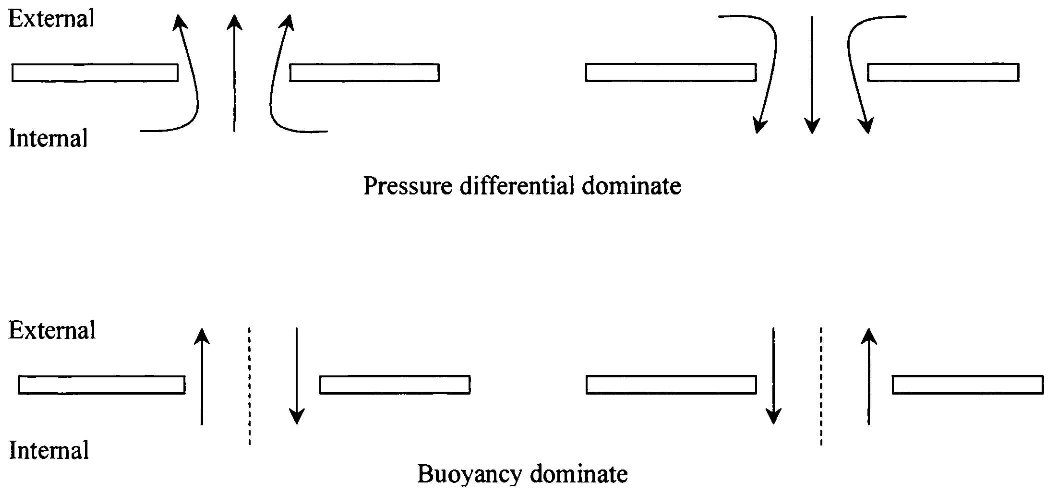



Figure 3.7 – Flow patterns for horizontal openings.

Stack effect

Stack effect [22] refers to the movement of air within buildings especially high rise buildings where flow takes place via building shafts such as stairwells, elevator shafts, mechanical shaft and etc.

Upward movement of air from the ground floor to the roof of the building occurs when the external ambient air temperature is colder that the building interior as seen in Figure 3.8(a). This is commonly known as normal stack effect and is often experienced during winter conditions.

Figure 3.8(b) shows the pressure difference between the building shaft and the outside under normal stack effect. Positive pressure difference indicates that the shaft pressure is higher than the external pressure while negative pressure difference point towards the opposite. Warm internal air which rises from building shafts, due to its buoyancy, will flow out of the building if openings where positioned in regions of positive pressure difference. In contrast, openings positioned in regions of negative pressure difference will have external air flowing into the building. Openings at the neutral plane will not see any significant air movement due to stack effect.

The opposite can be said for the reverse stack effects where air flow downwards instead of upwards under the influence of warmer ambient air temperature compared to the building interior. This is illustrated in Figure 3.8(c) and is frequently experienced during summer conditions.

The magnitude of the stack effect induced air flow is a function of the building height and the magnitude of the temperature differential between the building and ambient. The pressure difference correlation which is equally valid for both normal and reverse stack effect is expressed as

$$\Delta P = K_s\left(\frac{1}{T_O}-\frac{1}{T_I}\right)h \tag{3.16}$$

Where $\Delta P$ is the pressure difference; $K_s$ is the coefficient with a value of 3460; $T_O$ is the absolute temperature of outside air; $T_I$ is the absolute temperature of air inside shaft; and $h$ is the distance above the neutral plane.

The height of the neutral plane is highly influenced by the leakiness of the building envelop. If the leakage paths between the building and external are fairly uniform, the neutral plane will be located near the mid-height of the building. Otherwise, the position of the neutral plane varies considerably, if leakage paths are not uniform.

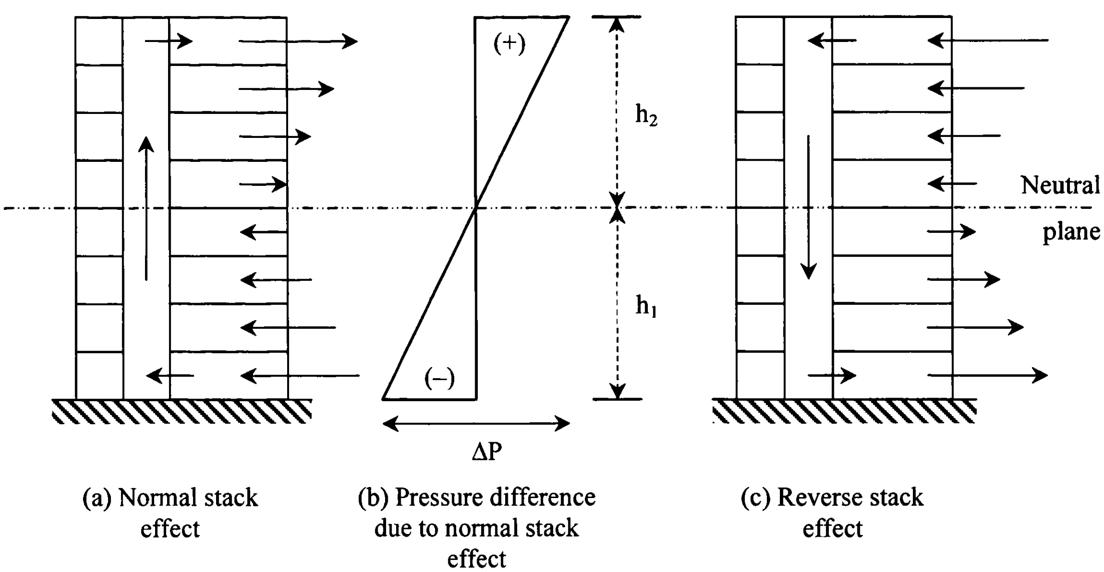



Figure 3.8 – Air movement caused by stack effect.

Smoke movement within a building fire can be dominated by a stack effect. Existing air currents due to normal stack effect can move smoke to considerable distances away from the fire origin. If the fire is below the neutral plane, building air movement will aid smoke to flow into and up the shaft. This upward movement is enhanced by any buoyancy forces possessed by the smoke due to its temperature. Smoke will then flow out of the shaft and into the upper floors of the building once this upward movement rises above the neutral plane.

If leakage between floors is negligible, floors below the neutral plane, except for fire floor, will be relatively smoke free until the quantities of smoke produced by the fire greatly exceeds the stack effect flows.

For fires above the neutral plane, air currents due to normal stack effect will encourage smoke to flow out of the building through any openings and leakage path on the building exterior. If leakage between floors is negligible, all floors other than the fire floor will be relatively clear of smoke until smoke quantities produced greatly exceeds the stack flow.

Wind

Wind effect [22] is another important characteristic in the movement of smoke in buildings. The effects are significant for leaky buildings or for buildings with open doors or windows. It is however less significant for tightly constructed buildings with all doors or windows closed.

Buildings exposed to wind, without significant obstructions, experience both positive and negative wind pressure. Positive wind pressure occurs on the windward wall of a building while negative wind pressure is experience on the both the leeward wall and the two side walls. The flat roof of the building experiences an upward pressure (negative pressure) with the maximum occurring at the windward edge. Figure 3.9 illustrates the wind pressure distribution around a building.

The pressure, $P_w$, that wind exerts on the surface can be expressed as

$$P_w = \frac{1}{2} C_w \rho_O v_w^{\ 2} \qquad (3.17)$$

Where $C_w$ is the dimensionless pressure coefficient, $\rho_O$ is the outside air density and $v_w$ is the wind velocity.

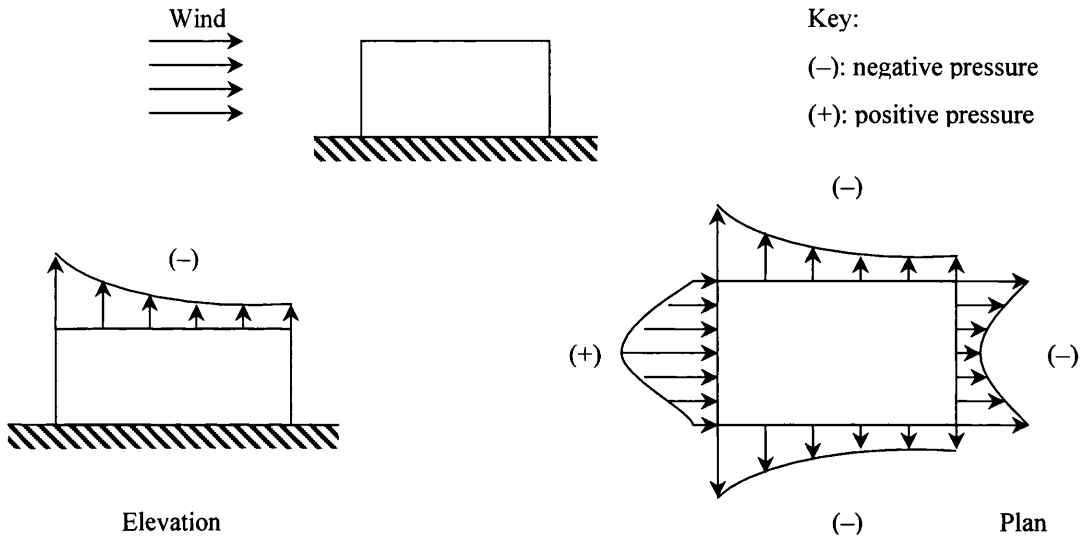



Figure 3.9 – Air pressure distribution due to wind

The pressure coefficient, $C_w$, has a value which varies between -0.8 and 0.8 and is determined by the shape of the building. Positive coefficient applies to windward walls whilst negative coefficient refers to leeward walls.

Air is known to follow the path with the least resistance. Based on this theory, major volume of air will flow over the roof of a short and wide building with less around the sides. In contrast, major volume of air will flow around a tall and narrow building with less movement over the top of the building. This flow pattern is frequently observed in unobstructed high rise buildings.

Due to the horizontal air flow across high rise buildings, the effects of wind pressure will influence the natural air movement within a building. The position of the neutral plane of the building will also be affected. A two tier neutral plane will occur where the location of the neutral plane is higher at the windward side and at the same time, a lower neutral plane occurs at the leeward side of the building.

In fire situations, it is typical for windows of the fire compartment to break. If the windows are on the leeward side of the building, the negative pressure will aid the removal of smoke from the fire compartment and greatly reduces smoke movement in the building. If the windows are on the windward side, positive pressure will force smoke out through the fire door and to other floors of the building. This endangers the lives of occupants in the building and hinders fire fighting. Pressure induced in these situations can be relatively large and can overcome air movement throughout the building.

### 3.4.3 Smoke properties

Smoke opacity

As discussed in G. Mulholland [72], smoke opacity is a measure to quantify smoke so that standards can be set for engineers when assessing a fire hazard in their design. Smoke obscuration or the reduction of visibility presents an indirect hazard whereby it impedes escape, thus prolonging the exposure to toxic combustion products i.e. the obscuration due to smoke works as a trap, with the toxicity and the heat being the main killer.

The most widely measured smoke property is the light extinction coefficient and is defined based on Bouguer's law which relates the intensity of the incident monochromatic light, $I_o$, to the intensity of the light, $I$, transmitted through the path length of the smoke:

$$\frac{I}{I_o} = 10^{-DL} \tag{3.18}$$

$L$ is the optical path length and $D$ is the optical density.

When expressed as natural log, Equation (3.18) becomes

$$\frac{I}{I_o} = e^{-KL} \tag{3.19}$$

$K$ is the extinction coefficient.

The optical density, expressed in terms of extinction coefficient is

$$D = \frac{K}{2.3} \tag{3.20}$$

Visibility

The ability for an individual to see while attempting to survive a fire hazard is of great importance. The visibility of an individual is highly influenced by many factors including the scattering and the absorption coefficient of smoke, illumination in the room, light emitting or light reflecting signs and the wavelength of the light.

The visibility correlation, as presented by Jin [15] is given by

$$KS = 8 \qquad \text{for light emitting signs} \tag{3.21}$$

$$KS = 3 \qquad \text{for light reflecting signs} \tag{3.22}$$

Where $K$ is the extinction coefficient; $S$ is the visibility in meters. Irritancy effect due to smoke is not considered in these data.

## 3.5 Concluding remarks

Whilst appreciating zone modelling stature as a competent fire analytical tool, field modelling approach is the preferred fire analytical tool. This is to address the increasingly complex geometries and flow mechanisms which are to be expected when assessing fire engineered smoke control systems for both high rise buildings and covered car parks.

The temperature-time curve (heat release rate-time curve) has provided a means of charting the history of the fire development. This coupled with the engineering correlations enables fire engineers to determine an appropriate fire scenario to be used for the analytical assessment. What consists of a fire scenario is discussed in Section 5.2.1.

Similarly, the smoke properties correlations allow for the tenability of the protected space to be assessed. One tenability criterion is the visibility. An example on the used of this criterion is presented in Section 5.2.2.1.

Methods that may be used to restrict smoke movement are also presented. Currently, only the natural [20] and pressurization [18] systems are prescribed by code of practice. Other smoke control methods are not and can only be designed as fire engineered solutions.

# Chapter 4 Computational Fluid Dynamics

This chapter presents the Computational Fluid Dynamics (CFD) formulation including a short list of commercial and open source CFD codes that has a track record of predicting fire and smoke movement. At the end of the chapter, factors that maybe used to assess the output of CFD modelling are briefly discussed.

So the age old question, what is CFD? Yeoh et al [16] sums it up perfectly that

> "CFD is simply the study of fluid systems that could be static or dynamically changing in time and space. The fluid dynamics component is performed through numerical methods on high-speed digital computers, which incidentally represents the computational description of the terminology. Additionally, the physical characteristics of a fluid in motion can usually be described by the consideration of fundamental mathematical equations, usually in partial differential form, governing a process of interest. In order to solve these mathematical equations, there are converted into discrete forms using high-level computer programming languages into in-house computer programs or commercial CFD software packages."

Why CFD as a design and assessment tool? [16]

Experimental and analytical methods have traditionally been used to study the various aspects of fluid dynamics and assist in the design of equipment and industrial processes involving fluid flow and heat transfer. The availability of digital computers, the lowering of cost associated with the hardware and greater speed of computer chips have helped the computational approach as another viable option in resolving complex fluid dynamic issues.

In addition, the evolution of CFD simulation to better encapsulate the flow process has inspired confidence for engineers and academics alike to scientifically adopt the CFD technique to find an unique solution to fluid dynamics and heat transfer problems. Multi-purpose CFD software packages offer further support to evaluate this activity.

The CFD approach has numerous advantages over traditional approaches. The first is the cost-effectiveness of carrying out multiple parametric studies with greater accuracy that allows for development of new or improved system designs and rigorous optimization carried out on existing equipment with substantial reduction in lead time resulting in enhanced efficiency and lower operating cost.

Secondly, CFD simulation provides a platform to the quest to gain an increased knowledge of how systems are expected to perform such that evolutionary improvements to the design and optimization process can be made. This allows for the investigative imagination to be challenged and offers predictions to "what if ...?" questions.

Maturity of CFD in field modelling

As presented in previous sections, CFD encompasses the study of fluids that are in motion, governed by the conservation equations, through computational means. A burning fire, however, constitutes more than just a description of fluid mechanism. In simple terms, fire involves the burning of fuel (in gases, liquids or solid state), subsequent release and spread of by products, which may be toxic, and heat to the atmosphere. Some significant mechanisms involved in this process are:

- The turbulent nature of the flow of the gaseous by product (smoke),
- Radiation from the flaming fire and the hot gaseous by product,
- Chemical combustion process of the fuel.

These mechanisms are disciplines in their own right where large database of literatures exists to primarily explain and address their respective fundamental principles and theories. Decades of dedicated research into these disciplines have led to a level of maturity where stable and robust models have been established for a wide range of applications. As such, these models and their application in CFD can now be readily employed to adequately describe the fire phenomena.

## 4.1 Short list of CFD software packages

Table 4.1 shows the shortlist, an extract from Olenick et al [42], of existing CFD software packages that have a track record in the modelling of fire and smoke movement.

<u>Multi-purpose</u>

CFX [55] and PHEONICS [73] are two leading commercial multi-purpose CFD software packages that have an extensive track record in fire and smoke movement modelling. CFX is a product of ANSYS Inc. and is capable of modelling geometries of various shape and sizes due to its employment of unstructured hybrid meshes and capability of adapting the mesh to fit the geometries that are under consideration. The CFD code adopts finite element base control volume and allows the user to add additional scalar sub-routine which may further enhance the code. CFX has often been the preferred choice for academics and industry alike and has an extensive list of validation on modelling fire and smoke movement [74-76].

PHOENICS, developed by CHAM Ltd, has a functionality that is similar to that of CFX but employs finite volume technique to solve for the conservative equations. The solver employs a structured Cartesian grid (mesh) system with a multi-block character that is enhanced by 'fine-grid embedding' which provides a sufficient ability to fit small-scale flow feature without the computational overhead of fully-unstructured grid. PHOENICS also allows additional scalar sub-routine and has been validated for use in modelling fire and smoke movement [77].

Specific to Heating, Venting and Air Condition (HVAC) modelling

FloVENT [56] is a product by Mentor Graphic and has been marketed as a CFD software package for the design as assessment of HVAC systems in the built environment. The solver is based on a Cartesian gridding system supported by a localised-grid technique that is similar to that adopted by PHEONICS. Validation of the package for use in fire and smoke modelling is given by Manz et al [78].

Specific to fire and smoke movement modelling

SMARTFIRE [57] and JASMINE [79] are commercial software packages developed specifically for fire and smoke movement modelling. Fire Dynamic Simulator (FDS) [58], on the other hand, is an open sourced program dedicated to the same cause.

SMARTFIRE [57] is a product developed by the Fire Safety Engineering Group (FSEG) of the University of Greenwich, UK. The CFD code employs a fully unstructured 3D mesh using finite volume methods to solve for the conservative equations and has no user access i.e. closed software package. Given its uses, SMARTFIRE has a long list validation in the modelling of fire and smoke movement and is characterize by the CIB W14 Round Robin test series [80] and the Development of Standards in Fire Field Models [81, 82].

JASMINE [79] is developed by the Building Research Establishment (BRE) UK. The code employs the finite volume methodology with a structured Cartesian grid system. JASMINE has been extensively validated [83, 84] and has been successfully used to simulate fire and smoke movement in a wide variety of construction projects which includes the design of smoke ventilation systems.

FDS [58] is the fire field model developed by NIST with the conservative equations approximated by the finite difference methodology and solved on a three-dimension rectilinear grid. This software package, as an open sourced package, is freely available and allows user access to the underlining CFD codes. Validation of this software package is again extensive [85, 86].

All of the shortlisted CFD software packages are capable of providing a reliable and accurate prediction of the fire and smoke movement for any built environment. They are also capable of predicting other properties that may be of interest e.g. visibility, toxicity level of the smoke produced (HCL and CO) and effects of sprinklers.

However, a fully validated CFD code that is 'closed' i.e. in which a user have no access to the codes by means of a user routine, is an ideal choice for use by fire engineers. This negates the risk of the user tweaking the CFD code to solve to for a particular problem while passing the need to validate the changes made to the CFD code thus preserving the integrity of the CFD code. For this reason, SMARTFIRE v4.1 is the software package of choice and is used in the analysis in the following chapters. The mathematical equations adopted by SMARTFIRE v4.1 are discussed in the next section.

| No | Descriptions | CFD Software / Notes (Comment) | | | | | |
|---|---|---|---|---|---|---|---|
| | | FloVENT | CFX | PHOENICS (FLAIR) | JASMINE | SMARTFIRE | FDS |
| 1 | Developer | Mentor Graphics | ANSYS Inc | CHAM Ltd | Building Research Establishment, UK | FSEG | NIST |
| 2 | Software purposes | Specialized for building HVAC | Multi-purpose | Multi-purpose | Fire and smoke movement | Fire and smoke movement | Fire and smoke movement |
| 3 | Mesh structure | Structured – Cartesian grid system | Unstructured | Structured – 'fine grid embedding' | Structured – Staggered Cartesian | Unstructured - rectilinear | Structured – Staggered Cartesian |
| 4 | Third party mesh generator | Not needed | Not needed | Not needed | Not needed | Harpoon | PyroSim |
| 5 | CFD codes | User sub-routine | User sub-routine | User sub-routine | User sub-routine | Closed | User sub-routine |
| 6 | Validation | Yes | Extensive | Yes | Extensive | Extensive | Extensive |
| 7 | Availability | Commercial Research | Commercial Research | Commercial Research | Commercial Research | Commercial Research | Open source |

Table 4.1 – CFD software packages

## 4.2 Mathematical sub models

What are sub-models? Sub-models are mathematical equations which represent the prevailing physical phenomena so as to fully capture the actual nature of the environment. In terms of field modelling, as stated before, the three core sub-models of concern are the turbulence models, radiation models and combustion models.

What do sub-models represent and why are they important? Turbulence models describe the local instability in the flow of a fluid. In a burning fire, the instability is created by the introduction of energy to the environment due to the release of hot gaseous combustion products (smoke plume) and the fire itself. As the plume rises due to buoyancy, the instability in the plume as it rises encourages the plume to mix with surrounding air known as entrainment. The instability of the hot plume is also evident when the hot plume accumulates under the ceiling of an enclosure as it is continuously fed by the fire and its subsequent venting through an opening when provided e.g. doors and windows. Turbulence models are therefore important to capture these mechanisms by means of encouraging a degree of mixing between the gaseous combustion products and air.

Radiation models depict the transfer of radiant energy from an entity to the surfaces of other entities and vice versa by means of electromagnetic wave. The energy is transferred in all direction and may take the form of: Fire to smoke plume, smoke layer, fuels (e.g. furniture and other combustible) and enclosure walls; hot smoke layer to fire, fuels, and enclosure walls; and walls to smoke layer and fuel. The need to properly depict this nature is important in fire modelling as the energy transferred is greatly dictated by temperature (temperature to the power of 4) of the entity i.e. hot smoke layer.

Combustion models describe the chemical reaction of specific fuels and the release of subsequent combustion products. These models are used to quantify the rate at which smoke is produced based on the chemical reaction. This is an alternative method to the simple volumetric heat release model which only considers the resulting effect of fire, not the chemical process by imposing a typically uniform distribution of heat and smoke over a prescribed volume that represents the expected characteristic of the flaming region in which combustion occurs.

### 4.2.1 Conservative equations

As discussed in Section 3.2.2, the equation for the conservation of mass in partial differential form is [54]:

$$\frac{\partial \rho}{\partial t} + div\left(\rho \underline{u}\right) = 0 \tag{3.4}$$

Where $\rho$ is the density, $t$ is the time and $\underline{u}$ the velocity vector.

Similarly, the equation for the conservation of momentum in partial different form is [54]:

$$\frac{\partial\left(\rho u_i\right)}{\partial t} + div\left(\rho \underline{u} u_i\right) = -\frac{\partial P}{\partial x_i} + div\left(\mu_{eff}\, grad\left(u_i\right)\right) + S_{u_i} \tag{3.5}$$

Where $u_i$ is the velocity in the x, y and z direction, $P$ is the pressure and $\mu_{eff}$ is the effective viscosity.

Likewise, equation for the conservation of energy is [54]:

$$\frac{\partial\left(\rho h\right)}{\partial t} + div\left(\rho \underline{u} h\right) = div\left\{\left(\frac{k}{c_p} + \frac{\rho \upsilon_t}{\sigma_T}\right) grad\left(h\right)\right\} + S_h \tag{3.6}$$

Where $h$ is the enthalpy, $c_p$ is the specific heat capacity and $S$ the source term.

These equations from the basis of all CFD codes and along with the ideal gas law solves for the variables of pressure and velocities in all directions (u, v, and w) that are of interest to the fire environment.

### 4.2.2 Turbulence model

SMARTFIRE v4.1 [57] uses the buoyancy modified k-ε turbulence model to capture turbulent nature of the fluid flow. The model is part of the Reynolds-Averaged Navier-Stokes (RANS) family which considers the time averaged mean scales of the instabilities known as eddies and is not aimed to resolve the turbulent motion but to provide the time-averaged characteristic quantities of the flow. The largest eddies in the fluid can be described as having a characteristic velocity and a characteristic length of the same order as the velocity scale and length scale of the mean flow [16]. This implies that the scales of the largest eddies are comparable to the mean flow and are dominated by inertia forces. Smaller eddies are the instabilities created by the transport of these larger eddies through the flow.

The differential equations associated with the buoyancy modified k-ε models consists of two parts, the turbulent kinetic energy equation

$$\frac{\partial k}{\partial t}+div\left(\rho \underline{u} k\right)=div\left\{\left[\mu_{lam}+\frac{\rho v_t}{\sigma_K}\right]grad\left(k\right)\right\}+P+G-\rho\varepsilon \qquad (4.1)$$

and the dissipation rate

$$\frac{\partial \varepsilon}{\partial t}+div\left(\rho \underline{u} \varepsilon\right)=div\left\{\left[\mu_{lam}+\frac{\rho v_t}{\sigma_\varepsilon}\right]grad\left(\varepsilon\right)\right\}+\frac{\varepsilon}{k}\left[C_{1\varepsilon}\left(P+C_3\max\left(G,0\right)\right)-C_2\rho\varepsilon\right] \qquad (4.2)$$

Where P is the turbulent production rate given by

$$P=2\rho v_t\left\{\left(\left[\frac{\partial u}{\partial x}\right]^2+\left[\frac{\partial v}{\partial y}\right]^2+\left[\frac{\partial w}{\partial z}\right]^2\right)\right\}+\rho v_t\left\{\left[\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right]^2+\left[\frac{\partial u}{\partial z}+\frac{\partial w}{\partial x}\right]^2+\left[\frac{\partial w}{\partial y}+\frac{\partial v}{\partial z}\right]^2\right\} \qquad (4.3)$$

and G is the buoyancy given by either

$$G=-\beta g\rho v_t\frac{\partial T}{\partial y} \qquad \text{or} \qquad G=gv_t\frac{\partial \rho}{\partial y} \qquad (4.4)$$

With the expansion coefficient $\beta$ given as

$$\beta=\frac{1}{\rho}\frac{\partial \rho}{\partial T} \qquad (4.5)$$

The turbulent kinematic viscosity, $v_t$ is defined as

$$v_t=C_\mu\frac{k^2}{\varepsilon} \qquad (4.6)$$

The initial values, as of the standard k-ε turbulence model, for the five constants defined previously is given as

| $C_\mu$ | $\sigma_k$ | $\sigma_\varepsilon$ | $C_{1\varepsilon}$ | $C_{2\varepsilon}$ | $C_3$ |
|---|---|---|---|---|---|
| 0.09 | 1.0 | 1.22 | 1.44 | 1.92 | 1.0 |

### 4.2.3 Radiation model

During a fire, two modes of heat transfer exist: convection and radiation. The former persists at low temperature from about 150°C to 200°C while the later dominates for temperatures above 400°C [16]. Radiosity and Six-Flux models are two radiation models available in SMARFIRE v4.1 [57].

Radiosity model

The radiosity is an average of the incoming and outgoing radiation fluxes integrated over all directions of the solid angle. The equation for the radiosity $R$, takes the form

$$\frac{d}{dx_i}\left[\frac{4}{3(\alpha+s)}\frac{dR}{dx_i}\right]+\alpha(E-R)=0 \tag{4.7}$$

Where $\alpha$ is the absorption coefficient, $s$ is the scattering coefficient and $E$ is the black body emissive power of the fluid determined from

$$E=\sigma T^4 \tag{4.8}$$

$\sigma$ is the Stefan-Boltzmann constant.

Six-Flux radiation model

The Six-Flux radiation model is only applicable to structured meshes and considers the radiation fluxes at each of the six faces of the control volume to be uniform, in this case the six coordinate directions (I, J, K, L, M, and N) of a rectilinear control volume and takes the form

$$
\begin{aligned}
\frac{dI}{dx} &= -(\alpha+s)I + \alpha E + \frac{s}{6}(I+J+K+L+M+N) \\
\frac{dJ}{dx} &= +(\alpha+s)J - \alpha E - \frac{s}{6}(I+J+K+L+M+N) \\
\frac{dK}{dy} &= -(\alpha+s)K + \alpha E + \frac{s}{6}(I+J+K+L+M+N) \\
\frac{dL}{dy} &= +(\alpha+s)L - \alpha E - \frac{s}{6}(I+J+K+L+M+N) \\
\frac{dM}{dz} &= -(\alpha+s)M + \alpha E + \frac{s}{6}(I+J+K+L+M+N) \\
\frac{dN}{dz} &= +(\alpha+s)N - \alpha E - \frac{s}{6}(I+J+K+L+M+N)
\end{aligned} \tag{4.9}
$$

Where $\alpha$ is the absorption coefficient, $s$ is the scattering coefficient and $E$ as the black body emissive power.

#### 4.2.4 Combustion model

In SMARTFIRE v4.1, combustion is modelled using the Simple Chemical Reaction Scheme (SCRS) that allows the complex combustion process to be modelled through a solution of a small number of equations. These equations can be classified into either diffusion controlled or kinetically (mixing) controlled reaction.

The chemical reaction takes the form of

$$F + sO_2 \rightarrow (1+s)P + heat \tag{4.10}$$

Where $F$ is the fuel, $s$ is the stoichiometric ratio of the oxygen to fuel, $O$ is the oxidant and the product $P$.

In diffusion controlled reaction, the mixture fraction $f$, as a conserved scalar, is solved from the partial differential governing equations. Mixture fraction is a concept that describes the degree of scalar mixing between fuel and oxygen and is a local quantity that varies both spatially and temporally [16]. The mass fractions of fuel, air and product are calculated by

$$m_f = \frac{(f-f_s)}{(1-f_s)}, \quad m_a = 0, \quad m_p - 1 - m_f, \quad if\ f > f_s \tag{4.11}$$

$$m_a = \frac{1 - f_s}{f_s}, \quad m_f = 0, \quad m_p - 1 - m_a, \quad if\ f < f_s \tag{4.12}$$

Where $m_f$, $m_a$ and $m_p$ are the mass fraction of fuel, air and product respectively.

In contrast, the kinetically controlled model i.e. eddy mixing controlled, the fuel mass fraction $m_f$ and the mixture fraction $f$ are two conserved scalar. The mass fraction of air and product are then algebraically calculated from the following

$$m_a = 1 - m_f - \frac{\left(f - m_f\right)}{f_s} \tag{4.13}$$

$$m_p = 1 - m_f - m_a \tag{4.14}$$

Where $f_s$ is the stoichiometric value of $f$ defined by

$$f_s = \frac{1}{1+s} \tag{4.15}$$

## 4.3 Assessment of CFD predictions of smoke movement

An important aspect in the use of fire field models as a design tool is the need to assess the outputs to ensure that the prediction is of good quality and is valid. In doing so, provide a degree of confidence to all stakeholders that the fire engineered design meets the requirement and is fit for purpose. This section presents a few criteria that are commonly used to assess the validity of the prediction and are based on Gobeau et al [8].

What measures are available to ensure that the CFD simulation is valid? There are several simple yet important characteristics to consider and are discussed later. They are:

- The CFD code and its version
- Computational domain of the model
- Inclusion of physical sub-model
- Fire source and smoke properties specification.

- Boundary conditions specifications
- Experience of the user

What is the measure of the accuracy of CFD simulation? The main criterion for this measure is the convergence of the solution. This is discussed in detailed in subsequent sections.

### 4.3.1 The CFD code

The CFD code employed should always be verified and validated for its uses which in this case for fire and smoke movement modelling. The process of verification ensures that there are no significant errors in the coding of the equations or problems with the numerical behaviour of the code. These errors are a very common occurrence as a typical CFD code consists of hundreds of thousand of lines of codes which embodied the physical and numerical sub-models and in some cases sophisticated interface to help create the geometry and define the problem.

The validation process assesses the accuracy of the CFD code against test cases and experimental data for the range of application the code claims to cover. It is also important to be aware of the extent to which the code has been validated as this may be useful to indicate if results, of the scenario under investigation that is far removed from validation cases, be on the side of safety or otherwise.

Commercial CFD codes and software packages as presented in Section 4.1 have, to an extent, been subjected to verification and validation for fire and smoke movement application. If a non commercial code is used, the extent to which the code has been verified and validated for fire and smoke movement should be sought.

Verification and validation of CFD codes is an essential part of the process to establish the reliability, capability and limitation of the code with the outcome readily available.

### 4.3.2 Computational domain of the model

The computational model should always be of a three-dimensional computational domain. This is to better capture and appreciated the characteristic of the three-dimensional airflow induced by the fire. Complex geometries have also ruled out feasibility of using two-dimensional simulation.

Another important aspect in defining the computational domain is the domain boundaries. Boundaries should be located such that they do not adversely affect the simulated smoke movement. For example, the fire source should not be located close to open boundaries as such boundaries allows the simulated smoke to be removed from the fire compartment of interest and the subsequent computational domain thus reducing the effect of smoke e.g. visibility and toxicity and heat e.g. temperature has on the compartment.

The level of geometric detail within the domain also needs be considered. For instance, anything that might affect the flow has to be included in the domain which may be in the form of obstacles, heat sources other than the fire, geometric simplifications and inlets/outlets (e.g. openings and forced ventilation).

Geometric simplification is commonly adopted due partly to the computational limit and processing time and partly due to the consideration of the region of interest only. For example, Gobeau et al [87] ignores the fixtures and fittings in all three real scenarios studied. The stairs were represented as empty towers for the building under construction as this is considered to be the worst case scenario for which smoke can rise freely and quickly to the upper floors without having to travel around the steps in the stairs.

The geometrical shape may also be slightly modified on condition that it is not likely to influence the flow to a great extent. The advantages of doing so allows for the generation of a less distorted grid (mesh) which tends to minimises the numerical error and further enhance the grid to better capture the more important flow feature. This advantage outweighs the loss of details in the geometry and is particularly true for structured grids.

### 4.3.3 Physical sub-models

The use of sub-models should be specified given their importance to better predict the environment within the fire enclosure and any adjacent rooms.

To recap, the mechanism involved in fire applications are:

- Turbulence: fire induced turbulent flow which encourages heat exchange with ambient air and affect smoke transport and dilution through mixing.
- Radiation: Exchange of heat between fire, hot smoke and wall surfaces.
- Combustion: Responsible for the production heat and smoke
- Buoyancy: Is the representation of the natural convection due to heat release which affects the turbulence flow.

Turbulence

Gobeau et al [8] recommends that the commonly used two equations k-e turbulence models must be modified to include for buoyancy effects. Simple zero- or one-equation turbulence models must not be used as they are unable to cope with the buoyancy effects nor be modified to account for these effects.

Radiation

Radiation or at least the radiative heat loss must be taken into account in fire modelling. This enables the redistribution of the heat energy within the smoke layer and avoids over prediction of the temperature.

For large fire in confined spaces, sophisticated radiation models such as those presented in Section 4.2 should be used to better predict the far field smoke temperature. For moderate fire in large open spaces, the choice of radiation models is less critical [87].

Combustion

Two modelling approach can be used to account for combustion:

- Volumetric heat release: Predicts the transportation of heat and smoke away from the fire but not their release. Heat and smoke release is uniform over the volume of the fire and is specified by the user along with its quantities.
- Combustion model: Predicts the chemical reaction that happened in the fire. Heat is predicted to be non-uniformly distributed and accounts for the influence of the local air flow.

It has been documented that volumetric heat source is comparable to combustion models on condition that the fire is not influenced by proximity walls or ambient air flows providing that the fire source is well specified i.e. heat release output and the volume representing the fire flame. Otherwise, combustion model is the preferred method ahead of volumetric heat source.

Buoyancy

Buoyancy which defines the flow due to temperature variation is often described by the Boussinesq approximation. The Boussinesq approximation assumes that the density is constant and is linearly dependent to the temperature [88]. This approach is only valid for very small temperature gradient in the order of a few degrees to tens of degrees and therefore only applicable to very early stages of fire development (or far field temperature with weak fire) but not for the later stages where the temperature gradient is extremely steep. Hence, this approach should not be used in fire and smoke movement modelling.

The non Boussinesq approximation should be used. Instead of assuming a constant density, this approach assumes that the fluid is compressible and that the density varies with temperature which is calculated based on the ideal gas law. Gobeau et al [87] found in favour of using this approach to quantify buoyancy.

### 4.3.4 Fire source and smoke properties specification

The parameters that characterise the fire source, defined by the user, are dependent on the modelling approach chosen and have to be specified so that it is representative of the fire scenario modelled. The parameters that often used to define the heat release rate have been presented in Section 3.4.1.

It is common practice that the rate of smoke production is proportional to the heat release rate by a yield factor determined experimentally. The selected smoke production rate should either be representative to the burning material in the scenario modelled or most likely be the worst case scenario. The yield factor refers to the product of aerosols combustion only and does not include the gaseous product. Detailed yield factors for a selection of material can be found in SFPE Handbook [72].

### 4.3.5 Boundary conditions

Boundary conditions are specified by the user to define the geometry of interest within the computational domain. This may be in the form of walls, ventilation conditions that influence the flow entering or leaving the region of interest, opening or closing of doors and etc.

Walls

There are two mechanisms to consider for impermeable walls. They are:

- Air flow
- Heat transfer

Impermeable walls are often assumed to be non slip implying that the fluid sticks to the solid boundary and therefore has zero velocity at the boundary [89].

For heat transfer, it is common practice that walls are assumed to be adiabatic which means that no heat transfer takes place between the wall and the hot gases [89]. This allows for smoke to propagate at a quicker rate which represents a conservative estimate. In contrast, by prescribing a temperature (or heat flux) to impermeable walls, this encourages maximum heat transfer to the walls.

Inlet and outlet

Inlets can be commonly used to prescribe the forced ventilation within the computational domain. In most cases, they are represented by the flow rates of the mechanical fans.

Outlets boundaries are cut off points where once flow pass through it, the flow is removed from the computational domain and is no longer be of interest. Since little is known about the flow in these regions, it should be prescribed as far downstream of the flow as possible to avoid errors propagating upstream.

It is recommended that these boundaries be prescribed away from the heat source [89] so that they do not adversely affect the convective flow of the fire and smoke concentration that may be of interest.

Another important flow feature is the presence of leakage flows especially in the built environment [61]. These flows, especially the convective flow generated by the fire, can have a significant effect on the flow inside and beyond the domain. It is therefore important that leakage flows are considered.

### 4.3.6 Expertise of the user

It is vital that the CFD practitioner has an in-depth knowledge of both CFD and fire and smoke movement dynamics [8, 87]. The CFD practitioner has to undergo complex processes which, first of all, is required to create the geometrical model that represents the problem being investigated, specify the boundary conditions associated to the problem, select the appropriate physical and numerical sub-models to account for the scenario, assess the solution convergence and finally analyse the prediction based on sound understanding of fire and smoke movement dynamics.

Similarly, when assessing a CFD prediction, the CFD assessor understanding of fire and smoke dynamics is essential. This allows the assessor to draw on past experience to decide if a prediction made by CFD is probable and comparable to real life scenario [8, 87]. Understanding of CFD will further aid the assessor in ensuring that the prediction is numerically valid i.e. suitable sub-models chosen and a converged solution.

### 4.3.7 Numerical issues

Temporal – Time step size

CFD simulations may be steady state or transient. Steady state simulations are analysis that are irrespective of time [89]. For example, fire and ventilation conditions are prescribed as constant and do not change with time. Information on the development of the predicted flow pattern is also not provided. This implies that the rate of smoke movement and evacuation time cannot be evaluated using this approach.

Transient simulations account for the fire growth, changes to airflow patterns and changes to the geometry at incremental time. Such simulations are particularly useful for analysing the performance of an emergency ventilation system where interactions of doors opening and closing, along with activation time delays of the life safety system after the ignition of the fire have to be considered. The time delay is due to the life safety system being designed to be triggered by smoke detectors.

Care should be taken when choosing the time increments (known as time step). Gobeau et al [8] recommends that the time step be chosen based on the physics of the flow and be consistent with the grid (mesh) where finer grid requires a smaller time step. This implies that smoke layer spreading at a faster rate modelled on a fine grid would require a smaller time step than a slowly moving smoke modelled on a coarse grid.

In most cases where the physics of the flow can be predetermined (e.g. opening and closing of doors during an escape), the values of the time steps can be determined automatically through a time-stepping algorithm. This algorithm corrects the values of the time steps at these intervals as the iterative process progresses to the final solution. This approach has been adopted in the analysis in this thesis.

Convergence criteria

Convergence is the solution of an equation, solved iteratively, converges on a single set of values [89]. In this case, the set of values satisfies the conservative equations both locally and globally. Convergence is determined numerically and through a grid independence study. This criterion, defined in advance by the CFD practitioner, determines when the iterative process stops for steady state simulations or the start of the next time step in transient simulations.

Numerical convergence is based on the measure of imbalance of the variables in the conservation equations against appropriate reference values (not always easy to define) [89]. This difference is known as residual errors. Another measure is the change of the residual errors between iterations. If the change is small, the solution is said to be converged. However, this criterion alone is insufficient as the residual errors, though small, may be of significance. As such, convergence should be supported by the monitoring of all variable values at key locations.

Errors due to the use of inappropriate convergence criterion can be significant as they are introduced at each subsequent time step and are accumulative. Another check for convergence, the grid independent study, is determined through numerical experiments i.e. repeating the calculation on a series of refined grid. If the method is stable and if all approximations used are consistent, the solution is converged to a grid independent solution [89]. This method ensures that errors that may arise due to the employment of different grid sizes are accounted for and not affect the solution. The use of this method is discussed in Chapter 5.

## 4.4 Concluding remarks

This chapter promotes the understanding of the underlying principle of CFD, the associated sub-models relevant to fire modelling and the responsible use of the technology. This enables the fire engineering communities and more importantly the fire authorities to make an informed decision on the submissions of fire engineered solutions designed using field modelling approach.

In addition, the maturity of the CFD formulations and the associated sub-models has offered further confidence to the viability and implementation to fire and smoke movement applications.

The software package SMARTFIRE v4.1 [57] has been chosen as the fire analytical tool for use in assessing the performance of the fire engineered smoke control system. The reason behind this choice is that the integrity of the software is preserved as the software is 'closed' where the end user has no access to the codes. This, therefore, negates the risk of failing to valid changes that have been made to the codes.

# Chapter 5 Simulation based design procedure

This chapter presents the process to which field modelling is applied to the design and assessment of the fire engineered smoke control system. The generic procedure sets out in the performance based codes described in Chapter 2 forms the basis of the simulation based design procedure with a typical five-storeys building being used as an example. The ventilation strategy that describes the fire engineered systems is the mechanical assisted extract system. It is also in this chapter that the following is identified and answered.

- Computational model, what needs to be considered and why?
- What are the design assumptions and their justification?
- Extract rates, how does it relate to choosing the correct fan?
- Has the design objectives been met?

Included in this chapter is the discussion on decision making process for the design of smoke control systems for above ground, which has been presented in Chapter 2 and that of a covered car park.

## 5.1 Design process

This section presents the decision making process associated to above ground and covered car park smoke control systems. Once the decision making process has established the need for a fire engineered solution, the implementation procedure of the fire engineered approach with the use of fire analytical tool, which in this case field modelling, is presented.

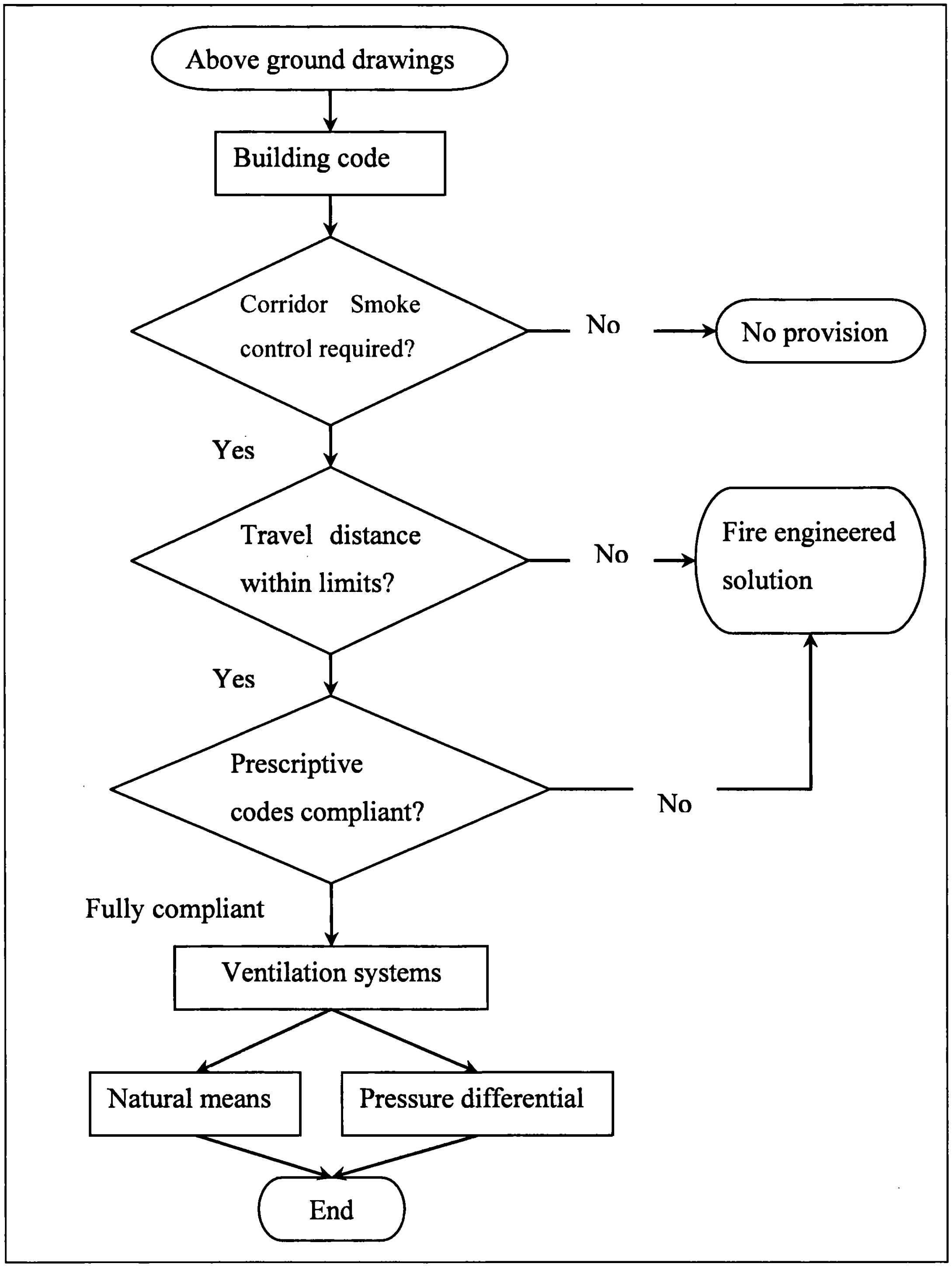
### 5.1.1 Decision making process

<u>Above ground</u>

As discussed in Chapter 2, the need for an above ground smoke control system is dictated by the three building characteristics which are:

- Height of the building;

- Maximum travel distance from the entrance of the furthest accommodation to the stair door; and
- Number of common escape routes i.e. number of stairwells.




From Figure 2.1 – Decision making process for above ground smoke control systems.

The choice of the smoke control systems is dependant on two factors which are

- Maximum travel distance; and
- Compliance to prescriptive codes.

If both factors are code compliant (to prescriptive and building codes respectively), the smoke control system can be designed based upon the criteria set out in prescriptive codes. Otherwise, if either one of the factors is code compliant or that none of the factors are code complaint the only possible means of designing an acceptable smoke control system is through the route of fire engineered solution. The typical decision making process is given in Figure 2.1.

Fire engineered smoke control systems are solutions whose performance are evaluated against a set of acceptance criteria [21]. One means of controlling the movement of smoke in protected spaces is the use of mechanical fans to extract hot smoke from the protected space. Although the method is not novel, the methodology is not prescriptive code compliant and as such is classified as a fire engineered solution. The use of field modelling fire analytical tools to assess such approach is presented is this chapter.

<u>Covered car parks</u>

In single storey covered car parks, the choice of smoke control systems is determined by the availability of the permanently opened free area [26]. For covered car parks with a free area of at least 2.5% of the car park floor area, of which 1.25% of the floor area is on opposite walls, the system can be designed to be vented naturally. The car parks are naturally vented using the principle of wind assisted cross-flow ventilation [26].

Covered car parks whose permanent free area opening is less than 2.5% of the car park floor area can only be mechanically ventilated [26]. Such systems can either be assisted by a network of ductwork serving the whole car park or by impulse fans strategically positioned within the car park so as to direct the bulk air flow in the car park towards the extract point.

Mechanical systems, assisted by impulse fans require further assessment [26]. This is to determine the location of the impulse fans with respect to the car park for the most effective performance. Field modelling approach, with its ability to asses the flow physics is therefore the ideal analytical tool for such an assessment.

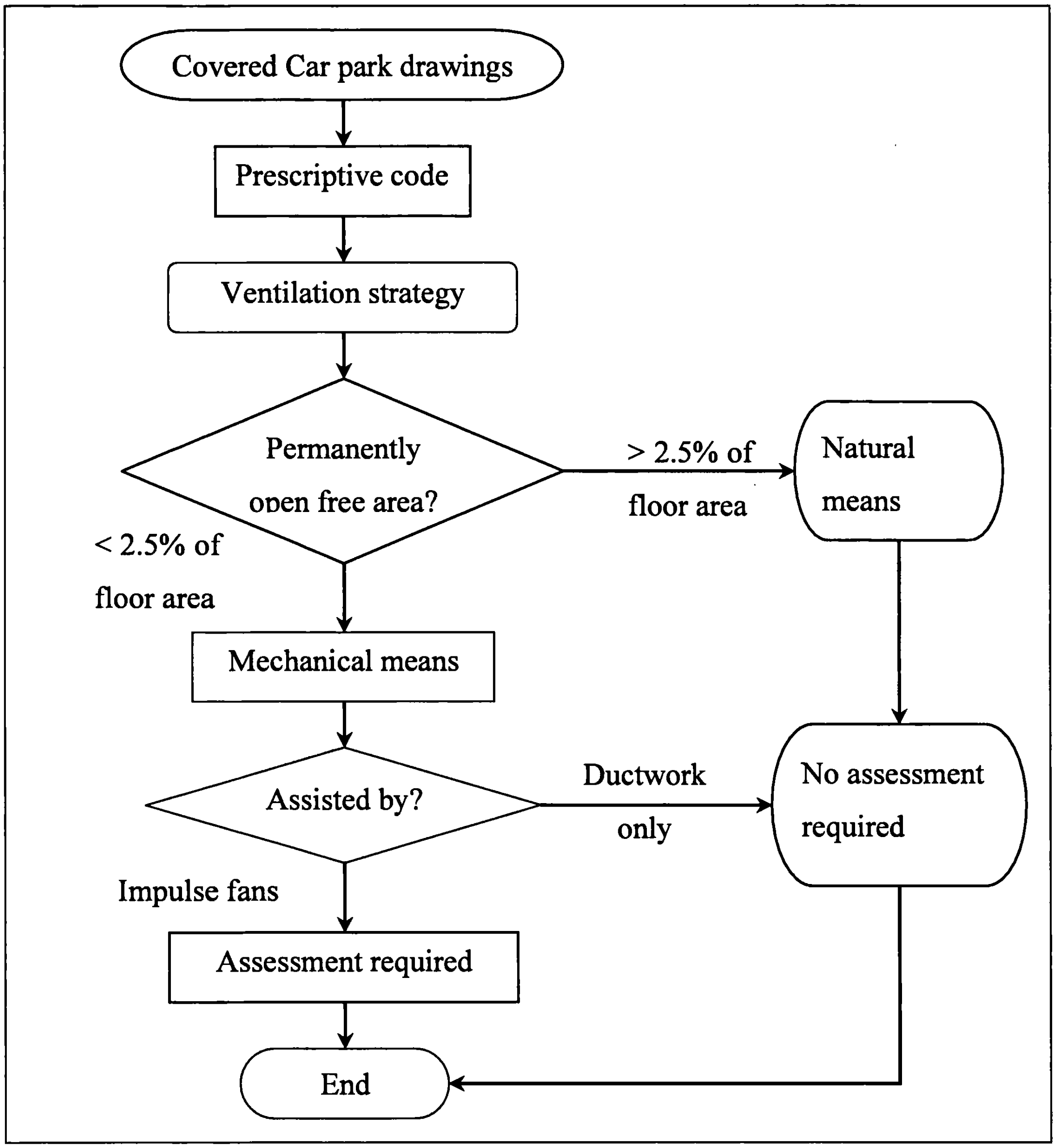



Figure 5.1 – Covered car park decision making process

The performance of the systems and the location of the impulse fans are assessed on the following criteria [26]:

- During both day to day ventilation and smoke clearance – there are no dead spots within the car park.
- Smoke control – maintain a visibility of 10m from the seat of the fire.

Mechanical systems assisted by ductworks and systems vented naturally do not require additional justification. Figure 5.1 shows the typical decision making process for the design of ventilation systems for covered car parks.

### 5.1.2 Application design procedure

The generic design process presented in Chapter 2 forms the basis of the design procedure and has been specifically tailored for the design of fire engineered smoke control systems by means of field modelling fire analytical tool. Figure 5.2 shows the tailored design flow chart.

Using the same terms as those presented in the generic process, the three main stages of the tailored design process are

- Qualitative Design Review;
- Quantitative analysis; and
- Assessment criteria.

#### 5.1.2.1. Qualitative Design Review (QDR)

The main purpose of this stage is to set out the scope of the fire scenario to be analysed. The outcome of this review is also presented to initiate discussions among stakeholders so that an agreement can be reached in order to define the direction for the subsequent modelling. This review includes:

- Design objectives;
- Assessment methodologies;
- Proposed fire engineered solution; and
- Definition of fire scenarios.

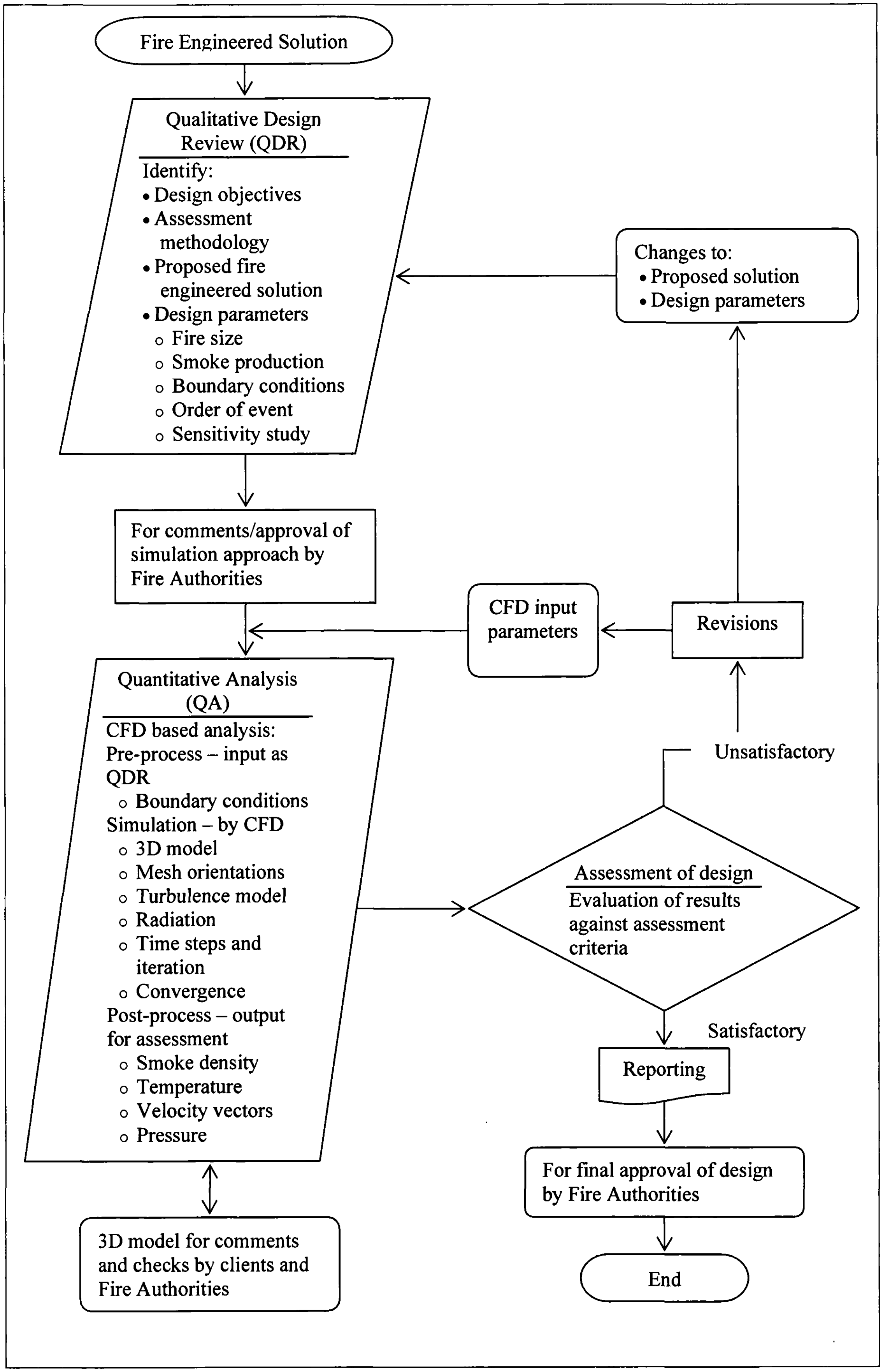



Figure 5.2 – Fire engineered solution flow chart.

Design objective

This sets out the aim of the analysis. The general aim when designing fire engineered solution is to assess the performance of the proposed solution and proof that the performance meets the defined assessment criteria. The proposed solution is acceptable for installation once final approval is obtained from the relevant fire authorities.

Assessment methodologies

The methodologies that may be used to quantify the performance of the fire engineered solution are identified. Assessment methodologies applicable to field modelling are comparative and deterministic methods. Their respective merits have been presented in Chapter 2.3. Probabilistic methodology is beyond the capability of field modelling and will not be discussed. The criteria which define these assessment methodologies are discussed under Assessment Criteria.

Proposed fire engineered solution

This identifies the proposed ventilation strategy based on the building floor plans. The proposed air flow path is identified as with all equipment associated with the ventilation strategy and failsafe provisions. Failsafe provisions in smoke ventilation are measures that minimise and, when possible, contain the spread of smoke within the intended space of protection (i.e. common corridor) under any circumstances that the system may fail to operate. Contamination by smoke in adjacent spaces (e.g. stairwell that serves the common corridor) is therefore minimised which will enable occupants and fire fighters alike to respectively escape and access the fire floor in a relatively safe environment.

Definition of fire scenarios

Field modelling predictions are only as good as the scenario they are defined by. The predictions would be meaningless if the scenario is not representative of the conditions of a burning fire and its surroundings (i.e. the relevant floor plans of the building under consideration). This entails the uniqueness of the prediction that is problem specific.

In the assessment of smoke control systems, the fire scenario is often defined to be the worst case and be representative to actual fire scenarios. This enables the system to be designed to cope with what may potentially be the extreme condition at which the system operates in.

Commonly, there are five characteristics that define a fire scenario. They are:

- Design fire and location of fire – Fire can be specified by one of two means: A steady fire which has a constant heat release rate and is independent of time; A growing fire which peaks at a predefined heat release rate. The rate of fire growth is time dependent. One means of specifying growing fire is the $t^2$ correlation as discussed in Chapter 3.4. The size of the design fire is dependent on the possible type of material that is burning and is linked to the type of occupation (use) of the building as presented in Table 3.1.

  The proposed location of the fire to be investigated should also be specified and agreed upon so as to ensure that the proposed location represents the worst case.

- Smoke production – Define the rate of smoke production and is assumed to be proportional to the heat release rate by a yield factor. The yield factor is identified for the material that is assumed to be burning. Detailed yield factors for a selection of material can be found in the SFPE Handbook [72].

- Boundary conditions – Boundary conditions shape the computational model to be representative of the actual geometry of the problem of interest. The main boundaries are Wall, Inlet, Outlet and Porosity. Wall boundary defines the impermeable barriers that enclose the computational domain of interest and is prescribed to represents walls, floors and ceilings of the enclosure. The flow at the faces of these boundaries is zero. Heat transfer to the boundary can be specified under the discretion of the user.

  The inlet boundary is the momentum force used to characterise forced airflow. This boundary is often prescribed to represent the duty of mechanical fans when analysing problems of forced ventilation. Outlet boundary is prescribed at the edge of the computational domain where flows, which are of no interest, are removed from the computational domain.

Porosity boundary is used to as though a permeable wall that allows for flows to pass through. This boundary can also be used to represent an opening, which has parts of its face area being blocked off, without the need to include the detail of the obstacles. Grilled louvers along with leakages around door, windows and wall are examples of such a setup.

- Order of events – This indentifies the potential events that may take place during a fire hazard. Events can be classified as either means of escape or fire fighting phase where the former is the period where occupants make their escape while the later is the event that takes place after fire fighters arrived at the fire scene. The potential events as defined by fire engineering criteria [90] for a flat on fire are:

  Initially where occupants make their escape (i.e. means of escape period)

  - Fire ignites in flat. Fire at design growth rate when applicable.
  - Fire is detected locally.
  - Flat occupant escapes. Door closer on the flat door assumed to operate.
  - Smoke egress into common lobby/corridor in the period that the flat door is open.
  - Smoke in common lobby/corridor detected.
  - Ventilator on the fire floor opens.
  - Head of stair vent opens.
  - Time delay to allow for the vents to open/operate. System in full operation.
  - Fans start up (for mechanically assisted systems only).

  Unless intentionally propped open, the door to a flat can be assumed to close as it is made self-closing. Similarly, the door that serves the stair is also made self-closing. This is to preserve the compartmentation of each space which is the most effective means of restricting smoke spread (refer to Chapter 3.3). The fact that flat doors stay closed in their normal day to day use of safeguarding occupants' belongings and their privacy further supports this assumption.

The ventilation system is required to protect the lobby/corridor until the arrival of fire fighters. After which, the system can be used to protect the stair whilst removing smoke from the lobby/corridor during fire fighting process and once fire is extinguished.

Fire fighting period

- Fire service arrives on scene. Fire assumed to be fully developed (at design fire).
- Floor on fire located. Identified by indicator panel located at the main entrance of the building.
- Investigate.
- Flat door open. Heavy smoke expected into the common lobby/corridor.
- Ventilation system switched to fire fighting mode if applicable. Fans to fire fighting mode (applicable to mechanical assisted systems only).
- Flat door shut. Light smoke is expected in the common lobby/corridor.

There is a possibility that the stair door on the fire floor may be open during this period. This is determined by the fire fighting strategy adopted where fire fighters may decide to tackle the fire from below the fire floor where a hose is laid from the outlet below the fire floor, up the stair and through the stair door. Otherwise, fire fighter may choose to lay the hose from the outlet on the fire floor whereby the stair door may be closed.

From these events, there are two analyses to consider:

- Transient analysis – Takes into account the order that the events take place in time and more importantly the duration of a specific event i.e. the duration of the door to the flat on fire opens and similarly to that of the stair door. The former dictates the amount of smoke enters the common lobby/corridor while the later enables smoke to spread throughout the building. The history of the development can be individually analysed in further detail. This approach is therefore useful to study the conditions within the common lobby/corridor as doors open and close for occupants escape and arrival of the fire service. More importantly, this approach considers the early stages of fire development (i.e. pre-flashover) through to a full developed fire.

  - Steady state – Time independent analysis does not consider the history of the events. This approach can be used to study the conditions within the common lobby/corridor during fire fighting phase as the fire would normally be assumed to have fully developed and at peak release rate.

- Sensitivity study – Identify the sensitivity study that will make the design more robust. One sensitivity study is to relocate the fire which will allow for the design of a system that is effective for any fire location.

#### 5.1.2.2. Quantitative analysis

This stage evaluates the proposed solution identified in the QDR through the use of engineering methods which in this case is field modelling. It is in this stage that the relevant CFD sub-models and numerical iterations are specified. In addition, the validity of the numerical solution by means of convergence and mesh independence is achieved. The specifications include:

- Computational model;
- Combustion model/volumetric heat release ;
- Turbulence model;
- Time step and iteration – for transient analysis;
- Mesh independence study; and
- Convergence.

<u>Computational model</u>

The computational model must always be 3-dimensional [8] and should be a close representation to the geometry of interest. Boundary conditions identified in the QDR are also prescribed to the computational model.

Combustion model/volumetric heat release

The heat source is handled with either the simple volumetric heat release or the more complex combustion model. The rate of heat release should conform to the design fire as determined in the QDR.

Turbulence model

Turbulence models must be used in the analysis to account for the turbulent convective flow of the fire. Note that the two equations k-e models, when used to account for turbulence in convective flow, must be modified to include for buoyancy effects [8].

Time step and iteration

Applicable only to transient analysis, the appropriate time step size and number of iterations are chosen for the analysis. The time step size is a measure of how much simulation time has passed each time a converged snapshot is calculated. SMARTFIRE [57] has recommended suitable time step sizes for use in fire modelling. They are:

| Time step size (s) | Usage |
|---|---|
| Greater than 5.0 | For very stable cases |
| 1.0 – 5.0 | Stable cases with moderate fire loads |
| 0.1 – 1.0 | High fire loads and / or complex geometries |
| 0.01 – 0.1 | Very high output fires, multiple fires, complex geometry |
| Less than 0.01 | Only needed for extreme flow conditions - e.g. breaking window |

Table 5.1 – Suggested time step size [57].

As suggested in the table above, cases with high fire load and other complexities may require a small time step so as to ensure a stable solution. This however comes at a cost of longer overall computational time in which smaller time step sizes would require more time steps to perform the same amount of total simulation time. Larger time step sizes are recommended to be used in cases with moderate fire load and relatively simple geometry.

Mesh independence study

Mesh independence is a measure that ensures errors in the solution process are not affected by the choice of grid used. This is done by repeating the calculations on a series of refined grids. The solution is said to be mesh independence if the variable is consistent for all grids used.

Convergence

Convergence can be measured by the residual errors of the variables between iterations. The solution, at a particular time step, is said to converge if the residual errors of the variables are at an average magnitude of $1.0 \times 10^{-3}$ or less [57]. The level of convergence that can be achieved depends on the current time step size, the stability of the simulation, the mesh quality and the current solution state [57].

Generic issues

These specifications can then be categorised into three sub-processes namely: Pre-process, Simulation and Post-process. Pre-process is where the computational model is setup based on the proposed building layout and the fire scenario agreed in the QDR. The preferred analytical tool is determined, in this case field modelling, as well as the choice of combustion and turbulence models.

Simulation is the process in which numerical modelling takes place. As part of this process, the appropriate number of iteration and time step size (for transient analysis) are chosen while the validity of the modelling results is also determined. The validity is based upon the Mesh independence study and Convergence criteria.

Post-process is the process where variables outputs i.e. pressure, velocity, temperature and smoke mass fraction are assessed against the acceptance criteria agreed in the QDR.

#### 5.1.2.3. Assessment of design

Outputs from the quantitative analysis are evaluated against a set of acceptance criteria based on the adopted assessment methodology. Comparative approach requires that the proposed fire engineered solution demonstrates a level of safety equal to or better than a solution that complies with recognised prescriptive codes. For this approach to be valid, it is recommended that the building layout (using residential flats as an example) for which the fire engineered solution is designed, must comply with building codes as the code compliant solution, for which comparison is made against, is strictly valid for buildings whose layout is compliant to building codes. The code complaint building layout here represents the point of reference for which comparison is based upon.

For buildings (residential flats) that do not comply with building codes, a fire engineered solution can only be assessed by means of deterministic approach as there are no similar points of reference for the use of comparative methods. One acceptance criteria that can be associated with a deterministic approach are the tenable limits. With this criterion, the fire engineered solution is required to return the protected space (lobby/corridor), which has been contaminated by smoke as occupants made their escape, to within tenable limits during means of escape period i.e. the period after occupants have escaped into the stair.

The tenable limits applicable are the temperature of the hot smoke and visibility within the protected space. The former are temperatures that can be tolerated by unprotected human skin as occupants escaping a flat on fire are typically wearing light clothing. The later ensure a prompt evacuation process as occupants need no further encouragement to escape if they are able to see the escape route [15].

Toxicity levels of the hot smoke is not discussed as the time of exposure to smoke for occupants escaping a flat on fire is limited as they are able to escape promptly in an environment that they are familiar with. For large complex buildings where prompt evacuation is not practical (e.g. shopping centres, airports and underground train stations), the time of exposure to toxic smoke needs to be considered as most occupants may not be familiar with environment and therefore require a prolonged period in order to escape to safety.

This method can also be used to assist in specifying the equipment to be used e.g. choice of extract fans with appropriate fire resistance can be determined by the temperature that the fans are exposed to.

#### 5.1.2.4. Fire authorities' comments

In the design process, ongoing dialogue with the approving fire authorities are important to ensure that the proposed design is inline with the approving fire authorities' requirements and that the design may potentially be an acceptable solution.

Approval of the design proposal and simulation approach is initially sought to ensure the fire scenario and all assumptions are relevant to the problem and as a reference document to all stakeholders prior to the start of the modelling process. In addition, approval should also be sought from the architect to ensure the validity of the 3D model and that the corresponding boundaries are as closely represented to the architectural drawings referenced.

## 5.2 Implementation of the design procedure

This section presents the implementation of the design procedure as discussed previously. The implementation process is described through the assessment of the fire engineered mechanical assisted extract system for a typical five-storey residential building. The analytical tool for this assessment is the SMARTFIRE v4.1 [57] field modelling software package.

This process is presented under two stages namely the Pre-processing and Post-processing stage. In the Pre-processing stage, a potential fire scenario based on the criteria identified in the QDR, is defined so that the performance of the fire engineered mechanical assisted extract system can be assessed. The setup of the fire engineered system and its ventilation strategy i.e. the airflow path are also discussed.

Post-processing stage discusses the performance of the fire engineered mechanical assisted extract system against both comparative and deterministic methods.

It is in this section that the questions previously identified at the start of Chapter 5 are answered. The questions are:

- Computational model, what needs to be considered and why?
- What are the design assumptions and their justification?
- Have the design objectives been met?

### 5.2.1 Pre-processing

This section looks to identify the characteristics that may define a potential fire scenario that reflects upon the type and use of the building. The computational model and the ventilation strategy of the fire engineered system are also presented.

#### 5.2.1.1. Ventilation strategy

An adaptation to depressurization system, the extraction system by mechanical means is a fire engineered system in which smoke on the fire floor is mechanically extracted through a smoke shaft located in the protected space. A general schematic of the setup and the direction of bulk air movement are shown in Figure 5.3.

Extraction systems are not designed as pressure differential systems to EN 12101-6 [18] nor are they intended as a direct replacement for pressure differential systems. Pressure differential systems (or pressurization systems), with decades of research into the subject, have reached a level of maturity that offers a highly effective yet low risk smoke ventilation strategy compared to naturally ventilated and extraction by mechanical means systems [21].

It is noted that extraction systems at this arrangement is in the early stages of development and will require further research. Therefore, there is currently no legislative literature or guidance document published in order to guide and support the design of such system. Hence, there is a need for fire analytical tools to assess such systems. The cost of these systems is relatively higher than natural ventilation systems due to the additional equipment needed and their constant maintenance.

Mechanical smoke venting can be designed to serve two possible purposes [66]:

- Return the smoke contaminated protected space to tenable conditions; and
- Offer protection to adjacent spaces e.g. the adjacent stairwell that serves the protected lobby/corridor in question by exploiting the pressure difference between the two spaces that is similar to a pressure differential scheme.

With all mechanical smoke venting schemes, it is essential to consider the provisions for make up fresh air [91]. Care is required to ensure adequate make up air is provided so that hazards due to doors being held tightly by the pressure difference are avoided [92]. This is to ensure that occupants, young and old, are capable of opening the stair door and escape into the stair.

Make up air and therefore the pressure within the protected space can be modulated by means of [93]:

- Dedicated low level inlet
- Dedicated inlet shaft
- Doors to be open
- Grilles in doors
- Variable speed fans

The first two approaches are to introduce a dedicated natural inlet. The former is suitable when the protected space has an exterior wall in which to position the inlet vent, whereas, the later is suitable when the protected space is an internal part of the building.

Open doors and grills in the doors are options which allows make up air to be drawn typically from the stairs. The stairwell itself, as prescribed in the guidance document [19], is required to be ventilated – normally by natural means via a vent positioned either at each floor level or a single vent at the head of stair. This therefore makes the approach viable.

The variable speed fan is an approach in which the fan speed is varied, by means of a pressure sensor, in order to maintain a pre-defined pressure difference. As a door is opened (i.e. the door between stair and protected lobby/corridor), the fan extracts at the design duty. When the door is in the closed position, the extract rate is reduced to 15% of the design duty to maintain the pre-defined pressure difference.

In this discussion, the mechanical extract system comprises of the following:

- A fire rated builders' work shaft rising the length of the building and closed at the bottom;
- Fire rated lobby ventilator opening into the smoke shaft on each floor;
- Fire rated extract fans positioned at the head of the smoke shaft; and
- A vent in the stair.

All equipment associated with this type of system is required to be made of fire resistance material as they are in constant contact with high temperature smoke while in operation.

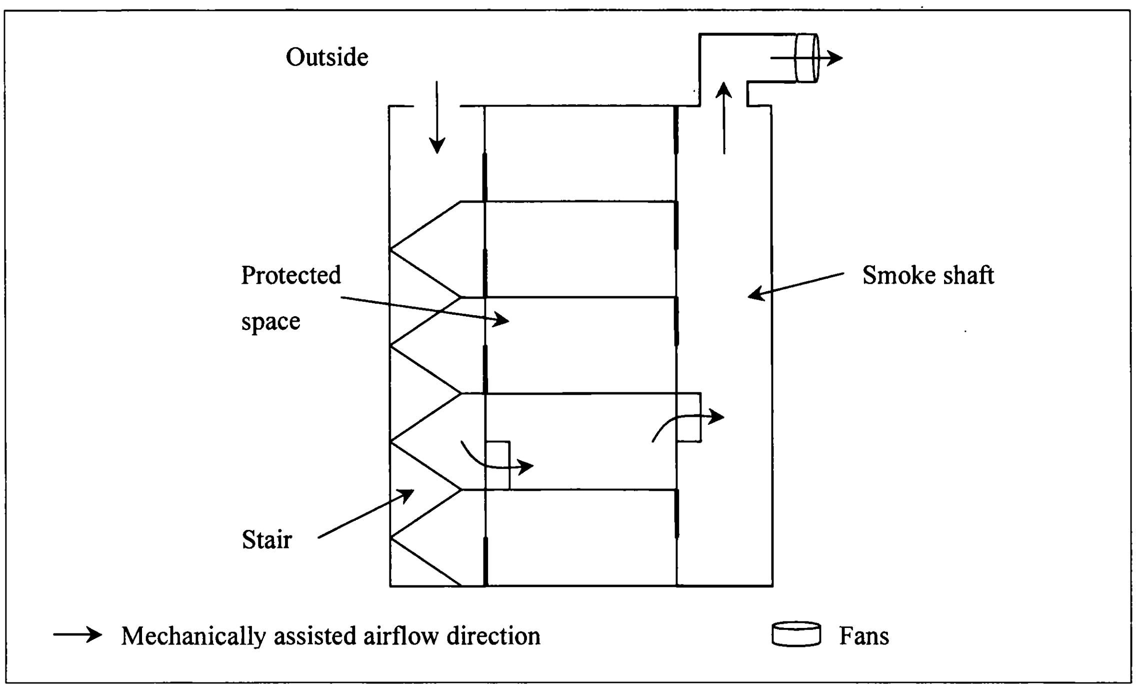



Figure 5.3 – Mechanical extract systems setup

Further to Figure 5.3, smoke that flows into the protected common lobby/corridor is extracted by fire rated fans via a lobby/corridor vent opening into a smoke shaft serving the length of the building. Make up replacement air is provided by the vent position at head of stair via the open stair door.

Leakages due to the gaps around the door and cracks around window need to be taken into consideration when designing such systems as these are pressure relief paths that may affect the pressure within the ventilated space i.e. protected common lobby/corridor. In addition, these leakages allow smoke, encouraged by the non-linear pressure differential distribution by the burning fire in the compartment, to flow between the two spaces [94].

Note that a highly negative pressure difference between the protected common lobby/corridor and the fire compartment will actively draw smoke into the protected common lobby/corridor thus further contaminating the space – a condition which is not ideal for escaping occupants of other flats when requested to do so. This supports the fact that the guidance pressure difference of 85Pa [92] is not applicable to this system.

The builder's work smoke shaft should be closed at the bottom and well sealed to avoid excessive air to be drawn via leakages in the shaft and from places other than the fire floor. A leaky smoke shaft would reduce the effectiveness of the extraction system.

On detection of smoke in the common corridor, by means of a smoke detector, the lobby ventilator opening into the smoke shaft at that level and the vent at the head of stair will open automatically – including the extract fans. All vents on other levels will remain closed.

#### 5.2.1.2. Geometry and computational model

Geometry

The design process is described through the use of a typical five-storey building that has an internal common corridor. Such building layout is popular with designers as most of the accommodation spaces are readily open to natural light making the accommodations more attractive to potential occupants.

The building is 14m in height where the fire compartment and corridor is 2.4m high while the finished floor to finished floor height is 2.8m. The floor layout is shown in Figure 5.4. Each floor of the building is assumed to consist of three flats, of which only two flats i.e. Flat 1 and Flat 2 are chosen as the flat on fire – one as the main analysis (Flat 1) while the other as a sensitivity study (Flat 2) of the system performance.

The internal corridor that serves the flats has a maximum travel distance of 7.5m and is code compliant. The internal corridor is 9.1m long and 1.5m wide which corresponds to a floor area of $14m^2$. It is to be ventilated by means of mechanical extraction via a builder's work shaft that is closed at the bottom. The smoke shaft has a free area of $0.6m^2$ (1.0m wide and 0.6m deep).

The ventilator that opens into the smoke shaft is $0.6m^2$ (0.6m wide and 1.0m high) and positioned at high level i.e. 1.3m above finished floor level.

Fire rated doors that serve the fire flat and the common lobby/corridor as well as between common lobby/corridor and stairs are of 2.0m high and 0.8m wide. Of the height, a 0.1m high gap is prescribed to at the foot of each door to represent leakages.

Similarly, a 0.1m high and 0.8m wide gap is prescribed at the foot of the lift to represent leakages due to the lift door. The lift shaft in this case is adjacent to the stair.

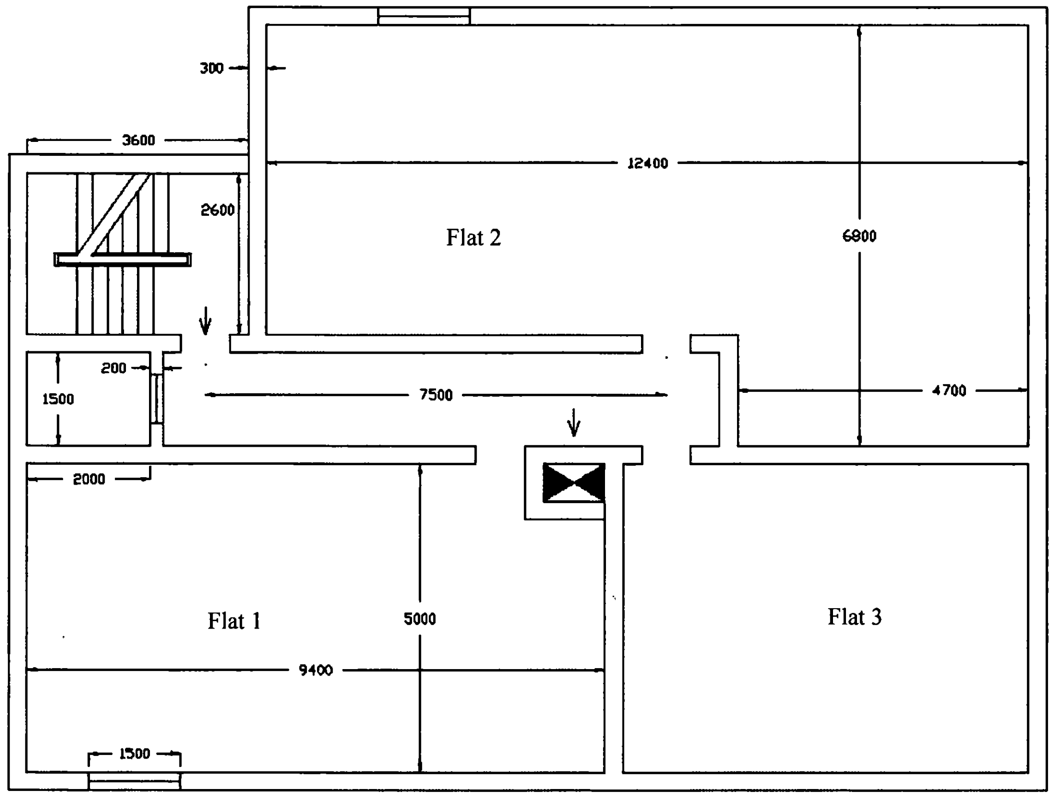



Figure 5.4 – Internal lobby floor plan.

A $1.0m^2$ opening is provided at the head of stair as of the guidance documents [19]. This opening will act as an inlet that allows for external fresh air to be drawn, via the stair door, as make-up air for the system while in operation.

A 'window' of $1.5m^2$ (1.5m wide x 1.0m high) is included in the flats to represent a typical window and is expected to break during a fire. The window is positioned at 1.0m above finished floor level.

At the foot of this window, a gap of 1.5m wide and 0.1m high is included to account for leakages around the window and walls. Its inclusion is to allow for external air to be drawn into the fire flat so as to sustain the burning fire and to regulate the pressure within the flat on fire prior to the window being broken by the excessive heat.

Computational model

Implementing the advice in Chapter 4.3.2, a few key things of note with regards to the setting up of the computational model in Figure 5.4 is addressed. They are:

- Domain boundaries;
- Boundaries adjacent to openings and vent; and
- Geometric simplification.

Domain boundaries should be located such that they do not adversely affect the simulated smoke movement. In this case, the inlet boundary which depicts the extract duties due to fans is positioned at the head of the builder's work smoke shaft. This ensures that air (or smoke) is drawn from the common corridor and into the smoke shaft and allows for flow downstream of the shaft to fully develop.

In addition, instead of specifying a mass flow rate of smoke as a boundary on the face of the corridor, it would be best practice to include the flat in which fire would be burning. This removes the need to approximate the prescribed mass flow rate of smoke while allowing the fire to determine the mass flow rate of smoke that flows into the corridor via the opened flat door, an opening of which may be specified.

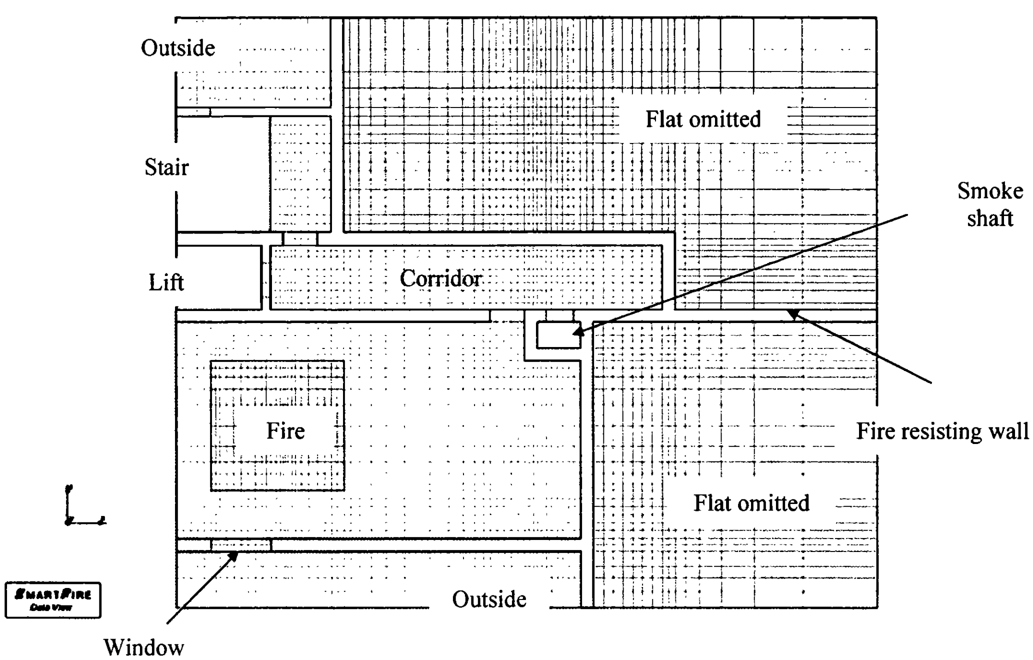



Figure 5.5 – Plan view of computational model.

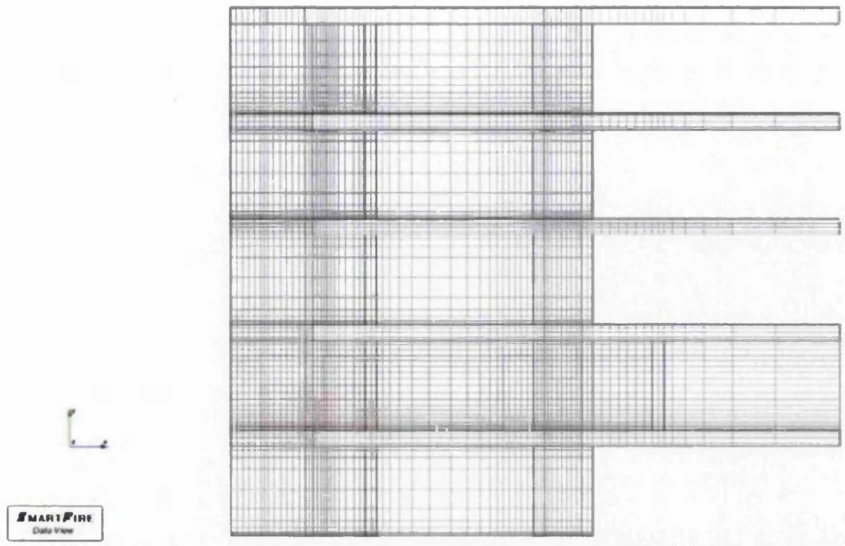


Figure 5.6 – Side view of the computational model.

When modelling open vents such as windows, head of stair vent, head of smoke shaft, it is recommended that the computational domain of these area be extended further to allow for the flow to fully developed before being removed from the computational domain. This is to minimise errors in the flow to propagate downstream.

Geometric simplification is commonly adopted due partly to the computational limit and processing time and partly due to the consideration of the region of interest only. In this model, Flat 2 and Flat 3 are of no interest and are omitted from the computational model – Figure 5.5, so are the floors above and below the fire floor, Figure 5.6. In addition, the detailing of the stair i.e. the flights of stair steps is again omitted so that smoke that enters the stair can rise freely and quickly posing the worst case scenario [87].

Another geometric simplification is the partitions of the flats. Similar to the modelling of the stair, partitions are omitted from the model so as to enable smoke to spread freely and quickly resulting in the worst case smoke filled room. Such simplification is logical as the partition doors are often in the open positioned for convenience to the occupants especially the door to the living room.

All in all, computational models are viewed as a close approximation to the actual geometry of the building. Boundary conditions are used to shape the computational models so as to have the characteristics of the geometry of interest while at the same time be positioned so as to not profoundly affect the flow within the domain of interest. This therefore answered the question "Computational model, what needs to be considered and why?"

The mesh of the computational model chosen is unstructured rectilinear and is scaled to accommodate the 0.1m gap at the stair door. Likewise, the mesh in the regions not of interest has been scaled up – shown in Figure 5.5 in regions of the flats that have been omitted from the computational model. The cell budget for this model is 420918.

#### 5.2.1.3. Fire scenario definition

From the question: What are the design assumptions and their justification? Design assumptions define the fire scenario at which the ventilation system is assessed against. The propose fire scenario is discussed below.

<u>Design fire</u>

The fire source is represented as a volumetric heat source with a volume of 3.0m (wide) x 3.0m (length) x 1.2m (high) and is assumed to represent the flaming region which theoretically be engulfed by the flame at peak output of 2.5MW. The design fire size is based on the value adopted in the BRE reports [24, 66].

The growth of the fire is assumed to be medium growing $t^2$ fire curve as recommended by the guidance document [29] for residential flats. This corresponds to a peak fire size of 2.5MW at 462 seconds and is shown in Figure 5.7.

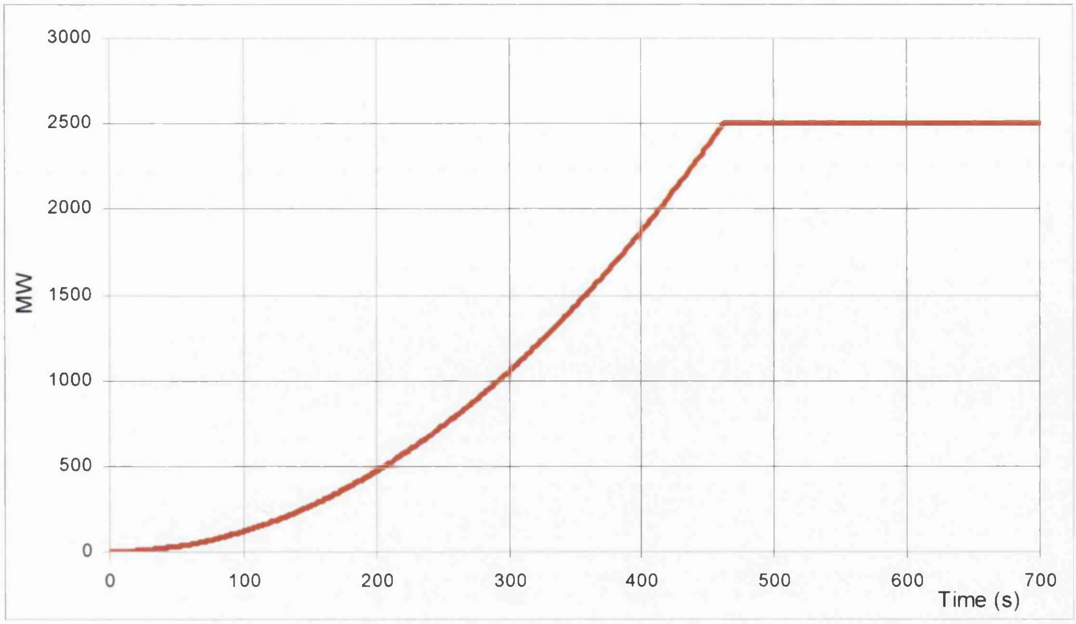



Figure 5.7 – Design fire curve

The primary analysis assumes that Flat 1 is on fire. The flat, shown in Figure 5.4 has a floor area of 47m$^2$. The secondary analysis i.e. the sensitivity study on the fire location, assumes that Flat 2, with a floor area of 70.46m$^2$, to be the flat on fire. The first floor of the five-storey building is assumed to be on fire.

Smoke production

As with most fire in a residential flat, it is reasonable to assume that upholstered furniture, generally made up of polyurethane foam, is on fire. The polyurethane foam correlation, with corresponding Heat of Combustion of 25MJ/kg and soot yield of 0.11 kg/kg (11%), is assumed for the production of hot gases [72] – shown in Figure 5.8. The smoke density, smoke absorption constant and smoke specific extinction coefficient is taken as 1800kg/m$^3$, 1200, and 7600 m$^2$/kg respectively.

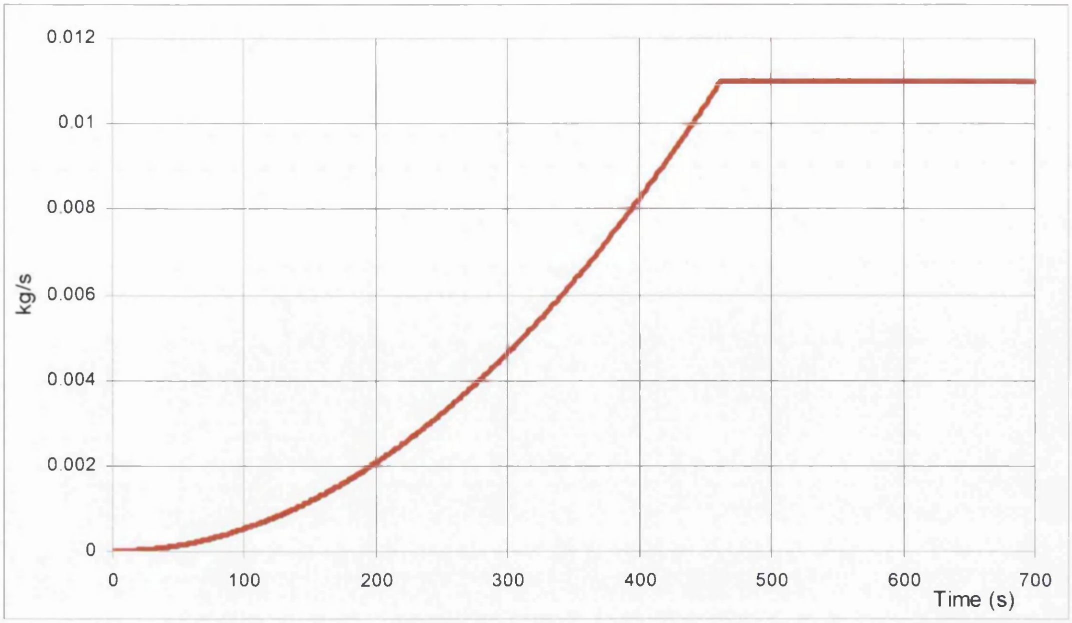



Figure 5.8 – Smoke production curve.

Mechanical fans duties

Mechanical extraction fans can be designed for two approaches, namely:

- Constant duty for duration of scenario; and
- 2 stepped duties for means of escape and fire fighting respectively.

The first approach is a straightforward in which the design duty stays constant for the entire duration of the fire scenario. The second approach specifies a low duty for means of escape phase due to the fact that fire is small and growing which in turn meant that the mass flow of smoke due to the growing fire is small. During fire fighting phase, the duty may be increased, on the discretion of fire fighters, to cope with the design fire and subsequent peak mass flow rate of smoke.

The second approach is adopted for this discussion. The design duties, shown in Figure 5.9 are:

- Means of escape: $2.0m^3/s$
- Fire fighting: $4.0m^3/s$

Inlet replacement air is assumed to be provided by the stair. During means of escape phase, air is provided via the stair door that is partially closed after occupants have escaped into the stair. In fire fighting phase, replacement air is provided by the fully opened stair door, mimicking the possibility that the stair door may be held open by water hose as fire fighters engage the fire.

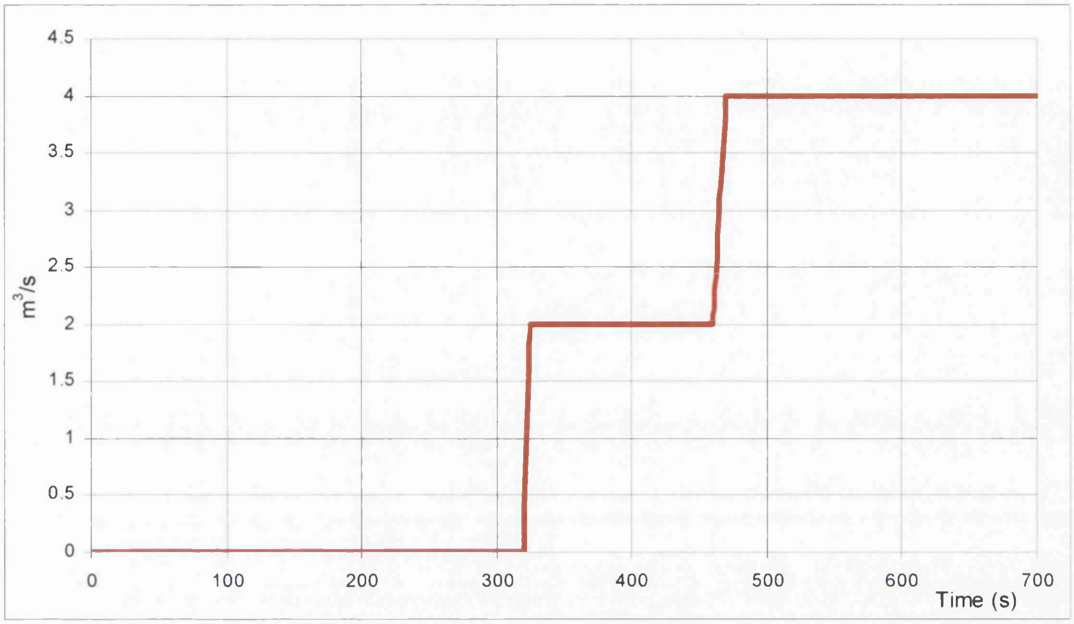



Figure 5.9 – Fan duty curve.

Boundary condition

Adiabatic and non slip condition is assumed for the walls surrounding the corridor and fire compartment.

Atmospheric pressure condition is assumed at the head of stair vent, head of lift and any area outside of the building.

Porosity boundary condition is prescribed to gaps predominately present at the foot of a door [94]. The porosity boundaries are prescribed as 0.8m wide and 0.1m high with an effective leakage area of $0.01m^2$ (the porosity factor is 0.125). These porosity boundaries allow for air to either enter or escape the corridor without modelling the details within the gaps. The effective leakage areas were taken as per BS 12101-6:2005 [18].

Porosity boundary prescribed at the foot of the window is 1.5m wide and 0.1m high with an effective leakage area of $0.01m^2$ (the porosity factor is 0.0667). This is to account for all leakages around the window and walls of the fire compartment.

Porosity boundary is again used to represent the effective leakage area due to the lift door. The porosity boundary for the lift door, position at the foot of the door, is 0.8m wide and 0.1m high with an effective leakage area of $0.06m^2$ (porosity factor is 0.75) [18].

Outlet boundary condition is prescribed to regions representing the outside of the building envelop and any extended regions that would otherwise be automatically created by SMARTFIRE to allow for the flow across an opening to develop fully. These regions include the regions above head of stair vent, above head of lift and above head of smoke shaft.

The modelling domain around the window is extended to 0.50m to allow for sufficient room for the flow around the broken window to fully develop.

Wind effects are not considered.

Turbulence

SMARTFIRE v4.1 [57] uses the buoyancy modified k-epsilon turbulence model as recommended by Gobeau et al [87]. The initial values of the kinetic energy, k, and dissipation rate, epsilon are determined automatically by the software.

Radiation

The more sophisticated Six-flux model within the SMARTFIRE v4.1 [57] is chosen to model radiation. The reason behind this choice is due to the analysis of a large fire in the confined space of a flat. In addition, this would better predict the far field smoke temperature i.e. smoke temperature in the protected corridor.

Wall emissivity, absorption at 700K, and absorption at 1400K is taken as 0.8, 3.5 $m^{-1}$ and 7.0 $m^{-1}$ respectively.

Order of events

In line with the cause and effect of the fire event as discussed in Section 5.1.2, the simplified events below are adopted:

*During means of escape phase*

At time, t = 0 seconds, fire starts.

At t = 293 seconds, flat door opened for occupants escape. Hot smoke flows into the common lobby/corridor, smoke detector in common corridor triggered. Glazed window broken.

At t = 323 seconds, flat door closed. Stair door opens for occupants escape. Smoke shaft ventilator on the fire floor and head of stair vent opens. Fans at design speed for means of escape.

At t = 353 seconds, stair door is closed leaving a 100mm gap. This gap enables constant fresh air to be drawn from the stair and in turn regulate the pressure within the common corridor. End of means of escape phase.

*Fire fighting phase*

At t = 463 seconds, flat door and stair door opened for fire fighting process. This corresponds to design fire size of 2.5MW. Fans at fire fighting design duty.

At t = 613 seconds, flat door and stair door closed. End of fire fighting phase.

At t = 700 seconds, simulation ends.

These events can be summarized in Figure 5.10.

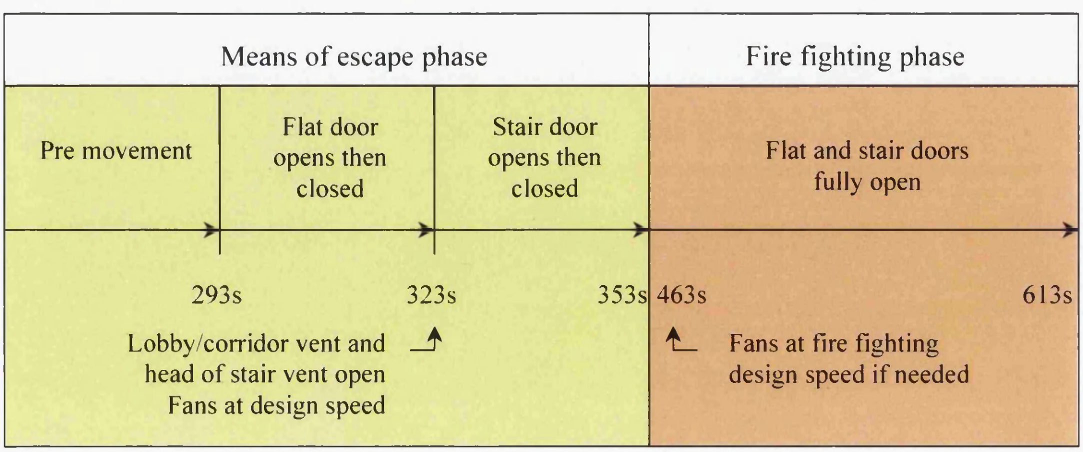



Figure 5.10 – Summary of order of events.

Sensitivity studies

Sensitivity analysis was carried out to study the robustness of the system when in operation. The following discussion presents the sensitivity study as a different flat on fire i.e. Flat 2.

In addition, a numerical study i.e. mesh independent study, is discussed as a means of validating the numerical iterations. This gives confidence that the numerical solution has converged.

Air properties

Initial conditions and air properties are given by:

- Ambient temperature $= 15^0$C
- Viscosity $= 1.5682 \times 10^{-5}$ Pa s
- Density of air $= 1.1774$ kg/m$^3$

Time step size

A 5 seconds time step size is used for all simulation as most of the simulation is stable except at intervals where doors are opened and closed. At these intervals, 'critical change' is enabled to ensure stability when simulating these effects. The number of iterations used is 50.

Generic issues

As recommended in the guidance document [21], it can be reasonably assumed that fire only occur in one flat where one flat is on fire per floor and one floor per building at any one time. In the analysis, only the doors i.e. stair door and fire flat entrance door, of the fire floor are assumed to be opened and closed

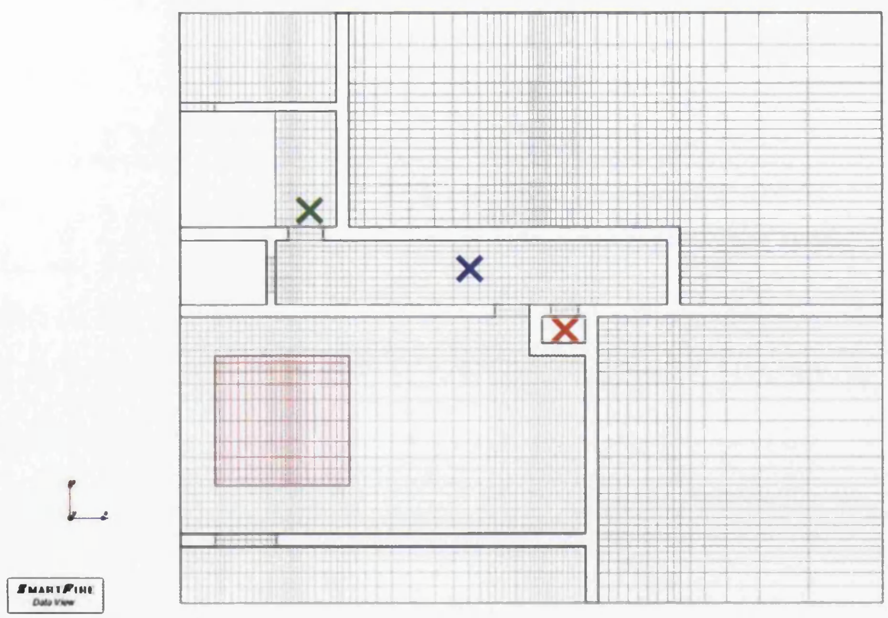
### 5.2.2 Post-processing

This section presents the analytical assessment of the mechanical extraction system performance. The discussion centres on the assessment by means of deterministic and comparative approaches. A sensitivity study on the different fire location is also discussed. Numerical validity is presented through the mesh independence approach.

Basis of this discussion is shown by line graphs through several strategically identified points in the building. The points are grouped into three sets namely: corridor, stair and smoke shaft. Figure below shows the location of the respective points while Table 5.2 summarised the points at their respective heights from the finish floor level.

| Reference (Colour) | Symbols | Dimension | Height from finished floor level |
|---|---|---|---|
| Corridor (Blue) | C1 | x=5.30 y=3.40 z=6.00 | 0.6m |
| | C2 | x=5.30 y=4.00 z=6.00 | 1.2m |
| | C3 | x=5.30 y=4.60 z=6.00 | 1.8m |
| Stair (Green) | L1 | x=2.90 y=4.00 z=7.60 | 1.2m |
| | L2 | x=2.90 y=4.60 z=7.60 | 1.8m |
| Smoke shaft (Red) | S1 | x=8.90 y=5.30 z=4.70 | 2.5m |
| | S2 | x=8.90 y=13.00 z=4.70 | Head of smoke shaft |

Table 5.2 – Location of points of interest



From Figure 5.5 – Showing the location of the points of interest

#### 5.2.2.1. Deterministic approach

Deterministic criteria

Before this approach is discussed, there is a need to identify and define a set of criteria which the performance of the system can be assessed against. The system can therefore be accepted when the criteria set is met. In this discussion two deterministic criteria are used as an acceptance benchmark. They are:

- The smoke contaminated common corridor is required to return to within tenable limits; and
- Stair is kept free of smoke during fire fighting process.

The first criterion requires that the common corridor returns to tenable limits in the period after the occupants have escaped. In other words, the common corridor, contaminated by smoke as occupant escapes (where smoke flows into the common corridor in the duration that the flat door is open), is returned to tenable limits in the period after the flat door is closed. The flat door can be assumed to close as they are fitted with door closer and to maintain the integrity of the compartmentation. The stair door however, is partially closed leaving a 100mm gap for replacement air. The tenable limits applicable to this assessment are:

- Temperature of 120°C for exposure to unprotected human skin.
- Visibility distance of 5m for small enclosed spaces. Visibility calculation is based on light reflecting background.

The second criterion requires that the stair is kept free of smoke during fire fighting phase. This enables the fire fighters to use the stairs as a safe bridgehead to operate in. In addition, a smoke free environment would allow the fire fighter to carry out preparation without the need for breathing apparatus which would be more efficient.

Common corridor

Figure 5.11 to Figure 5.13 show the conditions of the common corridor against time for the duration of the fire event. These figures show the smoke mass fraction, temperature and pressure respectively.

Prior to 160 seconds, the flat (flat on fire) is gradually filled with smoke produced by the medium growing fire. As time passes, the smoke layer in the flat increases in volume and descends to the floor until it reaches the gap prescribed at the foot of the door.

At 160 seconds, it can be seen that smoke starts to leak, through the gap, into the common corridor and brings about a rise in temperature. This continues steadily until 293 seconds after which there is a sudden increased in smoke and temperature as the flat door is opened for occupants to escape. The opened door allows for smoke, driven by pressure differences to flow into the common corridor. Conditions become untenable as the ventilation system is not yet in operation.

Conditions in the common corridor peaked at 323 seconds as the flat door is closed behind escaping occupants by the door closer. Concurrently, the stair door opens for occupants to escape. Meanwhile, the system i.e. head of stair vent, corridor ventilator on the fire floor and extract fans are activated. There is a degree of smoke stratification but due to the short time interval this is insignificant.

Conditions in the common corridor improve significantly after the system is activated and continued to so as the stair door is partially closed at 350 seconds and leaving a 100mm gap which provides a path for inlet replacement air.

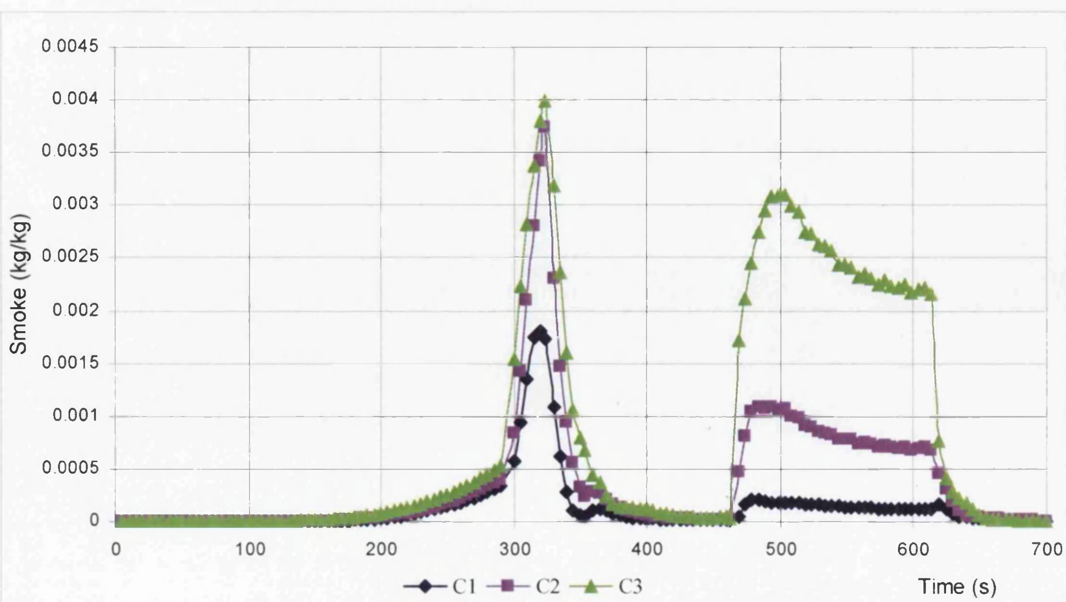


Figure 5.11 – Smoke vs time curve of the common corridor

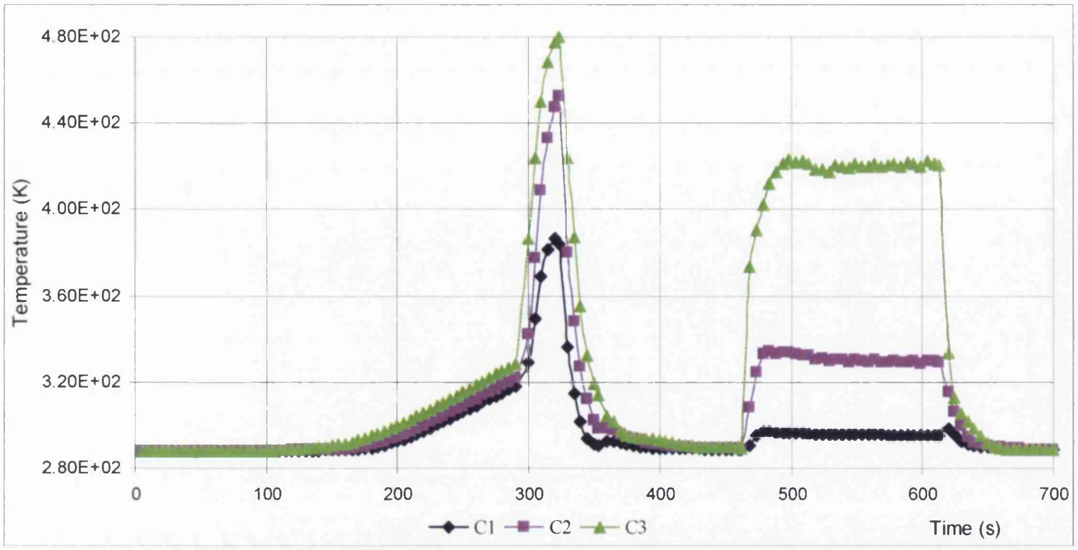



Figure 5.12 – Temperature vs time curve of the common corridor

In the period up to 460 seconds, conditions in the common corridor is said to have return to ambient conditions as the visibility, at smoke mass fraction in the magnitude of $10^{-5}$, exceeds 5m and an average temperature of 18°C. This confirms Condition 1 has been met.

The pressure within the common corridor at this period has increased from -8Pa to -30Pa. Under the influence of the negative pressure, small amount of smoke is leaking through the gap at the foot of the door (the smoke plot is close to zero) and vented with negligible effect to the conditions of the common corridor. This represents the end of means of escape phase.

At 460 seconds, the stair door and flat door is opened to signal the start of the fire fighting phase. Extract fans are operating at fire fighting duty. As the door to the fire flat opens, smoke spills into the common corridor and quickly reached a steady condition where the variables remains constant against time. The visibility at head level (C3) is approaching zero while at low level (C1) is approximately 3m. The corresponding average temperature at these levels is 150°C and 30°C respectively. This meant that the smoke plume has stratified. The pressure at this period is -9Pa.

These conditions, although exceeding the tenable limits, is acceptable as fire fighters are able to work in these conditions as they are equipped with protective clothing and breathing apparatus. Furthermore, fire fighters are more likely to crawl on the floor as they enter a smoke filled room and conditions at low level (C3) would enable them to do so.

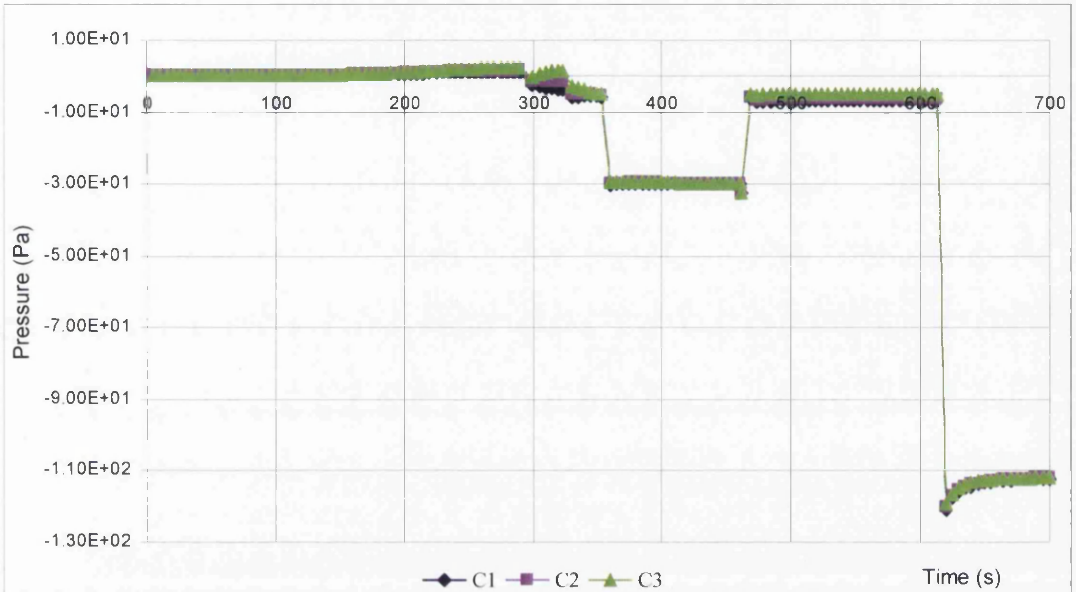



Figure 5.13 – Pressure vs time curve of the common corridor.

As the stair door partially closes for a second time (after 610 seconds), conditions improve significantly which implies that once the fire is brought under controlled or extinguished, the residual smoke can be effectively cleared from the common corridor. The pressure at this point in time is significantly higher i.e. at -110Pa (compared to means of escape period) as the common corridor is ventilated at a higher duty of 4.0m$^3$/s instead of the means of escape duty of 2.0m$^3$/s. Simulation ends at 700 seconds.

<u>Stair</u>

Figure 5.14 to Figure 5.16 show the conditions within the stair against time for point L1 and L2. The intervals of 265 seconds and 320 seconds saw traces of smoke leaking into the stair via the gap prescribed at the foot of the door.

This continues into 353 seconds where the stair door is opened for occupants to escape before promptly cleared by the extraction fans. Although smoke enters the stair, the quantity is so minute that it neither affects the visibility nor the temperature of the stair.

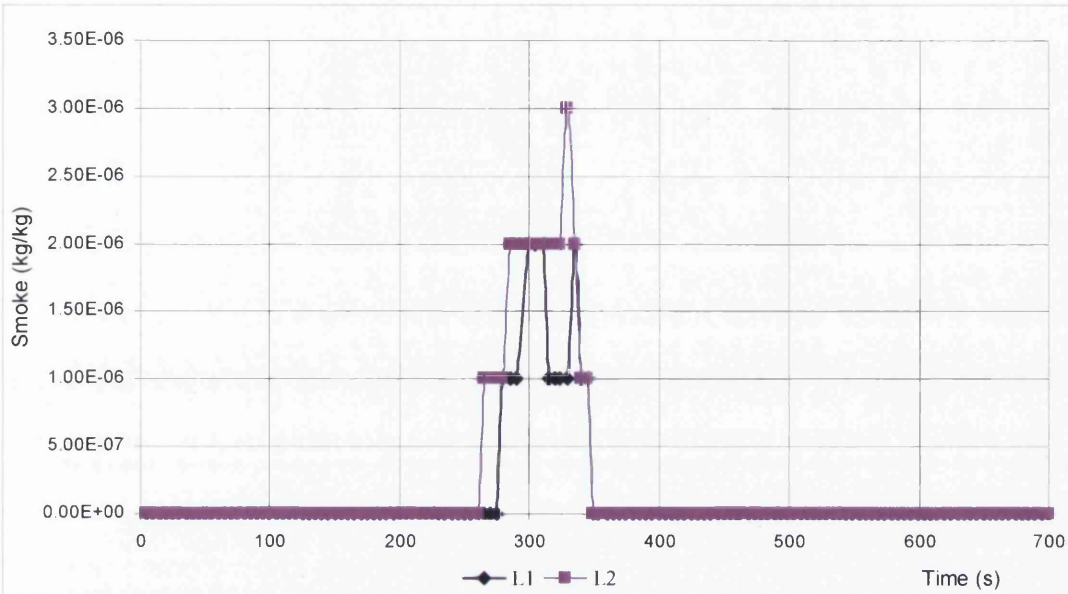



Figure 5.14 – Smoke vs time curve at the stairs.

Pressure in the stair is seen to remain atmospheric until the extract fans are activated. The pressure then jumped to -3.5Pa for the duration that the stair door is open for escape before dropping down to -2.1Pa after the stair door is partially closed.

The pressure difference across the partially closed stair door is -28Pa which is sufficiently low to prevent the door being held tightly. This observation implies that the inlet area provided is sufficient in preventing over-depressurization of the common corridor.

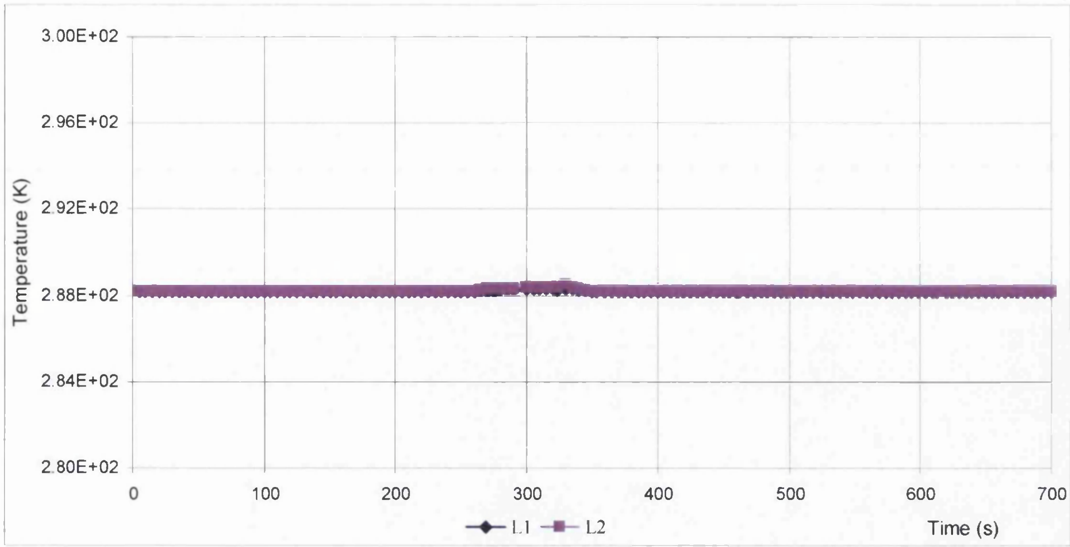



Figure 5.15 – Temperature vs time at the stair

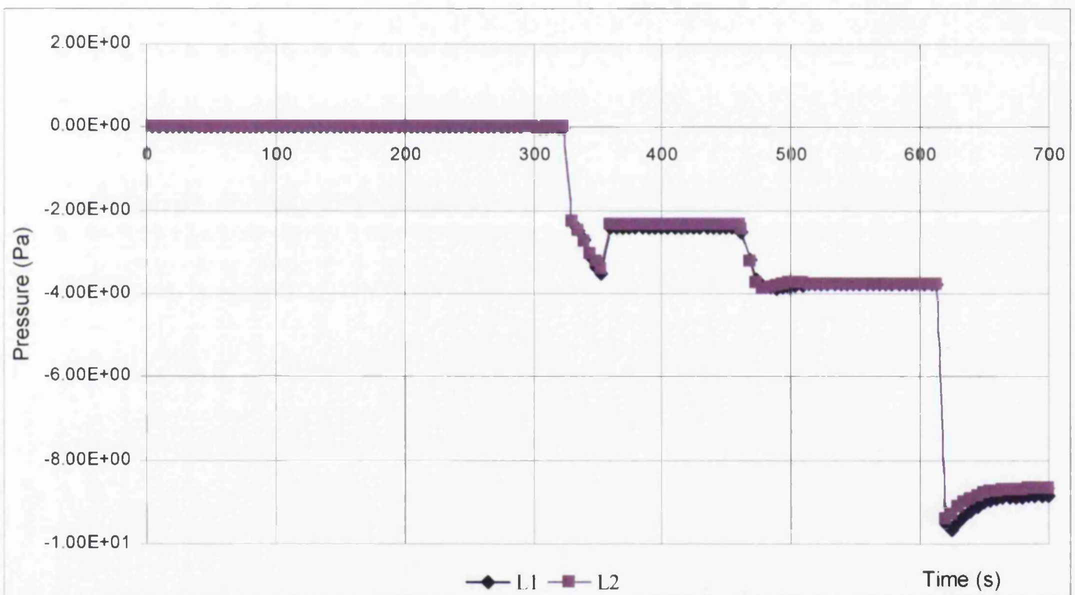



Figure 5.16 – Pressure vs time curve at the stair

During fire fighting phase, the stair is kept free of smoke and confirms that Condition 2 has been met. The pressure in the stair increased to -3.8Pa at this point in time, due to the increased in extract duty. The pressure difference between the stair and common corridor is -6Pa. These observations meant that the pressure difference is sufficient in preventing smoke from flowing into the stair.

As the stair door is partially closed for the second time, the pressure in the stair increased to -8.5Pa. The pressure difference between the stair and common corridor at this point in time is -100Pa which is excessive. It is therefore recommended that the stair door is held open until the system is switch off to prevent the stair door being held tightly.

Smoke shaft

Figure 5.17 to Figure 5.19 show the conditions of the smoke shaft. As expected, the smoke shaft is free of hot smoke until 320 seconds as the system has yet to be activated.

As soon as the system is activated, smoke is seen vented through the smoke shaft. The peak temperature observed in the smoke shaft during means of escape phase is 150°C. The pressure in the shaft increases to -25Pa as the extract fans gradually reaches design extract rate.

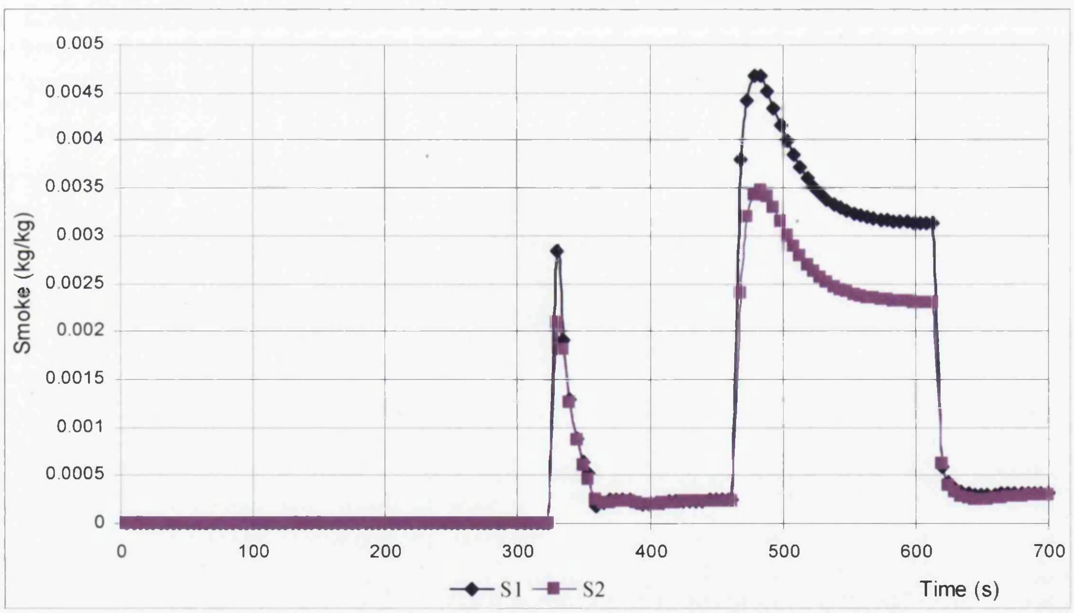



Figure 5.17 – Smoke vs time curve of the smoke shaft.

In the intervals between 350 seconds and 460 seconds, some smoke is seen vented through the smoke shaft. This is confirmed by the temperature plot where the average temperature in the smoke shaft is 30°C, slightly higher than the ambient temperature of 15°C. The reason behind this observation is that smoke, under the influence of the negative pressure of the common corridor, is leaking through the gap at the foot of the door and is then promptly vented through the smoke shaft without contaminating the common corridor.

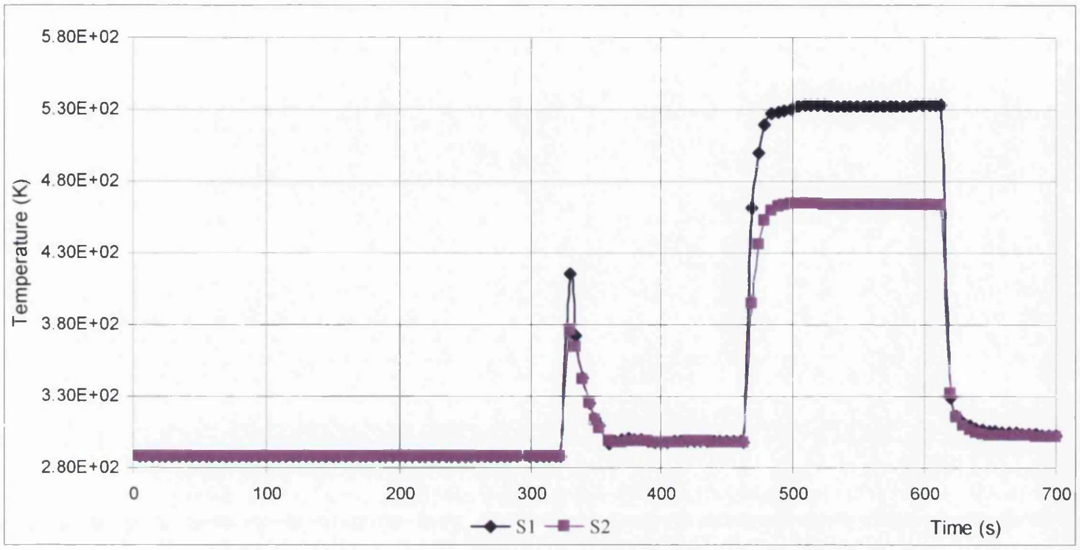



Figure 5.18 – Temperature vs time in the smoke shaft

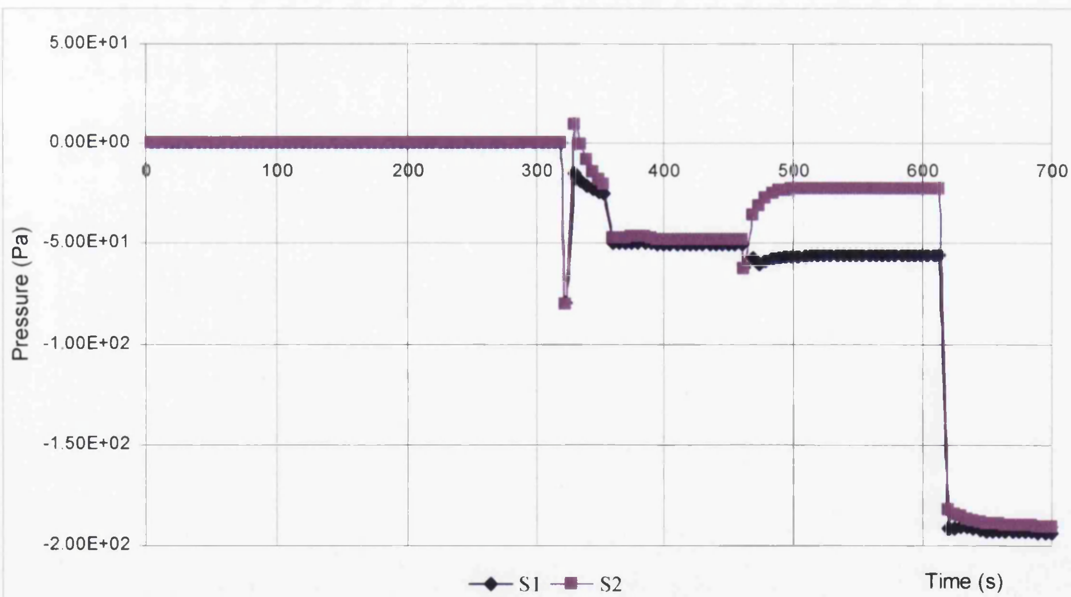



Figure 5.19 – Pressure vs time in the smoke shaft

At fire fighting intervals, the smoke shaft is filled with smoke as expected. The temperature near the extract fans (S2) is observed at 190°C. This implies that extract fans with a fire resistance of 300°C can be used for this case to extract the hot smoke.

The maximum pressure observed at this interval is -56Pa. Air flowing through a $90^{\circ}$ bend into the smoke shaft causes the pressure at the fire floor level (S1) to be higher than that near the fans (S2). This pressure value can then be used to choose the extract fans where fans are required to be able perform its duty at the stated pressure without stalling.

After 610 seconds, the smoke shaft should be cleared of smoke; instead this is not shown in Figure 5.17 as the fire in the flat was allowed to continue burning. It can therefore be assumed that if the fire was to be extinguished (removed from the model) at this point the smoke contaminated common corridor and subsequently the smoke shaft will be cleared of smoke.

<u>Concluding remarks</u>

From these results, it can be concluded that the proposed system is acceptable and fit for purpose as the assessment criteria are met. They are:

- Condition 1 – The proposed system is capable of returning the smoke contaminated common corridor to within tenable limits 60 seconds after the stair door is partially closed behind escaping occupants.
- Condition 2 – Although conditions in the common corridor are untenable, the stair is kept free of smoke at all times. This is acceptable as fire fighters are equipped with protective clothing and breathing apparatus. The smoke free stair provides a platform for the fire fighters to engage the fire as well as providing a safe environment for other occupants to escape when requested to so by fire fighters.

Although the pressure difference between the common corridor and stair would not prevent the stair door from opening, the negative pressure within the common corridor encourages smoke to leak into the common corridor which is then promptly extracted through the smoke shaft. The effect of this leak is minimal and can be further prevented by reducing the negative pressure in the common corridor by means of either increasing the inlet area or reducing the extraction rate.

The pressure and temperature observed at the smoke shaft can then be used to choose the appropriate extract fans. In this case, extract fans with a fire rating of 300°C for 1hour can be used to extract the hot smoke which is at a temperature of 190°C.

#### 5.2.2.2. Comparative approach

From Chapter 2.3, comparative approach requires that the fire engineered solution demonstrates a level of safety equal to or better than code compliant solution. In this discussion, the proposed mechanical extraction system (the results of which discussed in the deterministic approach) is compared to the prescriptive code compliant BRE smoke shaft.

The BRE smoke shaft (or BRE shaft) [24] is chosen as the benchmark system because of its similarity to the mechanical extraction system, namely:

- Suitable for internal corridors/lobbies;
- The corridors/lobbies are ventilated by builder's work smoke shaft raising the length of the building via a ventilator and closed at the bottom; and
- Airflow pattern is similar i.e. smoke shaft as exhaust only while inlet is provided by the stair.

Although the code compliant natural ventilation system with openable window opening to external air can be used as the benchmark system, it is not recommended as the airflow path is different to the BRE smoke shaft system. The former system acts as both the inlet and exhaust while minimal protection is offered to the stair [24]. In the later system, the ventilator opening into the smoke shaft and the smoke shaft itself acts as exhaust only while inlet is provided by the stair. The stair is protected provided that the smoke shaft and the ventilator is of a prescribed size [24].

The performance of the BRE shaft is assessed using SMARTFIRE due to lack of physical data in the published reports [24] and is based upon the fire scenario defined in Section 5.2.1.3. The parameters defined is Section 5.2.1.3, where possible, have been taken from the BRE report [24] to ensure continuity and validity of this analysis. Contour plots in the published report is then used to justify the results obtained (graph plots ending with –BRE). Simulated results have been shown to be comparable to the contour plots.

The results, taking the exact same points described in Section 5.2.2, are then compared to those discussed in Section 5.2.2.1. The proposed system is said to be acceptable if the performance is demonstrated to be equal to or better than the code compliant BRE shaft.

BRE smoke shaft

BRE shaft is a natural system that exploits the stack effects and buoyancy possessed by the hot smoke. The BRE smoke shaft for residential high rise buildings applies and consists of:

- A $1.5m^2$ fire rated builders' work shaft rising the length of the building and closed at the bottom (1.0m wide by 1.5m deep);
- $1.5m^2$ fire rated lobby ventilator opening into the smoke shaft on each floor and positioned at high level; and
- A $1.0m^2$ vent in the stair.

The top of smoke shafts (exhaust) should be located in regions with negative wind pressure coefficient. Positive wind pressure coefficient will severely hinder the performance of smoke shafts [24].

Common corridor

Figure 5.20 to Figure 5.22 shows the conditions within the common corridor against time for the duration of the fire event namely smoke mass fraction, temperature and pressure. The smoke mass fraction and temperature plots of the BRE shaft are seen to mirror those of the proposed mechanical extraction system while the pressure plots less so.

At 323 seconds, conditions in the common corridor of the BRE shaft system have seen to peak where smoke and temperature values are comparable to the mechanical extract system. As the system is activated and the stair door opened for occupants escape, conditions in the common corridor improved significantly and are again comparable to the mechanical extract system. The pressure in the period when the stair door is opened is observed at -10Pa.

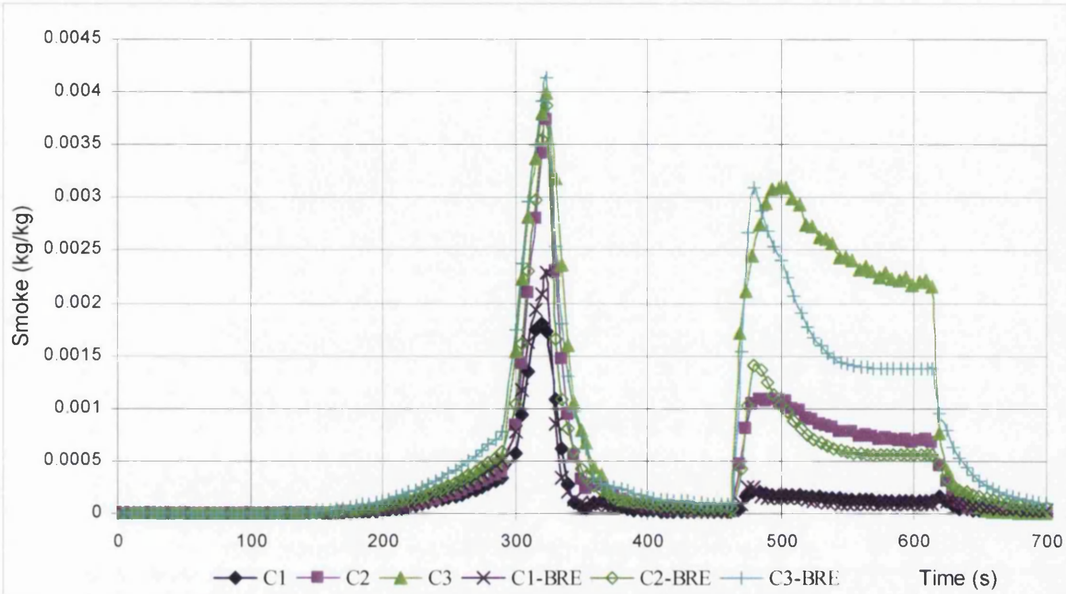



Figure 5.20 – Smoke vs time curve in the common corridor.

In the period between 350 seconds to 460 seconds, the rate at which smoke is cleared from the common corridor is reduced as the inlet i.e. the stair door, is partially closed leaving a 100mm gap. At 440 seconds, most of the common corridor can be said to have returned to ambient conditions (visibility exceeds 5m while the temperature is at 15°C) but with pocket of smoke at high level yet to be vented – shown by Figure 5.20 of the C3-BRE plot which sit just above the other plots. The pressure in the common corridor is observed at -3Pa.

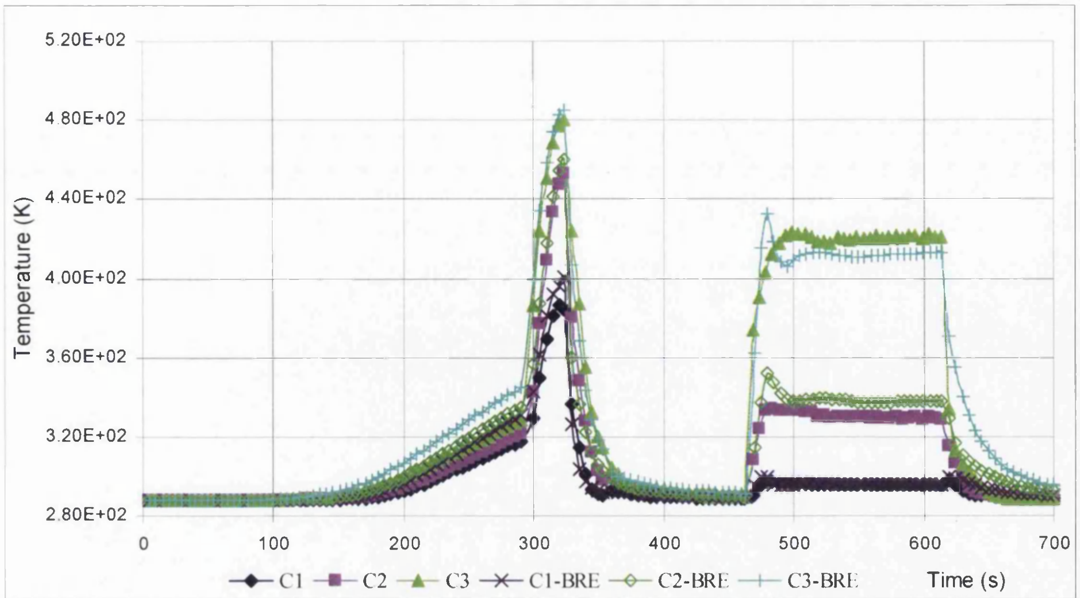



Figure 5.21 – Temperature vs time curve in the common corridor.

At 460 seconds, the opened flat door allows for smoke to spill into the common corridor with smoke quickly forming a stratified layer. The smoke mass fraction of the BRE system at mid and high level is initially comparable to mechanical extract system but later improves as time passes. At low level, smoke is similar to that observed in the mechanical extract system. The temperature values at mid and high level differs by 6°C while it is seen to be identical at low level. The pressure at this point in time is seen to be at -10Pa, a difference of -5Pa compared to mechanical extract system.

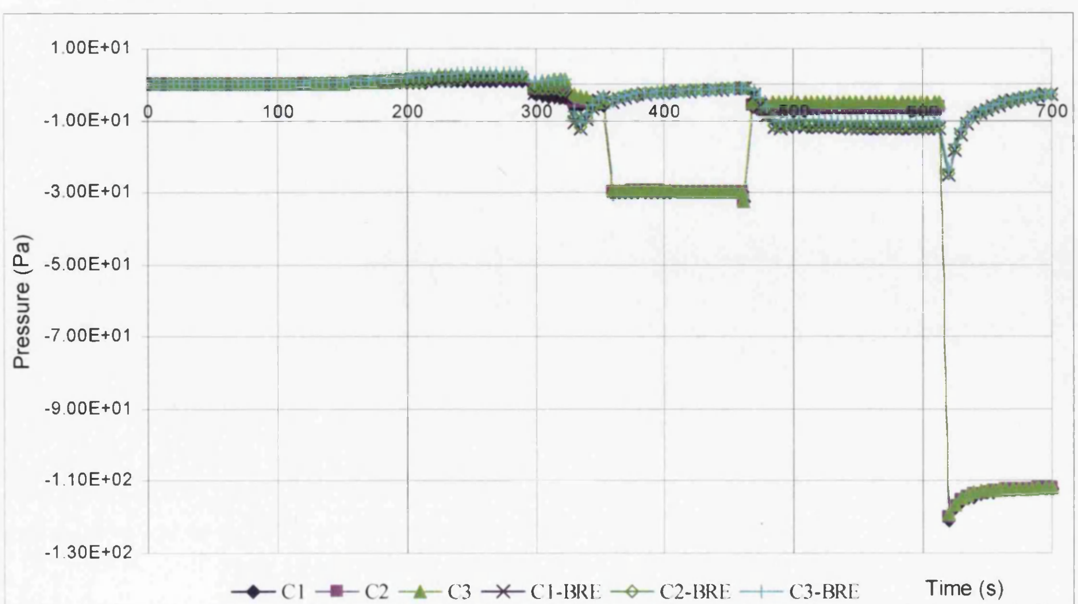


Figure 5.22 – Pressure vs time curve in the common corridor.

Based on the conditions observed in the common corridor, the performance of the BRE shaft system is said to be equal to the mechanical extract system

<u>Stair</u>

The stair is seen to be cleared of smoke except at the intervals between 320 seconds and 490 seconds. At 320 seconds, smoke is seen to flow into the stair at high level the instant the stair door is opened as occupants escape. This is due to the positive pressure exerted by the high level hot smoke. The pressure difference between the common corridor and stair that drives the smoke is 3Pa. The amount of smoke that enters the stair far exceeds those observed in the mechanical extract system.

In the period when the stair door is open (320 seconds to 350 seconds), smoke is gradually prevent from flowing into the stair as the pressure difference between the common corridor and the stair gradually drops, to -4Pa at 340 seconds and returned to -1Pa as the stair door closes at 350 seconds.

Up to 460 seconds, residual smoke is still present in the stair as the BRE system slowly vents the smoke from the common corridor. The stair continues to be a source of inlet, via the 100mm gap, as the pressure difference across the stair door is -2Pa.

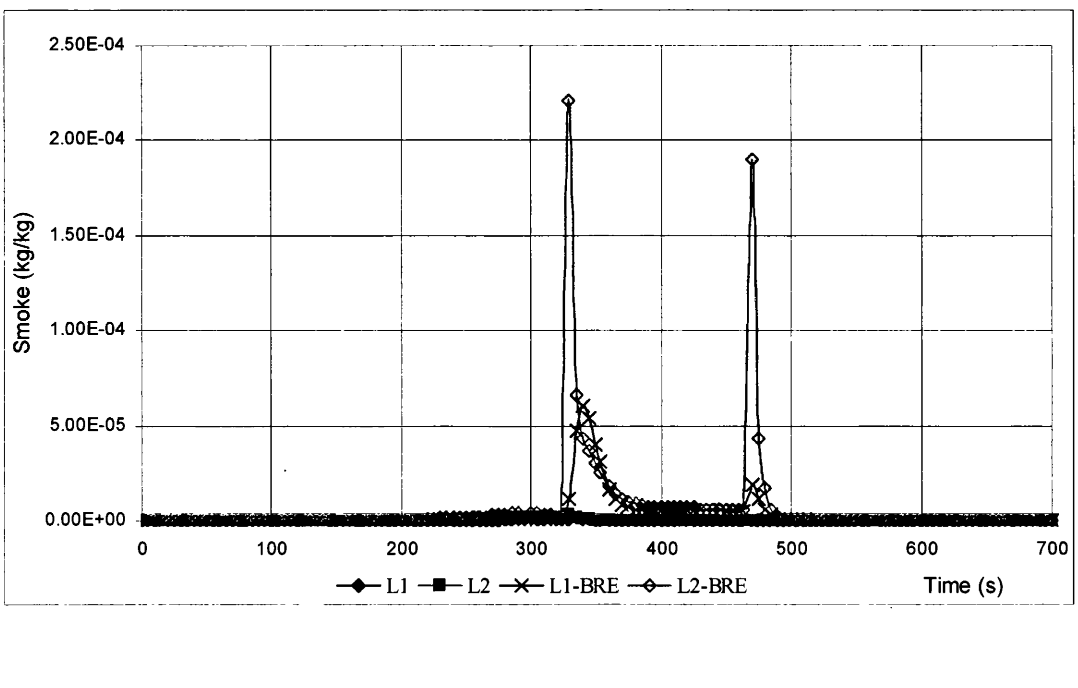


Figure 5.23 – Smoke vs time curve in the stair.

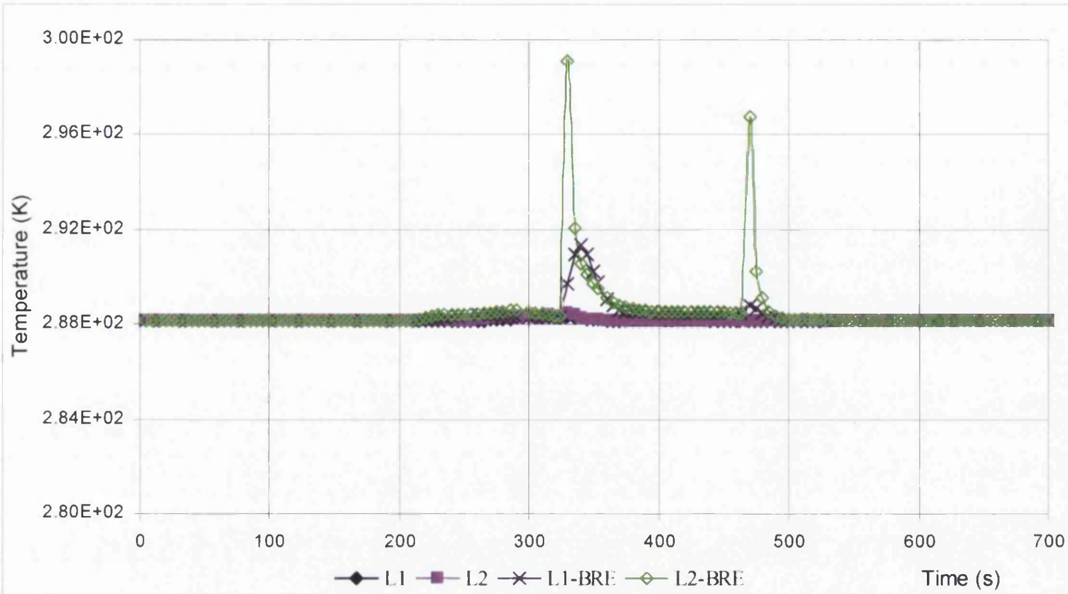



Figure 5.24 – Temperature vs time curve in the stair.

This trend is again observed at 460 seconds where some smoke entered the stair due to the pressure of the hot smoke overwhelming the pressure difference across the stair door. Smoke is quickly prevented from flowing into the stair as stack effects dominate beyond which the stair is free of smoke. The pressure difference across the stair door at this point is -6Pa.

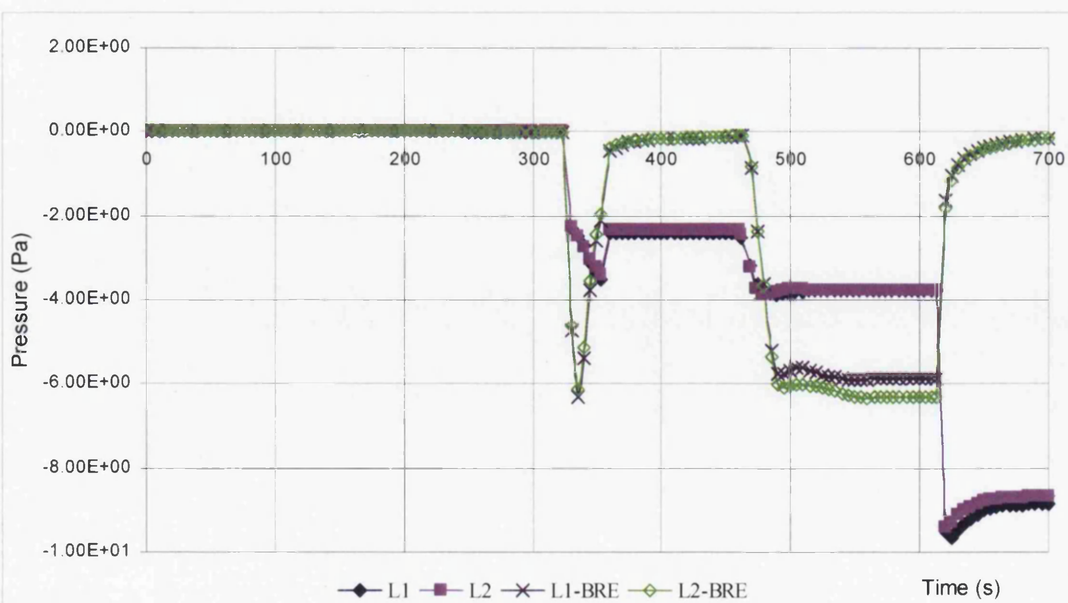



Figure 5.25 – Pressure vs time curve in the stair.

Based on these observations in the stair, the proposed mechanical extract system is seen to demonstrate a level of performance better than the BRE shaft system as the stair is kept free of smoke at all times.

Smoke shaft

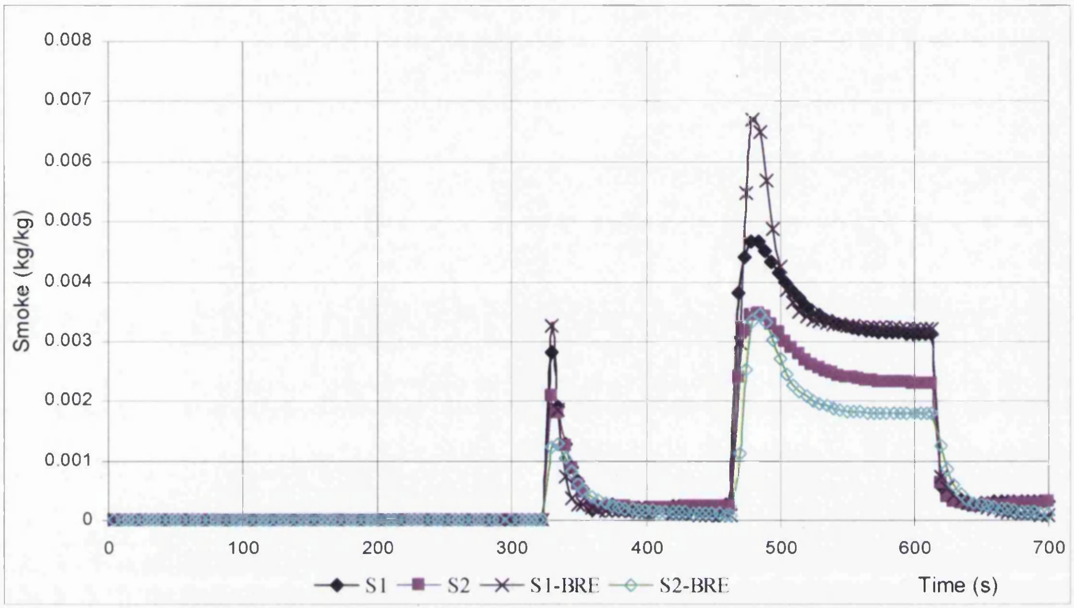



Figure 5.26 – Smoke vs time curve in the smoke shaft.

Figure 5.26 and Figure 5.27 show that conditions in the smoke shaft of the BRE shaft system are seen to mirror those observed in the mechanical extract system. In the intervals between 350 seconds and 460 seconds, some smoke is seen vented through the smoke shaft as confirmed by the temperature plot where the average temperature in the smoke shaft is 20°C. This is due to the fact that smoke in the common corridor is continued to be vented.

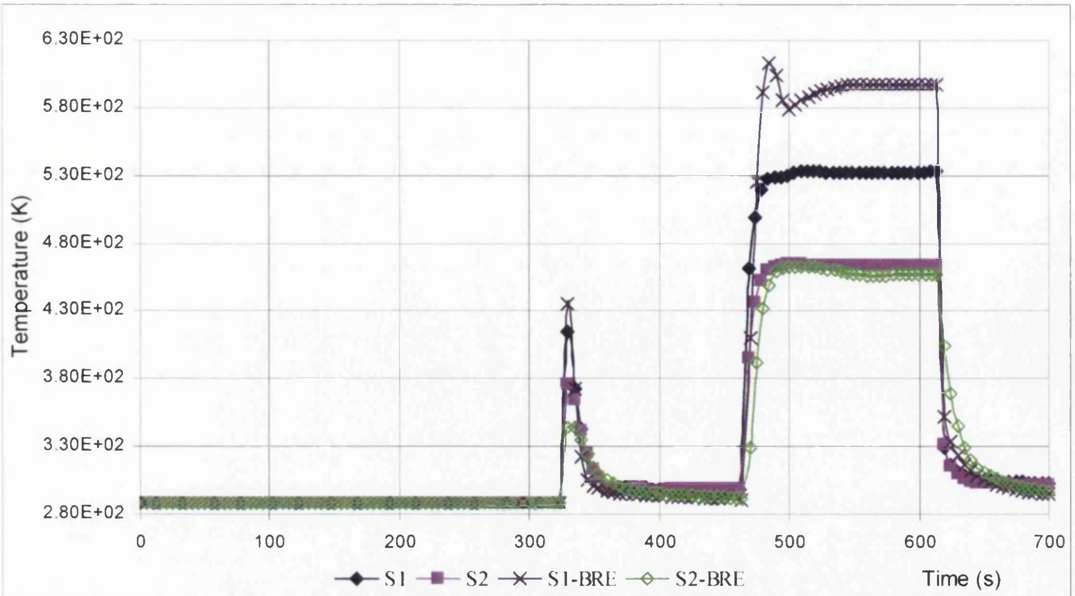



Figure 5.27 – Temperature vs time curve in the smoke shaft.

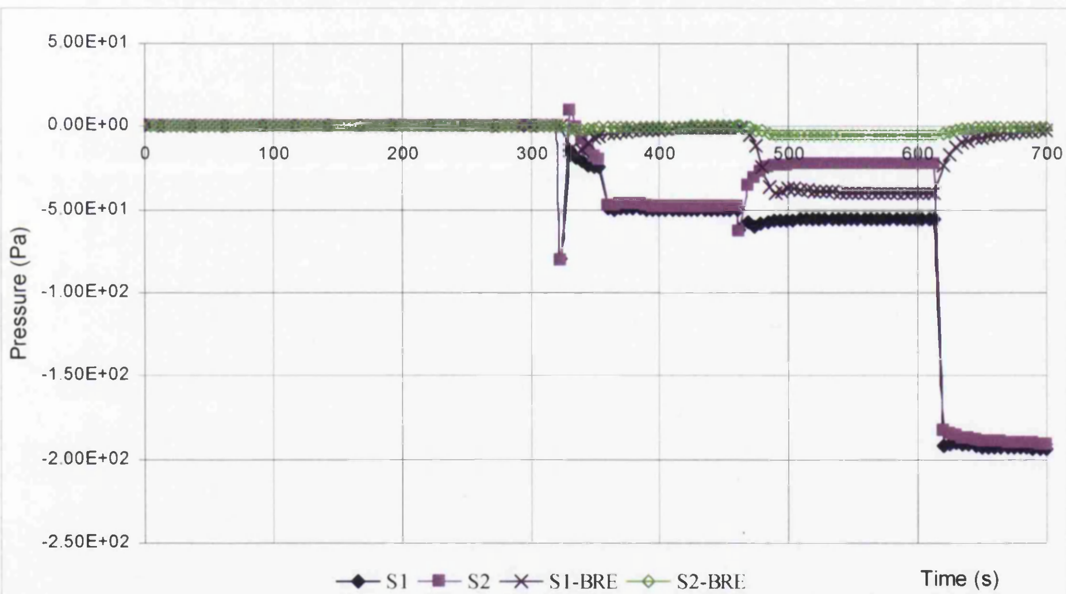



Figure 5.28 – Pressure vs time curve in the smoke shaft.

Figure 5.28 shows the pressure in the smoke shaft. The pressure at high level is observed at -5Pa while at the fire floor level is -40Pa. This is to be expected as the smoke shaft is open to atmosphere. The high negative pressure at fire floor level is due to air flowing along a $90^{o}$ bend.

Concluding remarks

The evaluation of the code compliant BRE smoke shaft using CFD is seen to provide a degree of protection to the stair at times of occupants escape and fire fighting. The results obtained here are inline to those discussed in the BRE 79204 report [24], therefore giving a degree of validity to the analysis.

It can therefore be concluded that, based on comparative approach, the proposed mechanical extract system is acceptable as the proposed system demonstrates a level of performance equal to or better than the code compliant BRE smoke shaft.

#### 5.2.2.3. Mesh independence

From Section 4.3.7, the convergence of the numerical analysis can be assessed by means of a mesh independence study. This section looks to discuss this study through the use of the mechanical extract analysis presented in Section 5.2.2.1.

For comparative purposes, the same time step size, number of iterations and the same fire scenario is used for the analysis of the mesh independent model. The cell budget of the mesh independent model is almost twice that of the referenced model and is given by:

- Reference mechanical extract model: Cell budget = 420918
- Mesh independent model: Cell budget = 741000

Similarly, the following discussion is based on the same coordinate points as previous.

<u>Common corridor</u>

Conditions in the common corridor of the mesh independent model, as shown in Figure 5.29 to Figure 5.31, are seen to be similar to the reference model. In Figure 5.29, the values of the smoke are consistent throughout the duration of the fire except at the fire fighting phase where the mesh independent values, at C3-Mesh level, exceed by 10%. At C2-Mesh and C1-Mesh levels, the errors are less significant at 4% and 1% respectively.

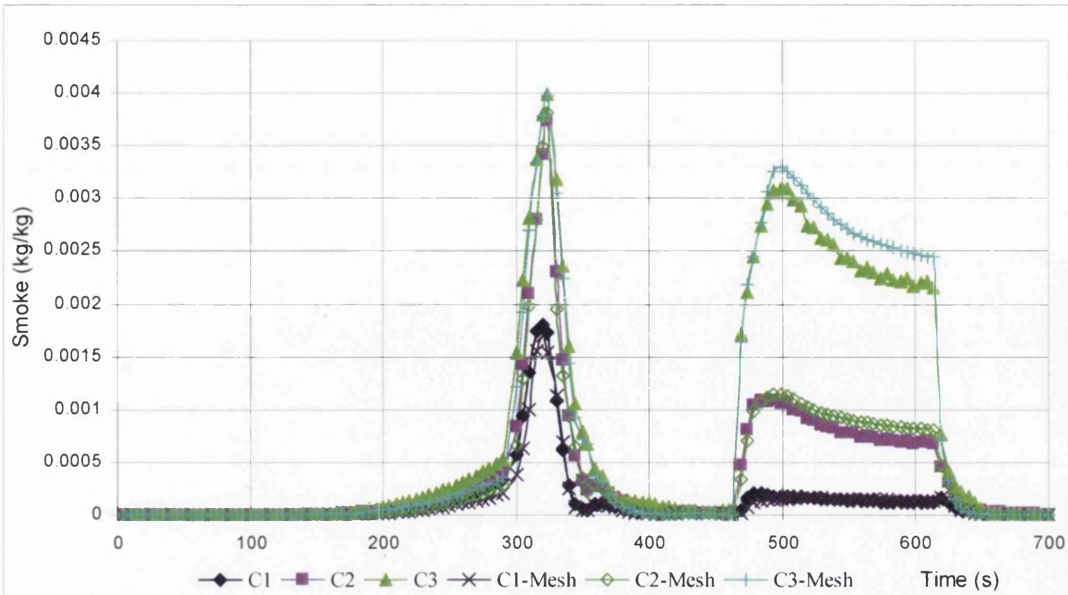



Figure 5.29 – Smoke vs time curve in the common corridor.

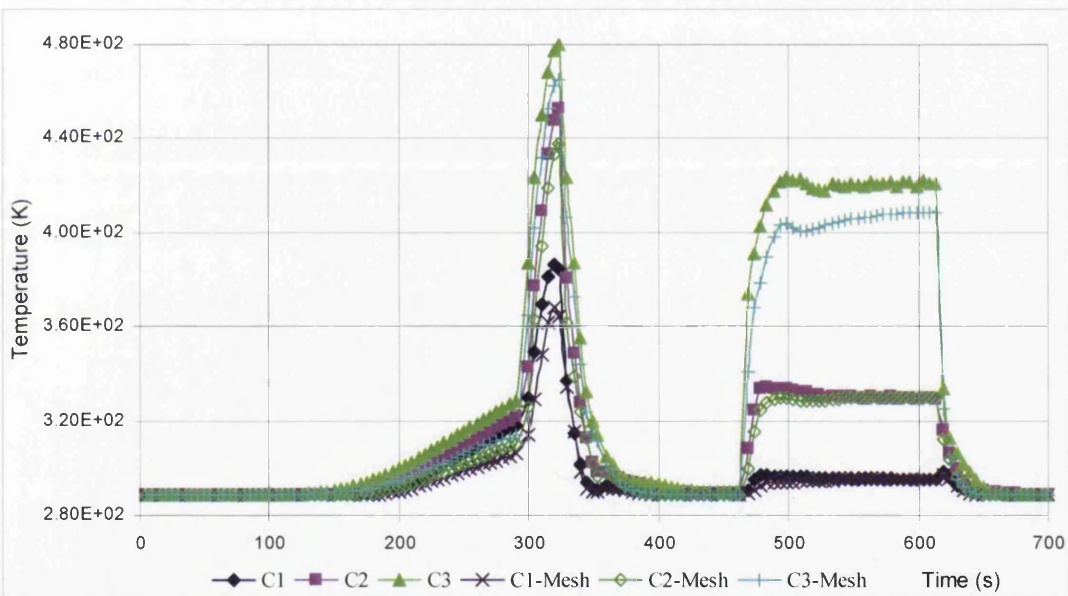



Figure 5.30 – Temperature vs time curve in the common corridor.

In Figure 5.30, the temperature values of the mesh independent model, at C3-Mesh, are 3% less than those observed in the referenced model. This is reduced to 0.5% at both C2-Mesh and C1-Mesh levels.

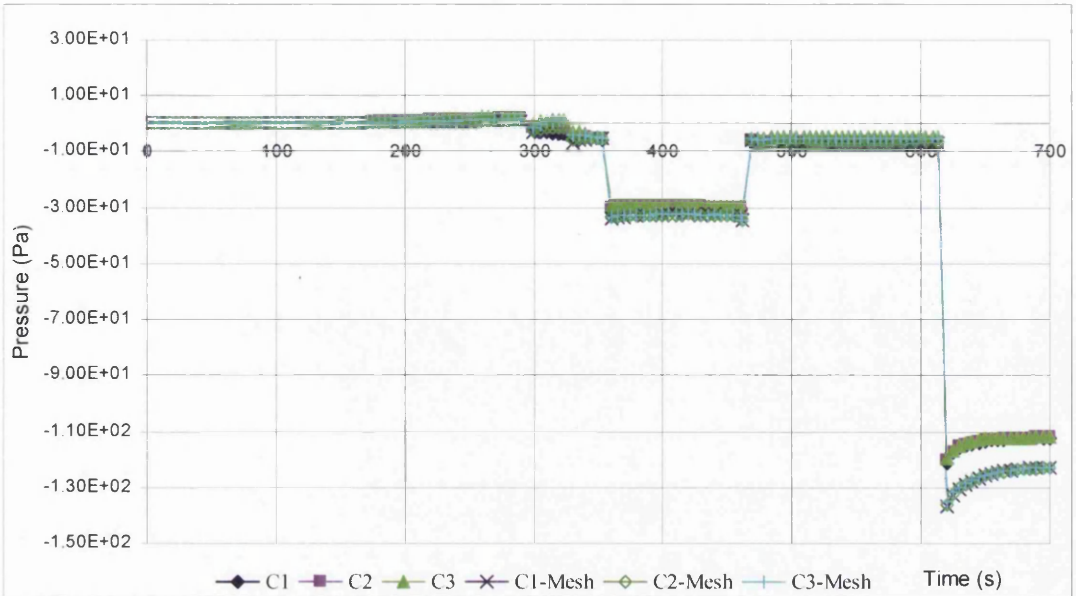



Figure 5.31 – Pressure vs time curve in the common corridor.

The pressure plots in Figure 5.31 show that there is a slight variation in pressure in the period between 350 seconds and 460 seconds. The errors at this period are calculated at 5%.

The errors observed in the common corridor are small which therefore confirms that the choice of mesh in this region is acceptable.

<u>Stair</u>

Figure 5.32 shows that the smoke values for the mesh independent model is significantly less than the referenced model. The errors calculated are as high as 66%. The errors in the temperature (Figure 5.33) and pressure (Figure 5.34) variables are less so and is in the region of 0.1% and 10% respectively. Given that smoke is a conserved scalar, this implies that the mesh in the referenced model needs refinement.

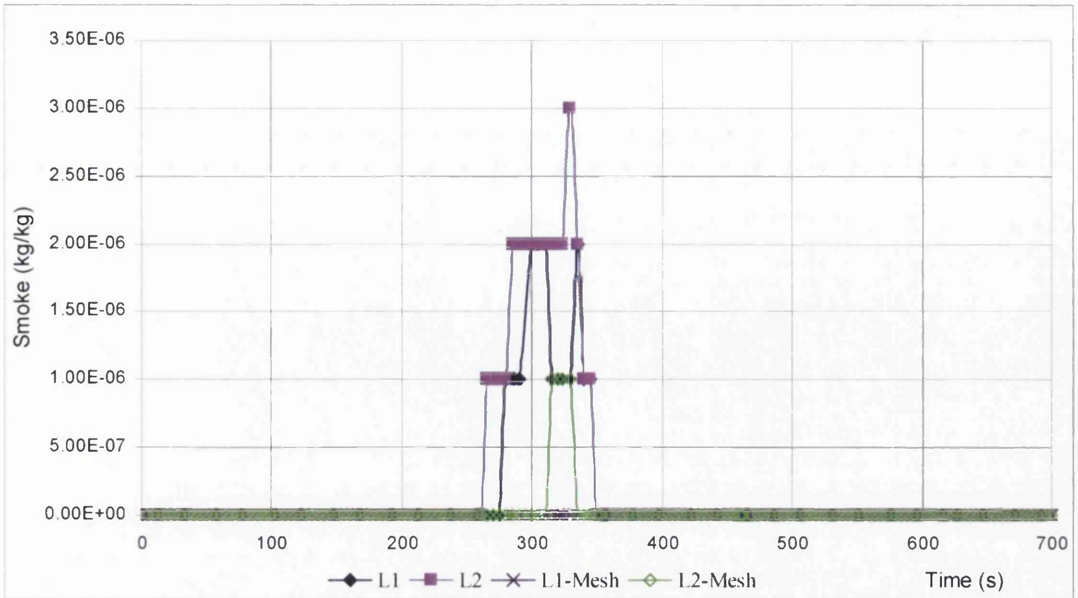



Figure 5.32 – Smoke vs time curve in the stair.

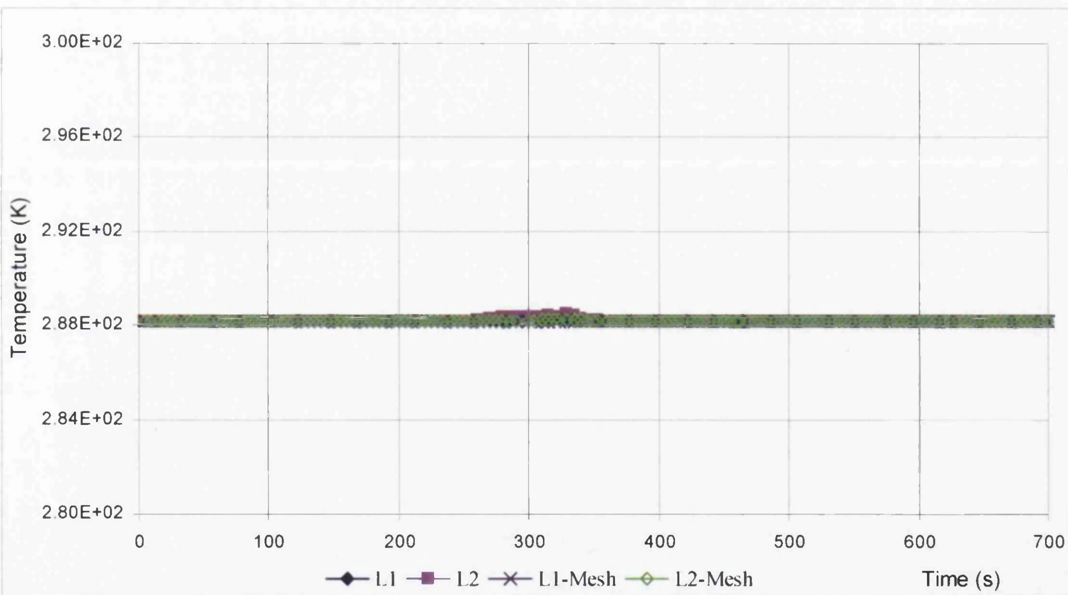



Figure 5.33 – Temperature vs time curve in the stair.

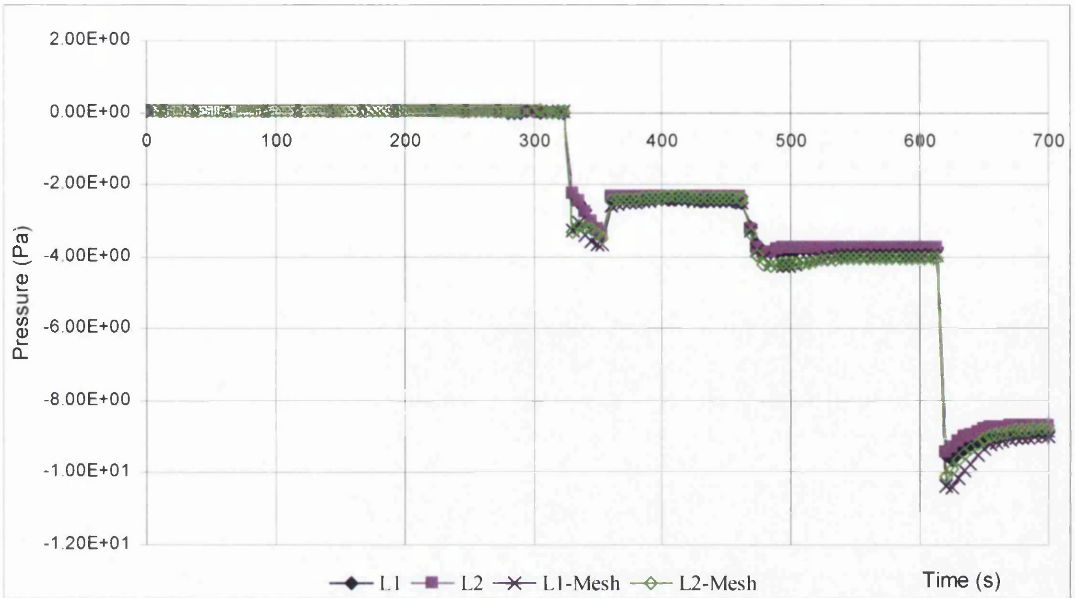



Figure 5.34 – Pressure vs time curve in the stair.

## Smoke shaft

Figure 5.35 shows that the smoke plots are similar to each other with the only exception at the S1-Mesh level during fire fighting phase. The errors as a result of this variation are 10%.

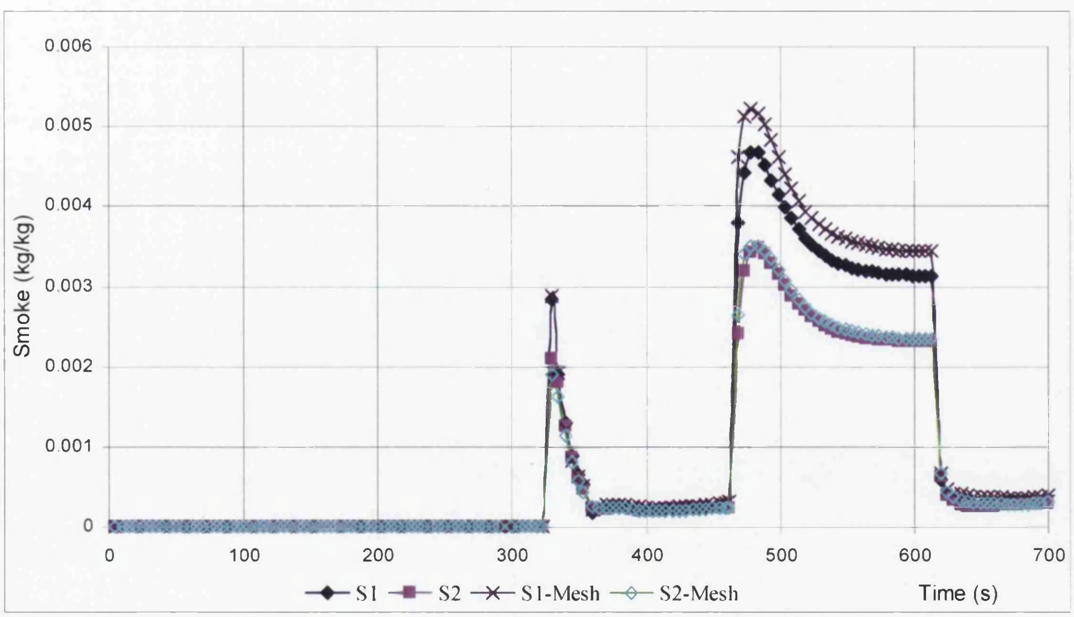



Figure 5.35 – Smoke vs time curve in the smoke shaft.

In the temperature plots of Figure 5.36, variations in the temperature values are seen at the S2-Mesh level instead of S1-Mesh level where the temperature is 3% lower than the referenced model. Otherwise, the temperature values are almost identical.

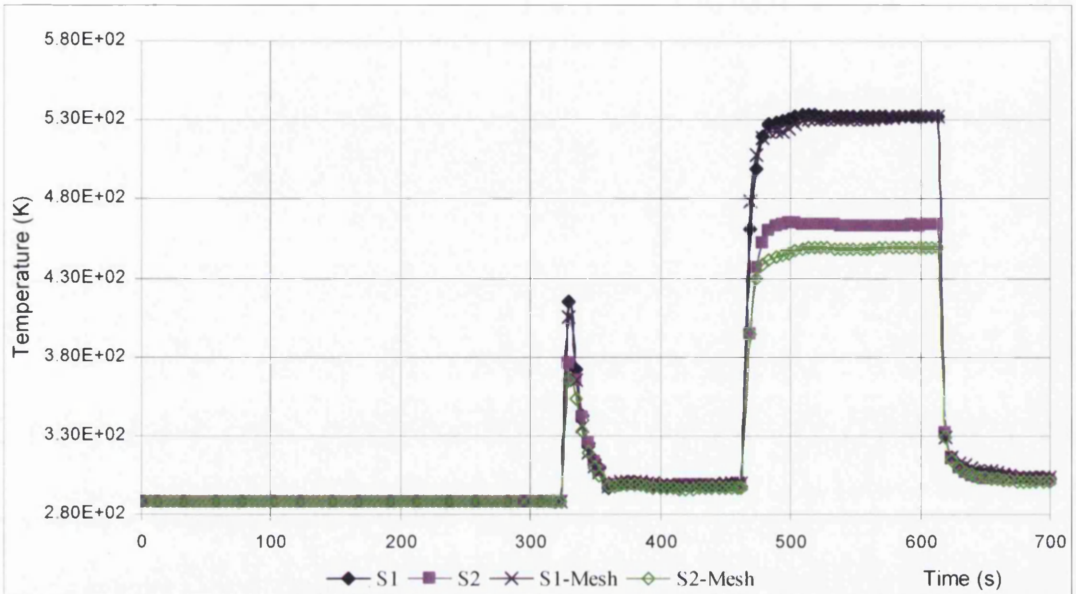



Figure 5.36 – Temperature vs time curve in the smoke shaft.

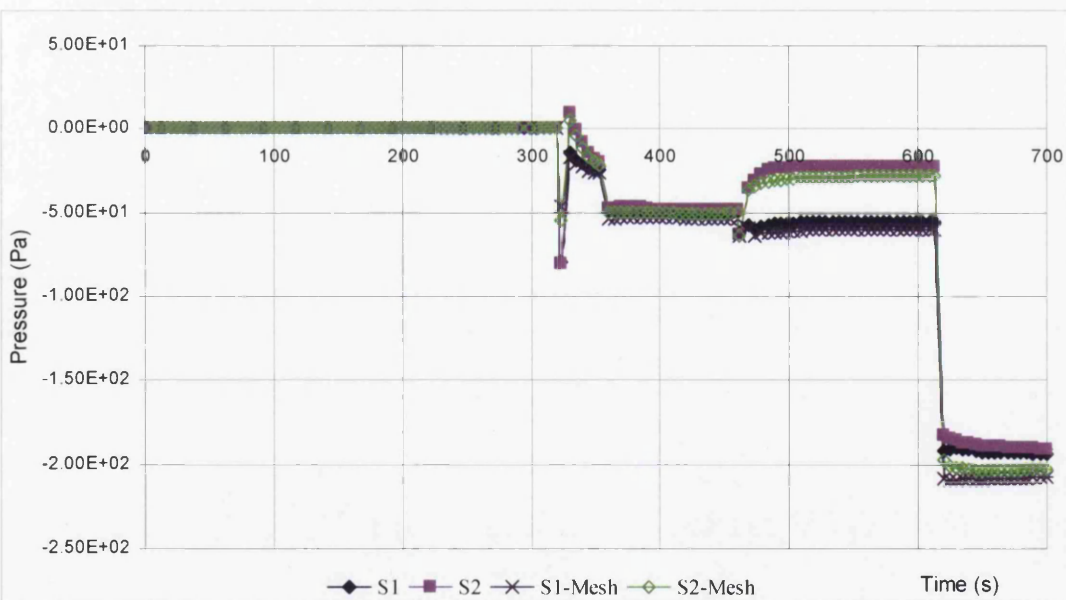



Figure 5.37 – Pressure vs time curve in the smoke shaft.

The pressure plots in Figure 5.37 shows a similar trend whereby the pressure variations in the intervals of 350 seconds to 460 seconds and intervals of 460 seconds to 610 seconds are within 10% of the reference model.

Concluding remarks

Generally, the errors calculated in the mesh independence study are within 10% of the referenced model except at the stairs where the smoke variable has an error of 66%. The high percentage errors are due to the predicted values of the referenced model being much worse than the predicted values of the mesh independent model. This implies that the mesh density chosen in areas other than the stair is acceptable, while those in the stair need further refinement.

In this case, the mesh in the stair of the referenced model is still acceptable as the small traces of smoke that has leaked into the stair are negligible. Hence, in the overall scheme of things, the mesh of the referenced model is suitable and the solutions can be said to have converged to a near mesh independent solution.

### 5.2.2.4. Sensitivity study

This section presents the sensitivity study as discussed in Section 5.2.1.3. The aim of this study is to ensure that the design of the proposed mechanical extract system is sufficiently robust to consider all location of potential fire hazards. In residential high rise buildings, fire is normally assumed to burn in flats instead of common corridors/lobbies as communal areas are often kept clear of fuel sources [21]. The results of this analysis is shown in the graph plots ending with –Fire and is compared to those obtained in Section 5.2.2.1.

For this reason, flat 2 is chosen as the potential flat on fire. Figure 5.38 shows the corresponding computational model. The same shaft size and extract duty is used for this analysis. This analysis is also assessed by means of deterministic approach as presented previously. The acceptance criteria are:

- The smoke contaminated common corridor is required to return to within tenable limits; and
- Stair is kept free of smoke during fire fighting process.

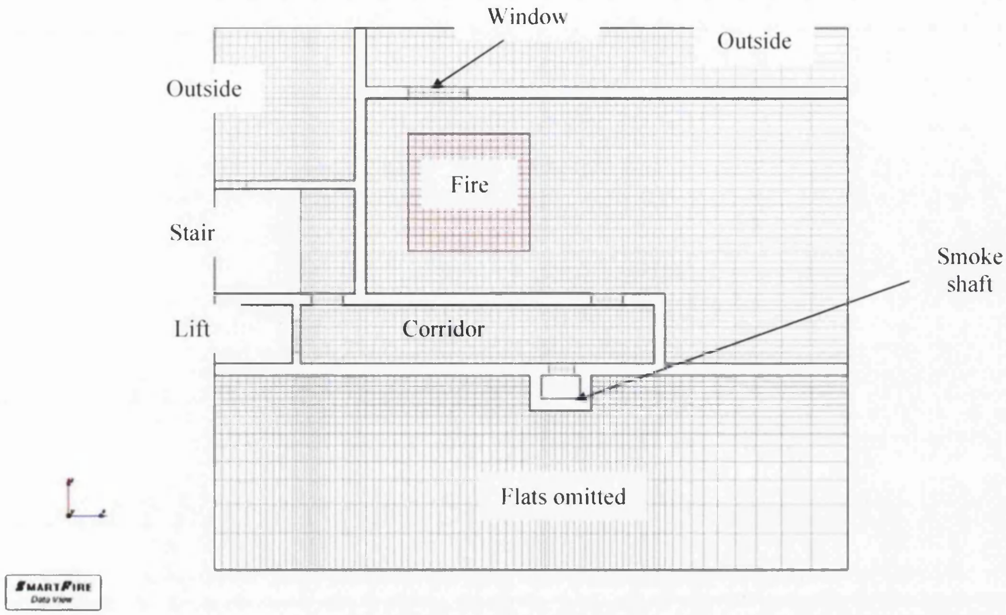



Figure 5.38 – Plan view of Flat 2 computational model.

Common corridor

The development in the conditions in the common corridor mirrors that of the Flat 1 on fire. Figure 5.39 and Figure 5.40 show that from 160 seconds, the common corridor is gradually filled with smoke leaking from the flat on fire which explains the raised temperature. This is then interrupted by the sudden influx of smoke at 293 seconds as the flat door is opened with occupants making their escape. Conditions quickly become untenable in the period when the door is open.

As soon as the flat door closes at 320seconds, conditions improve as the ventilation is activated and that the stair door is opened as occupants make their escape therefore providing replacement air for the ventilation system. Replacement air is continued to be provided through the stair via the partially closed stair door – 100mm gap.

Within 60seconds of the stair door closing, the common corridor has returned to ambient conditions as the visibility exceeds 5m while the average temperature is at 18$^{o}$C. Condition 1 has therefore been met.

The pressure at this point is -40Pa (Figure 5.41). The negative pressure encourages smoke to leak into the common corridor and is vented by the system with minimum effects to the conditions of the common corridor.

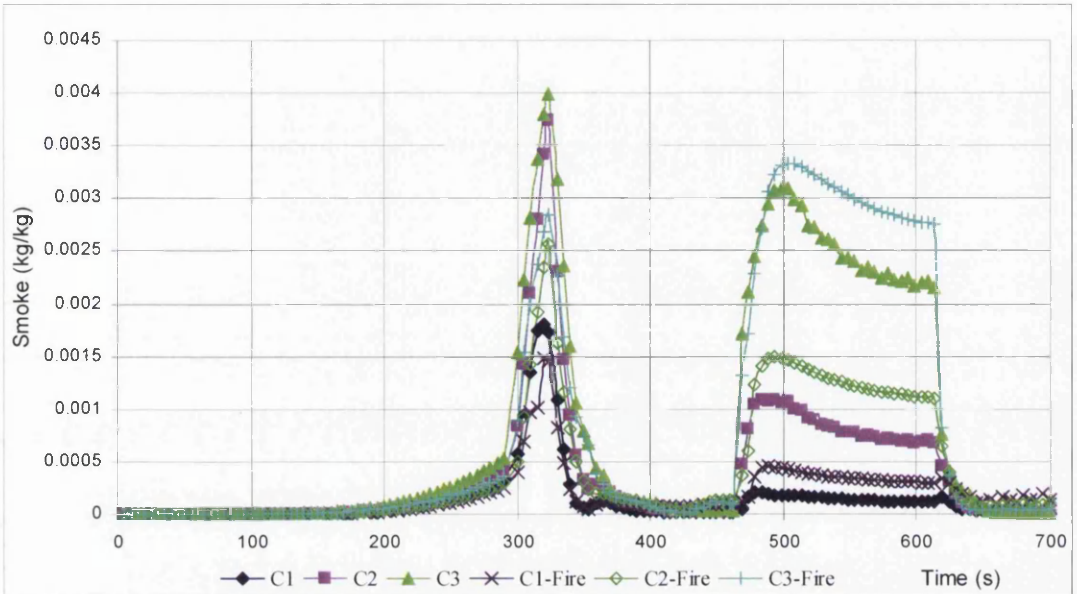



Figure 5.39 – Smoke vs time curve in common corridor.

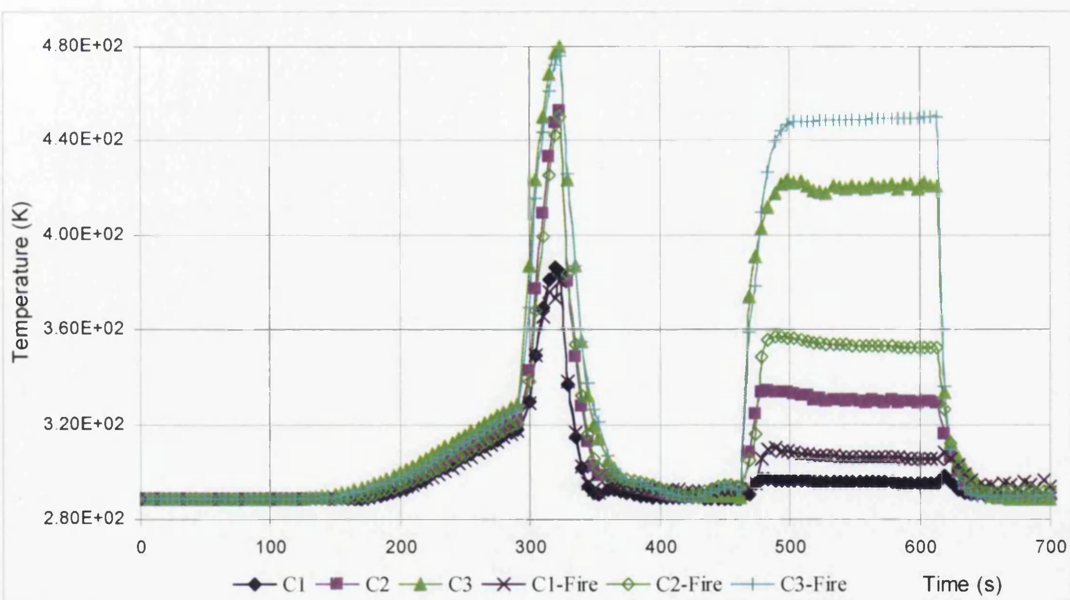



Figure 5.40 – Temperature vs time curve in common corridor.

During fire fighting phase and with extract fans at fire fighting duty, smoke plume has stratified where the visibility in the common corridor reduces to zero at head level (C3-Fire) and 1.5m at low level (C1-Fire). The average temperature at these corresponding levels is 180°C and 32°C. The pressure observed is -9Pa.

Similarly, these conditions, although untenable, is acceptable as fire fighters are capable of working in these conditions.

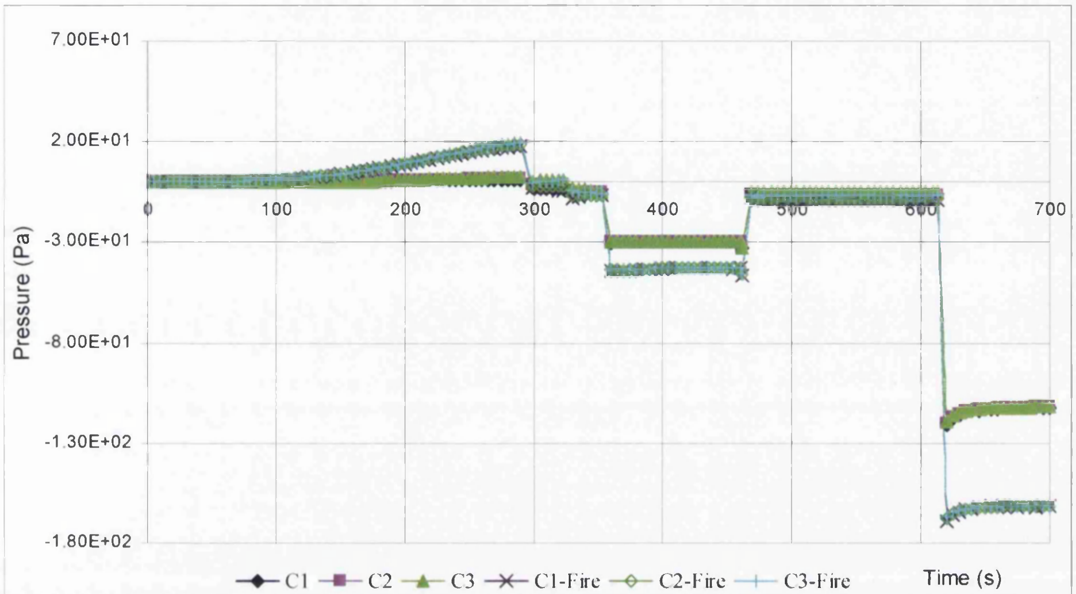



Figure 5.41 – Pressure vs time curve in common corridor.

<u>Stair</u>

In intervals between 265 seconds and 320 seconds, traces of smoke are again seen leaking into the stair – Figure 5.42. Although the amount is significantly higher than the referenced model, the affects on the condition of the stair is minimal. The visibility based on a smoke mass fraction of $1.8 \times 10^{-5}$ and light reflecting background is calculated as 18.6m while the temperature (Figure 5.42) is slightly raised to 17°C. A condition that would not impedes the escape of occupants. The smoke traces are then cleared from the stair shortly after the stair door is partially closed behind escaping occupants, leaving a gap for replacement air.

The pressure difference across the partially closed stair door is calculated as -40Pa and is sufficiently low to prevent the stair door being held tightly. Over-depressurization of the common corridor is therefore avoided.

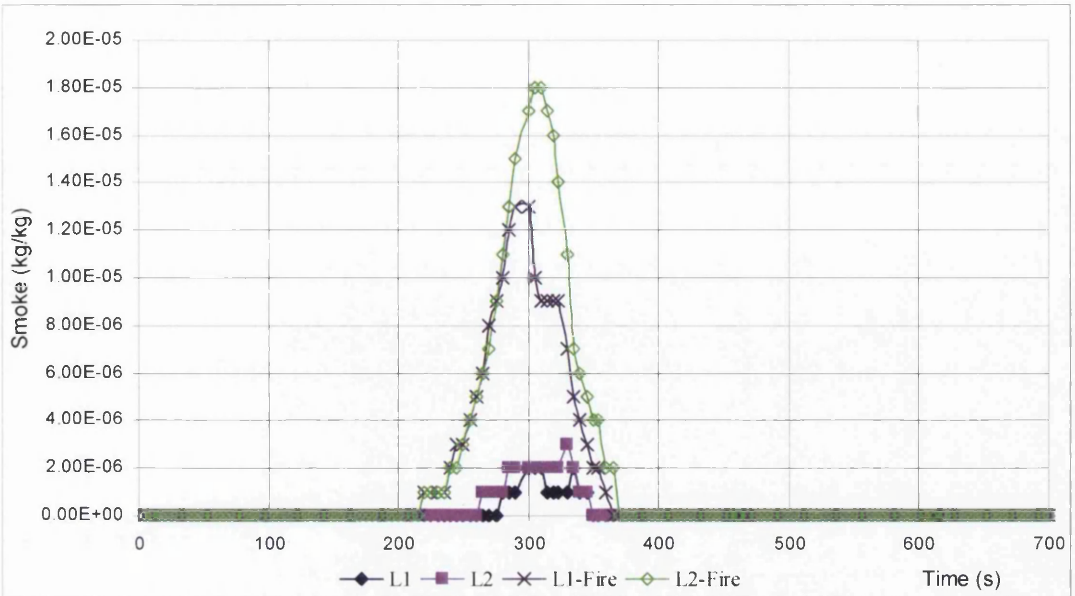



Figure 5.42 – Smoke vs time curve in stair.

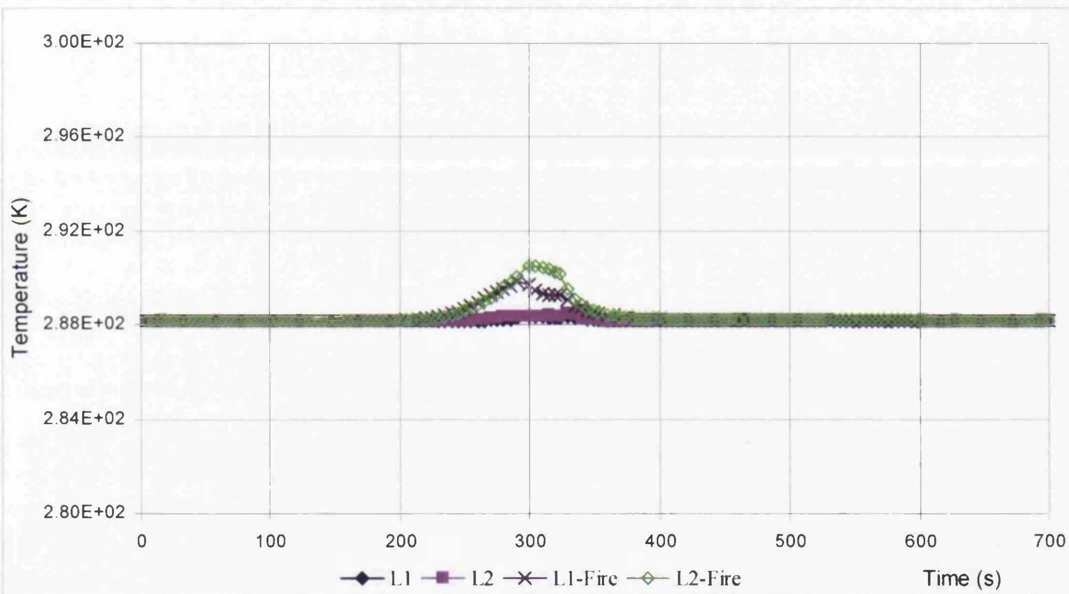



Figure 5.43 – Temperature vs time curve in stair.

During fire fighting phase, the stair is kept free of smoke and at ambient temperature. This confirms that Condition 2 has been met. At the same period, the pressure in the stair has increased to -4Pa due to the fire fighting extract duty. The pressure difference across the opened stair door is -5Pa.

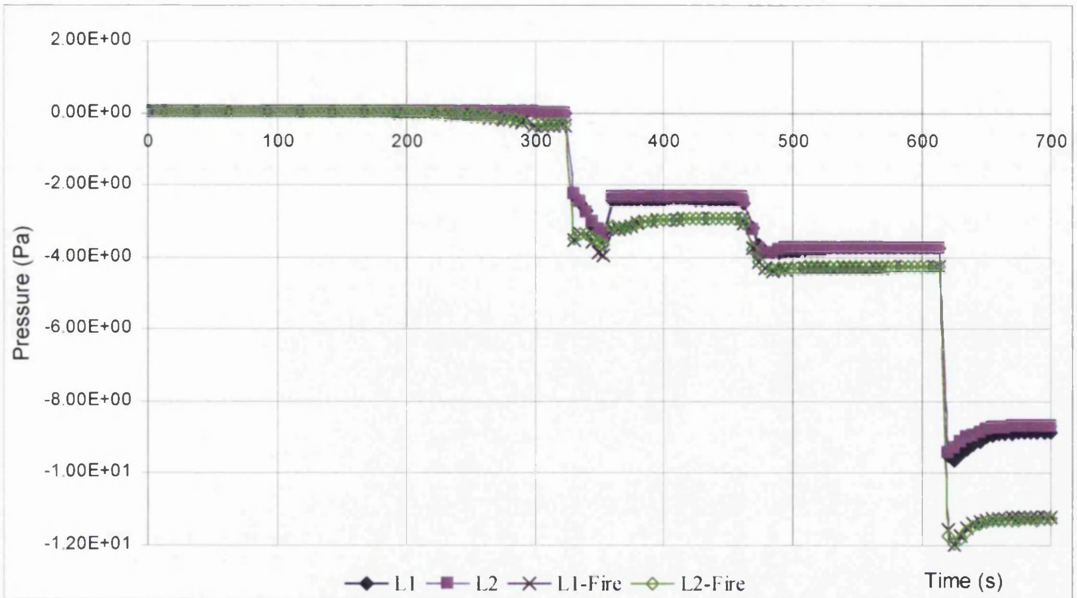



Figure 5.44 – Pressure vs time curve in stair.

## Smoke shaft

Conditions in the smoke shaft are similar to the referenced model. Prior to 320 seconds, the smoke shaft is cleared of smoke – Figure 5.45. Smoke is seen in the shaft after 320 seconds as the system is activated. Smoke and temperature (Figure 5.46) values peaked at 340 seconds and gradually reduced as the conditions in the common corridor improve.

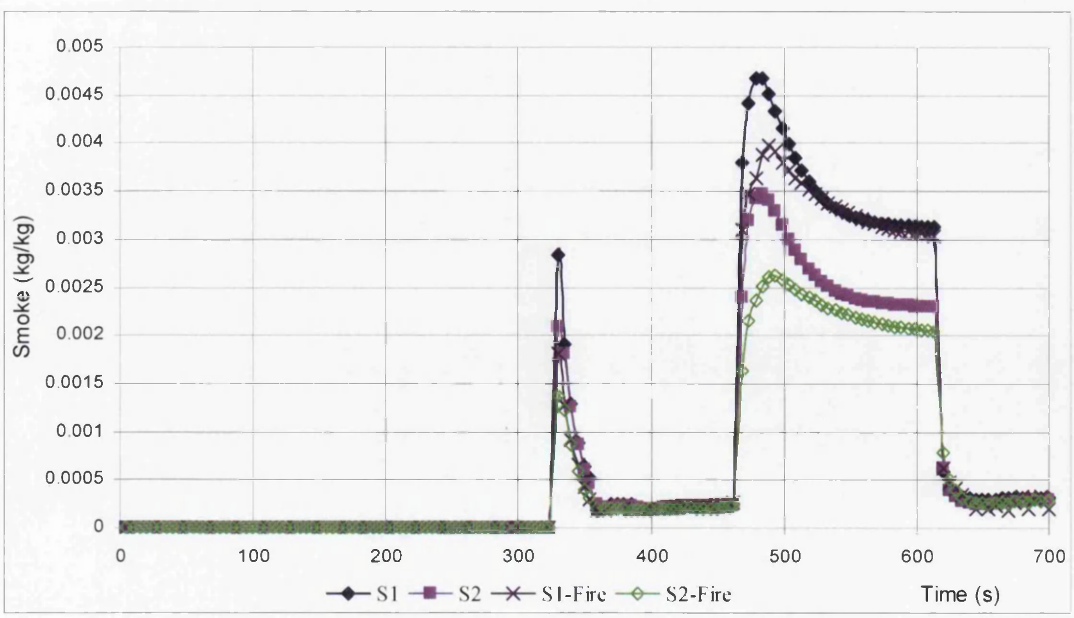



Figure 5.45 – Smoke vs time curve in smoke shaft.

The interval between 350 seconds and 460 seconds sees that smoke is vented through the smoke shaft and is confirmed by the temperature plots as the temperature is 25°C. This is because smoke which had initially leaked into the common corridor is vented through the smoke shaft. The maximum pressure observed at this period, Figure 5.47, is -63Pa.

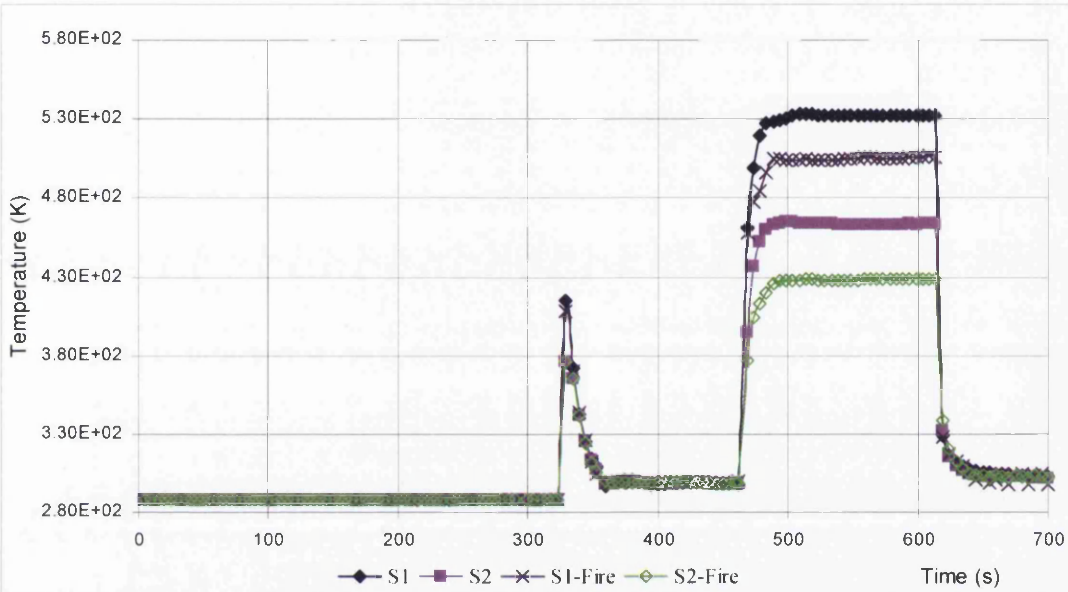



Figure 5.46 – Temperature vs time curve in smoke shaft.

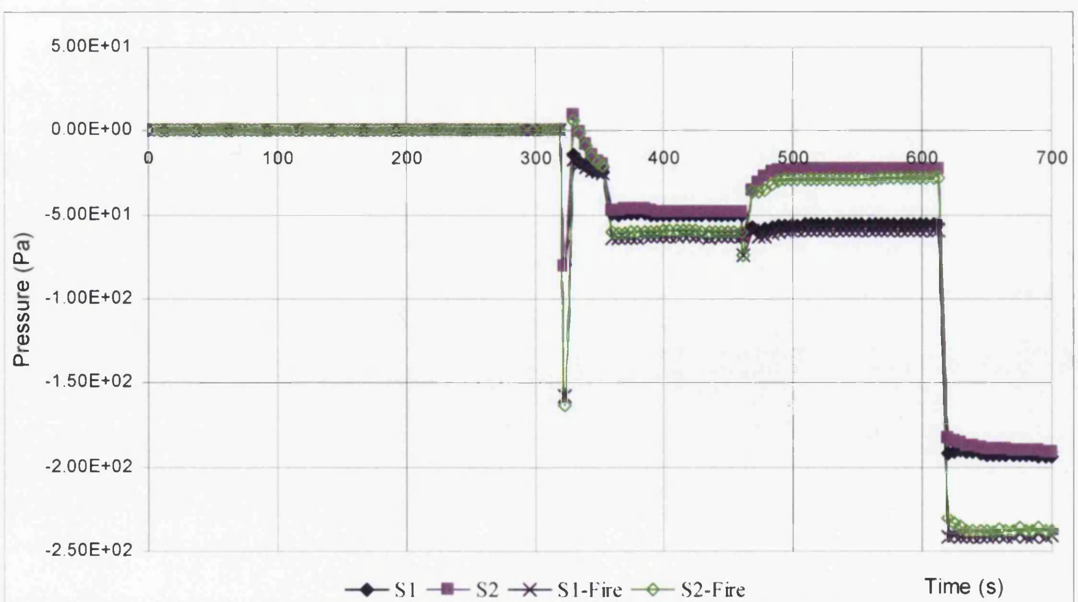



Figure 5.47 – Pressure vs time curve in smoke shaft.

During fire fighting phase, the smoke shaft is filled with high temperature smoke with the temperature observed at the fans (S2-Fire) is 160°C. This meant that extract fans with a fire resistance of 300°C can be used to extract hot smoke in this case.

The maximum pressure observed at fire fighting phase is -60Pa. This implies that the chosen extraction fans must be able to perform at this pressure without stalling as this proved to be the worst case pressure.

Concluding remarks

From these results, it can be concluded that the proposed system is acceptable and fit for purpose as the assessment criteria are met. They are:

- Condition 1 – The proposed system is capable of returning the smoke contaminated common corridor to within tenable limits 60 seconds after the stair door is partially closed behind escaping occupants.
- Condition 2 – Although conditions in the common corridor are untenable, the stair is kept free of smoke during fire fighting phase. This is acceptable as fire fighters are equipped with protective clothing and breathing apparatus. The smoke free stair provides a platform for the fire fighters to engage the fire as well as providing a safe environment for other occupants to escape when requested to so by fire fighters.

These results confirm that conditions may vary due to the location of the fire source (flat on fire). It is therefore imperative that sensitivity study is carried out for a different fire location to ensure that the proposed system is sufficiently robust to cover all identifiable fire locations. This in turn gives confidence to all stakeholders that the proposed system is effective for fire locations that have been identified and is fit for purpose.

## 5.3 Concluding remarks

Once the need for fire engineered smoke control systems is established, the proposed simulation based design procedure provides a framework for which the fire engineered solution can be designed and assessed. The framework consists of four main stages namely:

- Qualitative Design Review (QDR);
- Quantitative Analysis (QA);
- Assessment; and
- Fire authorities' comment

QDR is the first stage where information on the impending simulation is determined and identified. Information includes the building information, the proposed ventilation strategy, the potential fire scenario and the assessment approach that may be adopted.

The next stage is the QA where information identified in the QDR is used to define the computational model and the subsequent numerical analysis. The best practice in setting up the computational model (i.e. definition of boundary conditions and choosing of appropriate time step size) is also presented to the benefit of the fire engineering community. The measure to determine the accuracy of the analysis is also presented to ensure a valid prediction which then allows for an informed decision to be made.

The assessment stage is where the outputs from QA are assessed against the acceptance criteria of the chosen assessment approaches. The assessment approaches that may be used are the comparative and deterministic approaches. The former compares the performance of a fire engineered system to a code compliant system with a recommendation that the building layout be code compliant. The latter has no such restriction and uses the tenable limits as one of its acceptance criteria. The use of deterministic approach is further discussed in the case studies in Chapter 6.

Fire authorities' comment plays a significant role in that the Fire Service opinions are accounted for in the proposed CFD simulation. The reason is that the Fire Service will need to approve the proposed fire engineered system and it is therefore prudent to involve them during the consultation process.

The application of this proposed simulation based design strategy to industry challenges is presented by means of case studies in Chapter 6.

# Chapter 6 Case studies

This chapter presents the application of simulation based design procedure to industry specific challenges. Thee challenges are discussed, two of which are the design and assessment of the above ground (ventilation of protected common corridors/lobbies) ventilation systems while the other is the covered car park smoke ventilation system.

**Case Study A** – The first above ground case study is to assess/design the smoke ventilation system for a dead end common corridor of a residential high rise building. The common corridor, whose maximum travel distance exceeds the permissible 7.5m [19], is ventilated by the fire engineered mechanical extraction system. The deterministic approach is used as the basis of the assessment criteria as the dead end corridor is non code compliant and that the fire engineered ventilation system has been adopted.

**Case study B** – The second above ground case study is to assess/design the smoke ventilation system for a common corridor of a residential high rise building whose travel distance exceeds the permissible 7.5m [19]. The common corridor is to be ventilated by the fire engineered mechanical extraction system. Similar to Case Study A, the deterministic approach is used as the basis of the assessment criteria.

**Case Study C** – The covered car park study involves the assessment of the smoke ventilation system that is the mechanical extraction system with assistance from strategically positioned impulse fans. The system is intended for smoke clearance only [26] where the system is required to assist in clearing smoke from the car park once fire is under controlled (extinguished).

## 6.1 Case study A – Mechanical extract for above ground 1

### 6.1.1 Problem description

The building of interest is a residential block of apartments that consists of ground plus four storeys and includes two main escape stairs. The escape stairs are served by protected common corridors.

The common corridor of interest is the dead end corridor on the first floor of the building – highlighted as of Figure 6.1, which has a maximum travel distance to the nearest exit (fire door serving the dead end corridor and adjacent corridor) that exceeds the permissible 7.5m in accordance to ADB 2006 [19]. The dead end corridor has been proposed to be ventilated by the fire engineered mechanical extraction system. Figure 6.2 highlights the region of interest i.e. the dead end corridor.

The adjacent common corridors that serve the accommodations between the stairs have a maximum travel distance compliant to Approved Document B [19]. These code compliant common corridors are designed to be naturally ventilated and will not be further discussed.

The fire engineered mechanical system comprises of the following:

- Fire rated ceiling grille and damper connect by ductwork to extract fans;
- Run and standby extract fans rated at 300°C for 1hour positioned on the roof;
- Head of stair vent with a free area of $1m^2$;
- A fire rated builders' work shaft rising the length of the building.

Figure 6.1 – CAD Floor plan courtesy of SCS Group [95].

The fire rated builders' work shaft serves the adjacent code compliant common corridor and acts as a dedicated natural inlet for the fire engineered system when in operation. This natural smoke shaft will also be used to exhaust smoke from flats that is served by the code compliant corridor.

Inlet replacement air is provided by the smoke shaft when the system is in operation. Air is constantly drawn into the dead end corridor via the fire door that serves the extended corridor while the system is in operation. This is possible as the fire door opens in the opposite direction of escape which allows the system to hold the door open (initially by pressure difference) thus preventing excessive depressurization of the dead end corridor.

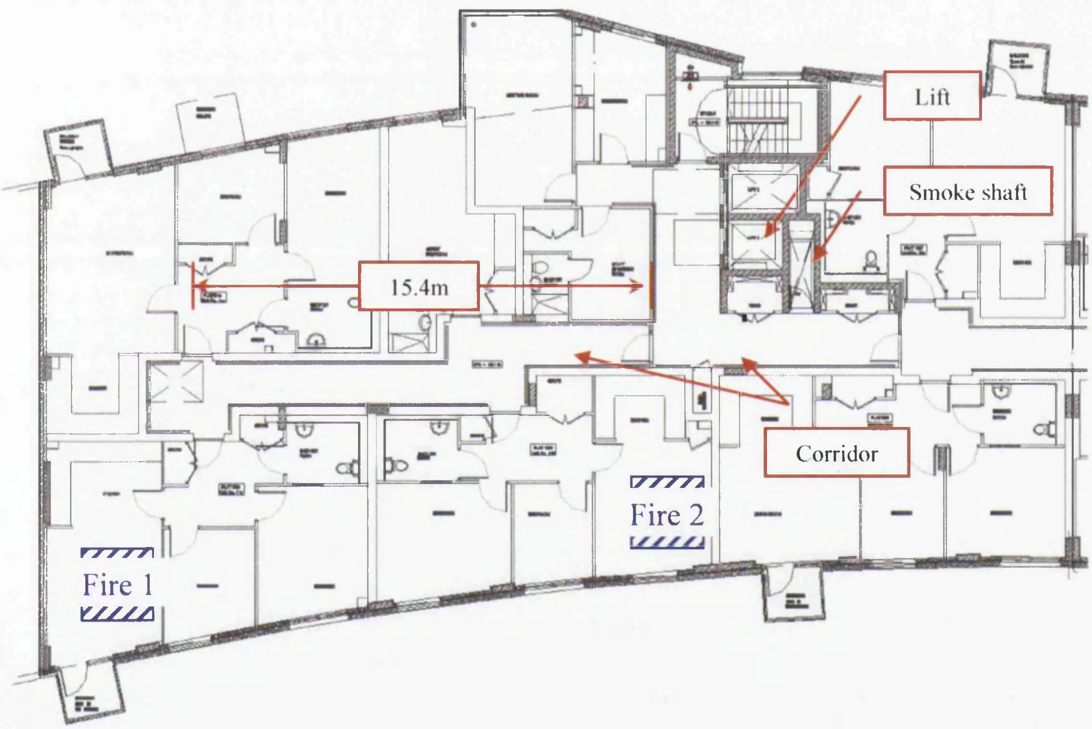



Figure 6.2 – Region of interest.

On detection of smoke in the common corridor, the lobby ventilator opening into the smoke shaft at that level and the vent at the head of stair open automatically. All vents on other levels remain closed.

Consideration is given to the operation of the fire service as this building falls within the requirements for fire fighting as detailed in BS 9999 [20].

### 6.1.2 QDR

The fire scenario at which the fire engineered mechanical extract system is assessed against is presented.

#### 6.1.2.1. Design assessment

The proposed mechanical extract system, as requested by the fire authority, is deemed acceptable when the following deterministic conditions are met.

- Tenable conditions shall be maintained within the common corridor during the escape phase i.e. the common corridor shall be relatively cleared within two minutes of the flat door being closed (300 seconds – 320 seconds).
- The stairwell shall be clear of smoke during fire fighting phase.
- The hot smoke temperature at the extract fans is less than 300°C during fire fighting.

#### 6.1.2.2. Scenarios modelled

Two fire scenarios will be modelled. They are

- Flat A – Fire assumed located as of Fire 1 in Figure 6.2.
- Flat B – Fire assumed located as of Fire 2.

These flats are chosen as their respective entrances (location of smoke ingress to corridor) are at opposite end of the dead end corridor and therefore provide a full picture throughout the dead end corridor as to the performance of the mechanical extract system when in operation.

The proposed design duties, shown in Figure 6.3, for the mechanical assisted systems are:

- Means of escape: $2.0m^3/s$
- Fire fighting: $6.0m^3/s$

The extract duties are assumed to increase linearly to aid in the stability of the simulation. The means of escape duty is assumed to increase from $0m^3/s$ to $2m^3/s$ in 5 seconds while the fire fighting duty increases from $2m^3/s$ to $6m^3/s$ in 10 seconds.

Over-depressurization of the common corridor is unlikely to occur as the pressure differential across the fire door holds the door open behind escaping occupants. The arrangement of the fire door where it opens in the opposite direction of escape (opening into the corridor instead of stairwell) assists in this aspect and acts as a pressure relieve damper during the operation of the main extract fans. This door is assumed to be held open half way until fire service arrive where it is then held fully open for fire fighters access.

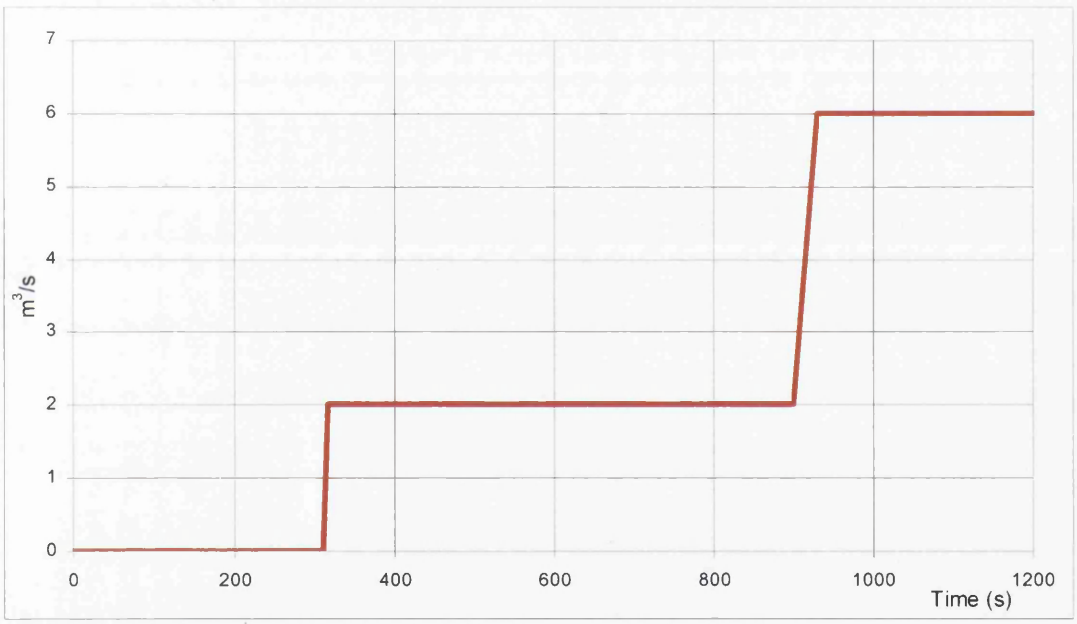



Figure 6.3 – Extract duties curve.

### 6.1.2.3. Tenable conditions

Tenable conditions as per PD 7974 part 6:2004 [34] are classified as

- temperature of less than 120°C
- Visibility of 5m for small enclosure

#### 6.1.2.4. Fire size

The volumetric fire model is used to represent the fire. A volume of 3.0m (wide) x 3.0m (length) x 1.3m (high) is used to represent the flaming region which theoretically be engulfed by the flame at peak output.

The design fire is assumed to be medium growing $t^2$ fire as for a residential building [29] and is assumed to peak at 4MW in 585 seconds. The severity of the fire is deemed suitable as a typical living room is assumed to be on fire. The fire is maintained once peaked output is reached.

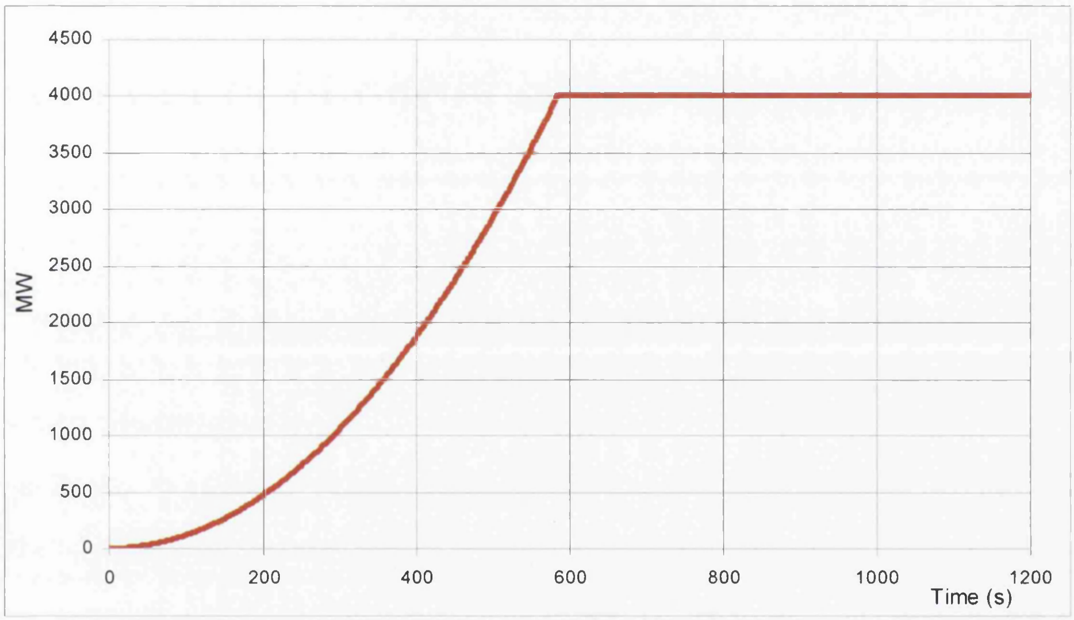



Figure 6.4 – Proposed fire curve.

#### 6.1.2.5. Smoke production

The polyurethane foam correlation, with corresponding heat of combustion of 25MJ/kg and smoke yield of 0.1kg/kg [72] is used for the production of hot gases. This is a valid assumption as upholstered furniture is mostly likely to catch fire in residential flats. Figure 6.5 gives the smoke production curve.

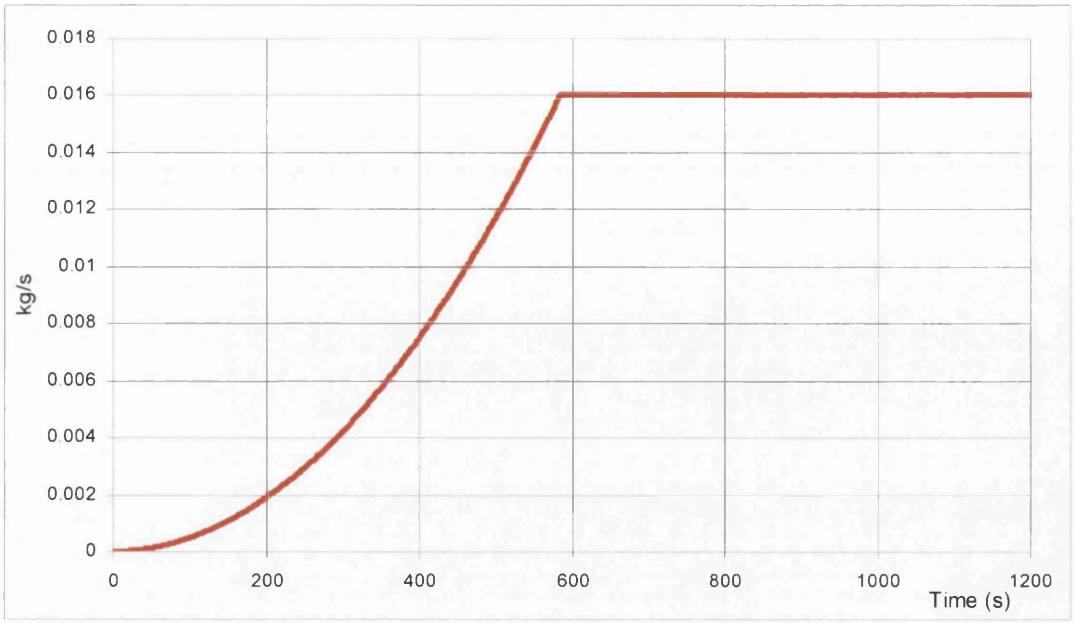



Figure 6.5 – Smoke production curve.

The smoke density, smoke absorption constant and smoke specific extinction coefficient is taken as 1800kg/m$^3$, 1200, and 7600 m$^2$/kg respectively.

### 6.1.2.6. Order of events

Based on the events stated in LDSA LFB discussion document [90] and the fire brigades' recommended time scale, the order of events are:

Means of escape

At time, t = 0 seconds the fire starts. Fire growing at design growth rate

At t = 300 seconds door to the flat on fire opens to allow for occupants escape.

At t = 310 seconds door flat door closed by successful activation of door closer. Fire door serving the extended corridor opens for occupants escape. Smoke detector is triggered by flow of hot smoke. Head of stair vent, automatic ventilator to the smoke shaft on the fire floor and ceiling damper opens/activates. Extract fans activated.

At t = 320 seconds door serving stair opens as occupants escape. Main extract fans at means of escape design extract rates.

At t = 330 seconds door serving stair is closed by the door closer as inlet air is provided by the natural smoke shaft.

Fire Fighting

At t = 900 seconds fire service arrival. Stair door opens. Extract fans switched to fire fighting duty.

At t = 930 seconds fire door fully open for fire fighting access. Extract fans at fire fighting duty.

At t = 960 seconds flat door opens for firefighting access.

At t = 1200 seconds simulation ends.

The time at which door closer is successfully activated is 10 seconds. This gives for an effective door closing mechanism and is accepted by the fire authorities as reflected in LDSA LFB discussion document [90].

The window included in the fire compartment is assumed to break as the fire reaches 1.0MW.

### 6.1.3 Quantitative analysis

This section presents the computational models and the respective boundary conditions relevant to the residential building of interest.

#### 6.1.3.1. Computational models

Two adjacent flats on the first floor of the residential building are chosen as the flats on fire for this assessment. These flats are chosen as their respective entrances (location of smoke ingress to corridor) are at opposite end of the dead end corridor and therefore provide a full picture throughout the dead end corridor as to the performance of the mechanical extract system when in operation.

The finished floor level to ceiling height of the flats is 2.3m while the ceiling to finished floor level of the storey above is 0.55m. The common corridors serving the floor have a common width of 1.5m except where otherwise stated in Figure 6.6 and Figure 6.7. These figures show the plan of the proposed mechanical assisted smoke extract model for Flat A and Flat B respectively. All doors are taken as 0.8m wide and 2.0m high. An opening of 1.0m$^2$ is provided at the head of stair to account for head of stair vent.

The geometric area of the builder's work smoke shaft is taken as 1.98m$^2$ (0.9m x 2.2m), positioned next to the lift shaft and be closed at the bottom. The ventilator has an area of 1.53m$^2$ positioned at 0.50m above the floor level and shall have a smoke/fire resistance performance at least that of an ED30S fire door [19]. The ceiling grille has a dimension of 1.2m (width) x 1.5m (length).

The effective leakage area through a single leaf door is taken as 0.01m$^2$ [18]. The effective leakage area for the lift landing door is taken as 0.06m$^2$ [18]. These leakage areas are prescribed at the foot of each corresponding doors by means of porosity boundary.

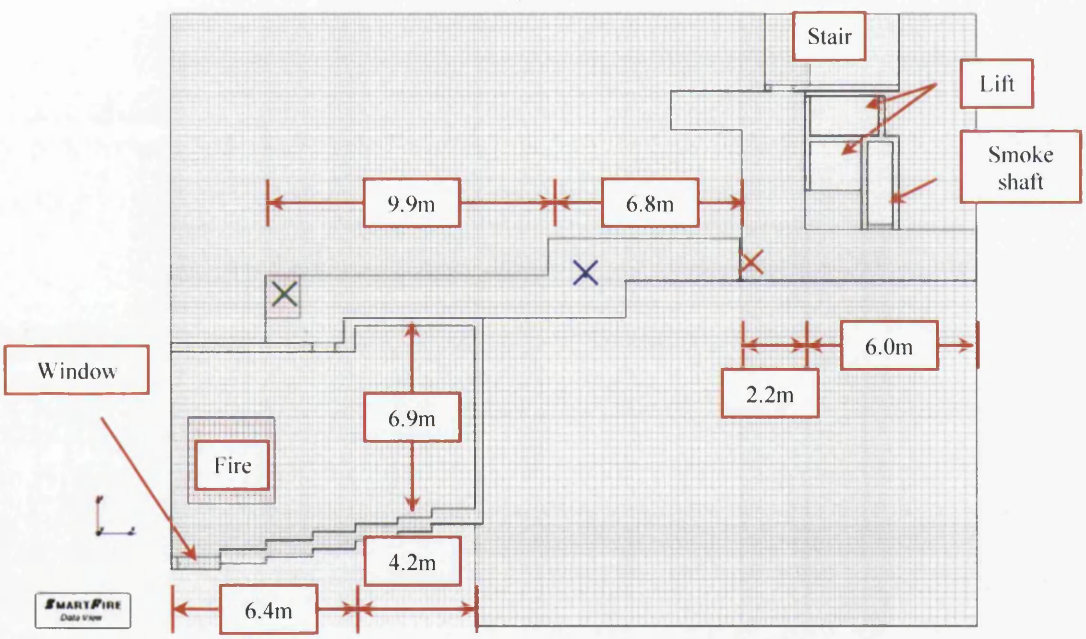



Figure 6.6 – Plan view of model for Flat A.

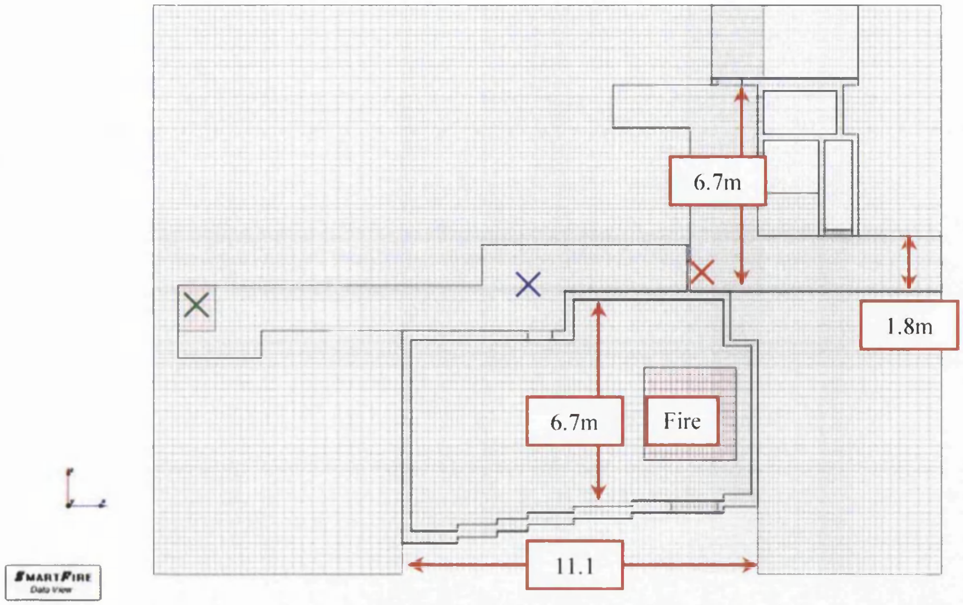



Figure 6.7 – Plan view of model for Flat B.

A 1.5m$^2$ glazed window is included in the model to account for the window breaking due to intense heat. An additional leakage area equivalent to 0.01m$^2$ (by means of porosity boundary) is prescribed at the foot of the glazed door to regulate pressure within the burning compartment prior to the glazed window being broken.

It is also assumed that fire only occur in one flat per floor and one floor per building at any one time. In the proposed system, only the doors i.e. stair door and fire flat entrance door, of the fire floor are opened and closed.

### 6.1.3.2. Boundary conditions

Adiabatic and non slip condition is assumed for the walls surrounding the corridor and fire compartment.

Atmospheric pressure condition is assumed at the head of stair vent, head of lift shaft and any area outside of the building.

Porosity boundary condition, position at the foot of each door, is prescribed to gaps predominately present at the foot of a door. The porosity boundary allow for air to either enter or escape the corridor without modelling the details within the gaps. The effective leakage areas are taken as per BS 12101-6:2005 [18]. The porosity boundaries for single leaf doors are 0.8m wide and 0.1m high with an effective leakage area of 0.01m$^2$ (porosity factor of 0.125)

Porosity boundary prescribed at the foot of the window is 1.5m wide and 0.1m high with an effective leakage area of 0.01m$^2$ (the porosity factor is 0.0667). This is to account for all leakages around the window and walls of the fire compartment.

Porosity boundary is again used to represent the effective leakage area due to the lift door. The porosity boundary for the lift door, position at the foot of the door, is 0.8m wide and 0.1m high with an effective leakage area of 0.06m$^2$ (porosity factor is 0.75).

Outlet boundary condition is prescribed to regions representing outside of the building envelop and any extended regions that would otherwise be automatically created by SMARTFIRE to allow for the flow across an opening to develop fully.

The modelling domain around the window will be extended to 2.0m to allow for sufficient room for the flow around the broken window to develop.

Wind effects are not considered.

#### 6.1.3.3. Radiation

The six-flux model is used for this simulation for the fire is large and is burning in a confined room. In addition the far field temperature is better predicted especially at the extract fans where they are in constant contact with high temperature smoke. Wall emissivity, absorption at 700K, and absorption at 1380K is taken as 0.8, 3.5 m$^{-1}$ and 7.0 m$^{-1}$ respectively.

#### 6.1.3.4. Cell budget

The number of cells used for mechanical assisted extract system is:

- Flat A: 584640 at 0.20m (length) x 0.21 (wide) x 0.21 (height).

- Flat B: 516672 at 0.21m (length) x 0.20m (wide) x 0.21 (height).
- Mesh independence study for Flat A: 796290 at 0.15m (length) x 0.15m (wide) x 0.17 (height).
- Mesh independence study for Flat A: 787200 at 0.16m (length) x 0.15m (wide) x 0.17 (height).

#### 6.1.3.5. Turbulence

SMARTFIRE v4.1 uses the buoyancy modified k-epsilon turbulence model and is part of the RANS turbulence model family.

#### 6.1.3.6. Air properties

| | |
|---|---|
| Ambient temperature | = $15^0$C |
| Viscosity | = 1.5682 x $10^{-5}$ Pa s |
| Density of air | = 1.1774 kg/$m^{3s}$ |

#### 6.1.3.7. Simulation parameters

| | |
|---|---|
| Time step size | = 5 seconds |
| Sweeps per time | = 50 |
| Total simulation time | = 1200 seconds |
| Tolerance | = $1x10^{-6}$ |
| Initial pressure | = 101325 Pa |
| Initial temperature | = 15.15 $^0$C = 288.15 K |

The 5s time step size is chosen as the simulation is highly stable except during the intervals where doors are opened and closed. At these intervals, the time step size is refined to 0.01s to capture the changes and ensure stability of the solution.

### 6.1.4 Assessment

#### 6.1.4.1. General

This section presents the analytical assessment of the mechanical extraction system performance. Similar to Chapter 4, the basis of this discussion is presented by line graphs through several strategically identified points shown in Figure 6.6 and Figure 6.7. Table 6.1 summarises the points at their respective coordinates with respect to each model.

| Reference (Colour) | Symbols | Dimension (Flat A) | Dimension (Flat B) |
|---|---|---|---|
| Corridor (Blue) | C1 | x=14.5 y=0.6 z=12.3 | x=12.2 y=0.6 z=9.4 |
| | C2 | x=14.5 y=1.2 z=12.3 | x=12.2 y=1.2 z=9.4 |
| | C3 | x=14.5 y=1.8 z=12.3 | x=12.2 y=1.8 z=9.4 |
| Fire door (Red) | D1 | x=20.3 y=0.6 z=12.7 | x=17.9 y=0.6 z=9.8 |
| | D2 | x=20.3 y=1.2 z=12.7 | x=17.9 y=1.2 z=9.8 |
| | D3 | x=20.3 y=1.8 z=12.7 | x=17.9 y=1.8 z=9.8 |
| Ceiling vent (Green) | V1 | x=3.9 y=2.5 z=11.6 | x=1.4 y=2.5 z=8.7 |

Table 6.1 – Location of points of interest

#### 6.1.4.2. Results

<u>Dead end corridor</u>

The smoke plot shown in Figure 6.8 suggests that conditions in the dead end corridor for both Flat A and Flat B models are relatively free of smoke except at intervals where the flat doors are opened i.e. means of escape period (300 – 310 seconds) and fire fighting phase (900 to 1200 seconds).

At 300 seconds, smoke egress into the dead end corridor as the flat doors in both flats open as occupants made their escapes. Conditions peaked at 310 seconds as the flat doors are closed by the successful activation of their respective door closer. Temperature plots shown in Figure 6.9 highlight this observation where the temperature peaked at 340K in Flat A and 440K in Flat B.

Prior to 300 seconds, Figure 6.9 and Figure 6.10 show that there is a steady increase in the temperature and pressure within the dead end corridor of the two models. A temperature rise of 15°C (305K) and pressure increase of 9Pa respectively. These observations are due to the hot smoke leaking into the dead end corridor via leakages prescribed at the foot of the flat doors. The amount of smoke that leaked into the dead end corridor is sufficient to reduce the visibility to less than 3m.

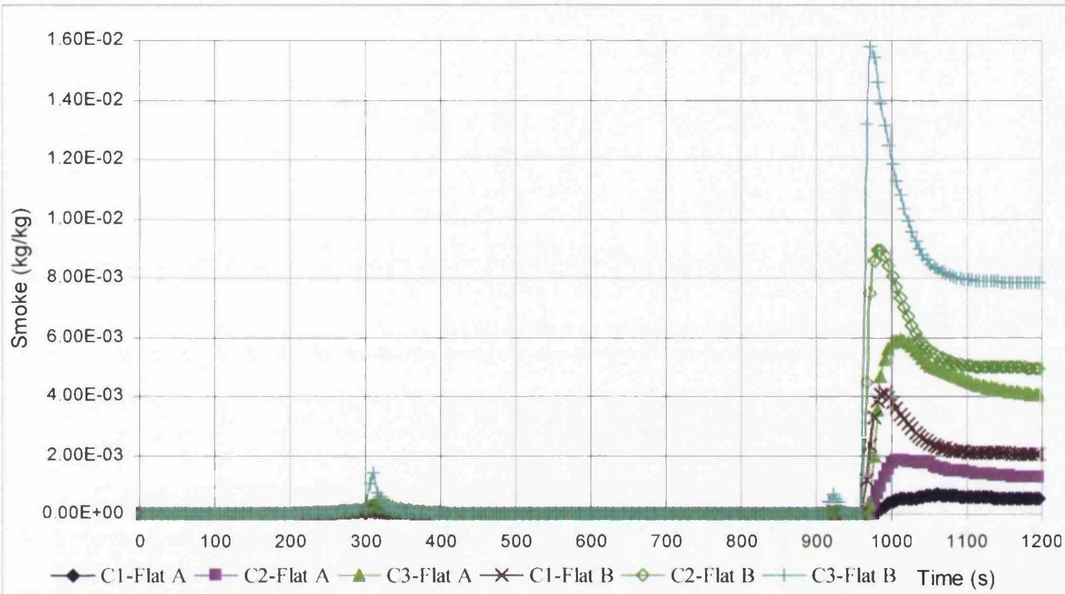



Figure 6.8 – Smoke vs time plots in the dead end corridor.

Conditions in the dead end corridor of both models after their respective flats doors are closed have improved significantly and by 400 seconds, the visibility is calculated to have exceeded 5m while temperature are observed to have return to ambient. No smoke is seen leaking into the dead end corridors of both models at this point. This continues until 900 seconds at which fire fighters arrived at the fire floor. The pressure in both models at this interval is seen to be similar at -7Pa. This implies that the pressure is sufficiently low and has prevented smoke from leaking into the dead end corridors.

These observations confirmed that Condition 1 of the acceptance criteria has been met.

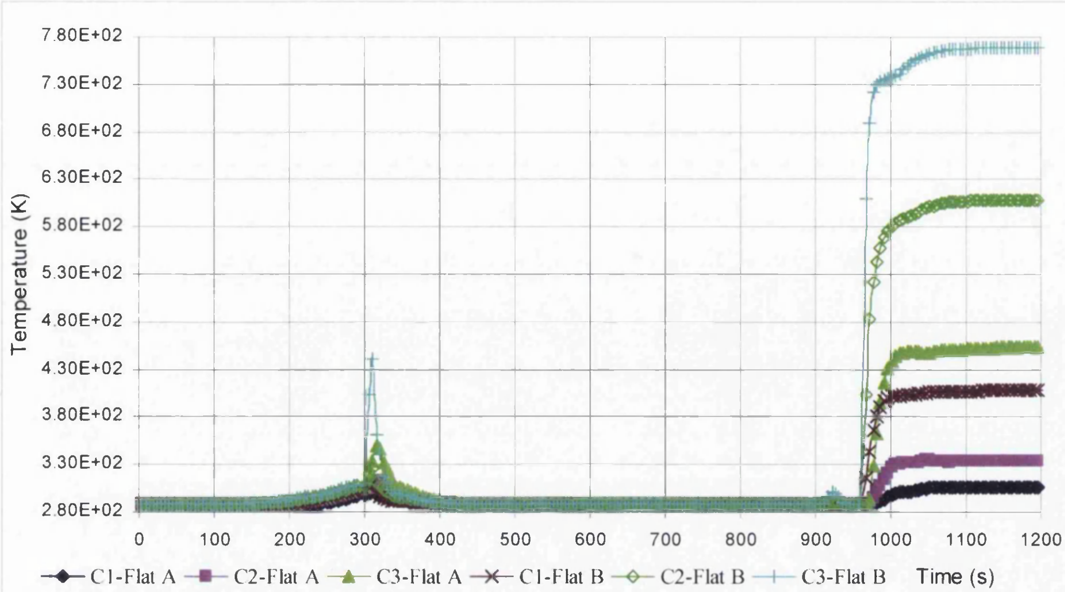



Figure 6.9 – Temperature vs time plots in the dead end corridor.

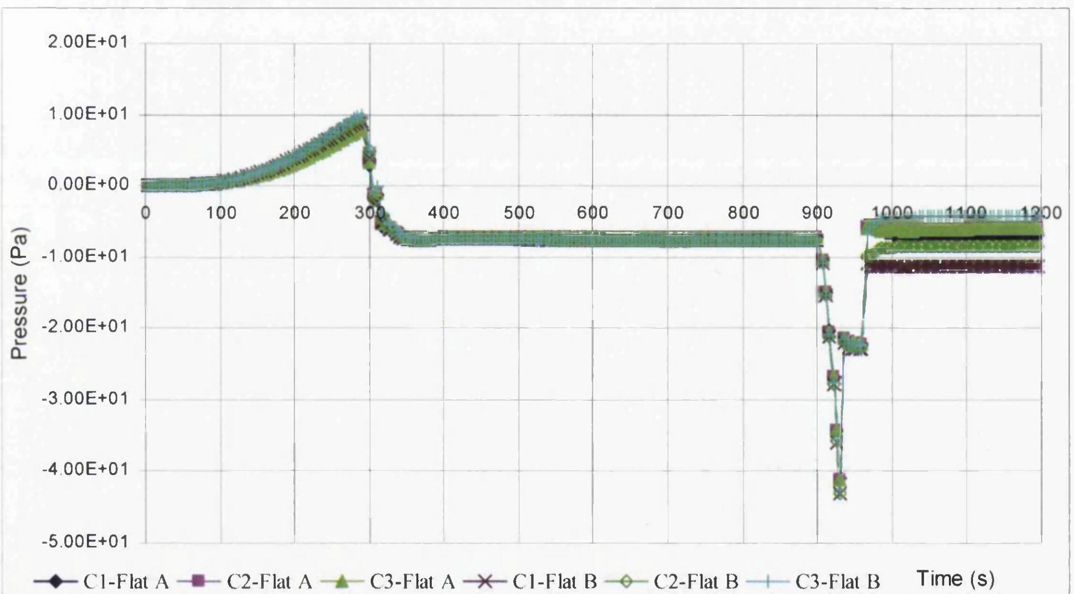



Figure 6.10 – Pressure vs time plots in the dead end corridor.

As fire fighters arrive on the fire floor i.e. 900 seconds, the system is assumed to have switched (In actual fire scenario, this is under the discretion of the fire officer) to fire fighting mode where the extract duty is increased from $2m^3/s$ to $6m^3/s$. This increase in extract duty results in a sudden drop in pressure to -44Pa as the fire door to the dead end corridor is yet to be fully open by the fire fighters. This highly negative pressure actively draws smoke from the respective flats and is the reason behind the small rise in smoke and temperature plots.

Conditions improve significantly once the fire door is fully open by the fire fighters. The pressure at this stage rises to -22Pa with traces of smoke drawn into the dead end corridor but with little effects to the conditions of the dead end corridor.

At 960 seconds, the flat doors open to allow hot smoke to spill into their respective dead end corridors thus making the corridors untenable. This is shown by the sudden increase in smoke and temperature. The conditions eventually stabilised to a stratified smoke layer. Flat B is seen to be the more onerous of the two models because the point of interest is taken in front of the flat entrance. The pressure has risen to -10Pa.

Ceiling vent

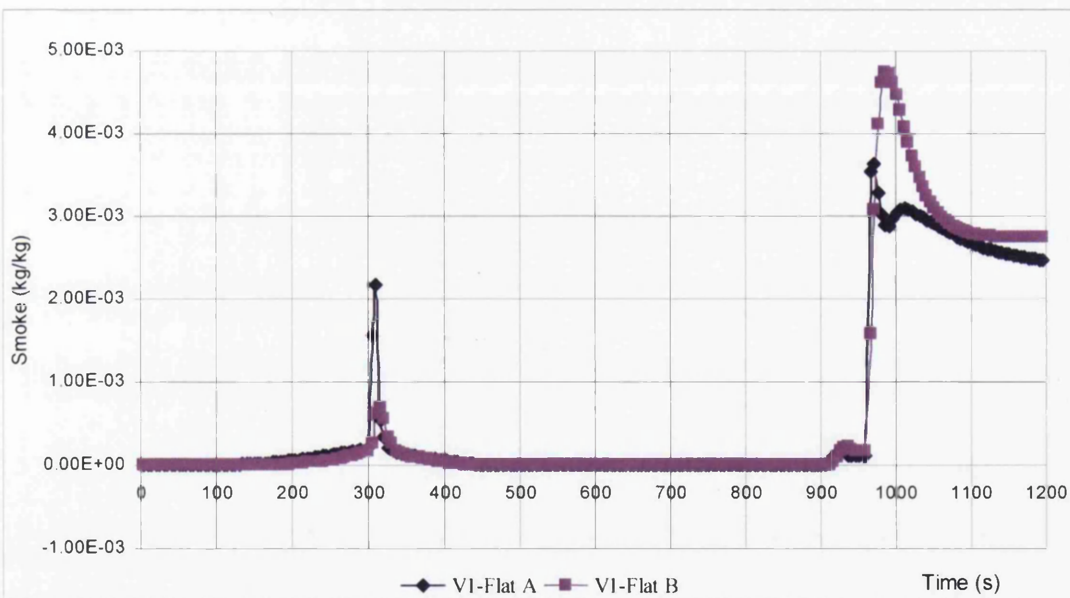



Figure 6.11 – Smoke vs time plots at ceiling vent.

Conditions in the ceiling vents of the two models mirror that of the dead end corridor. Prior to 310 seconds, smoke that has leaked into the corridor can be seen in the vents as it has yet be vented - Figure 6.11. The temperature (Figure 6.12) and pressure (Figure 6.13) in the vents are similar to those of the dead end corridor.

As the flat doors are opened for occupant escape i.e. 300 seconds, the smoke and temperature values at the ceiling for the Flat A model are greater than those observed in the Flat B model. The reason behind this observation is because of the location of the flat entrances with respect to the point identified. The model Flat A is nearest to the ceiling vent which implies that hot smoke has little time to entrain fresh air before it is exhausted. This lack of entrainment also explains the high temperature observed. In contrast, the Flat B model is furthest away from the ceiling vent and hot smoke from the flat has time and space to entrain fresh air before it is exhausted. The entrainment lowers the temperature of the hot smoke and is therefore less harsh to the extract fans.

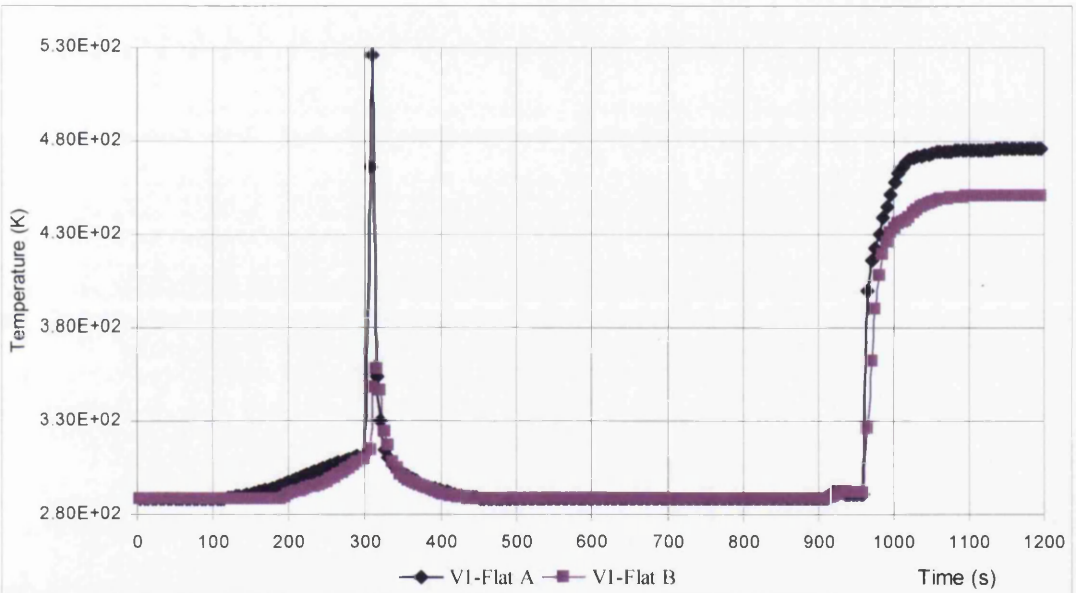



Figure 6.12 – Temperature vs time plots at ceiling vent.

In the period after the flat doors are closed behind escaping occupants, conditions in the ceiling vents in both models have subsequently returned to ambient conditions where no smoke is seen extracted until 900 seconds. This is because no smoke has leaked into the dead end corridor in both models until extract fans are switched to fire fighting mode.

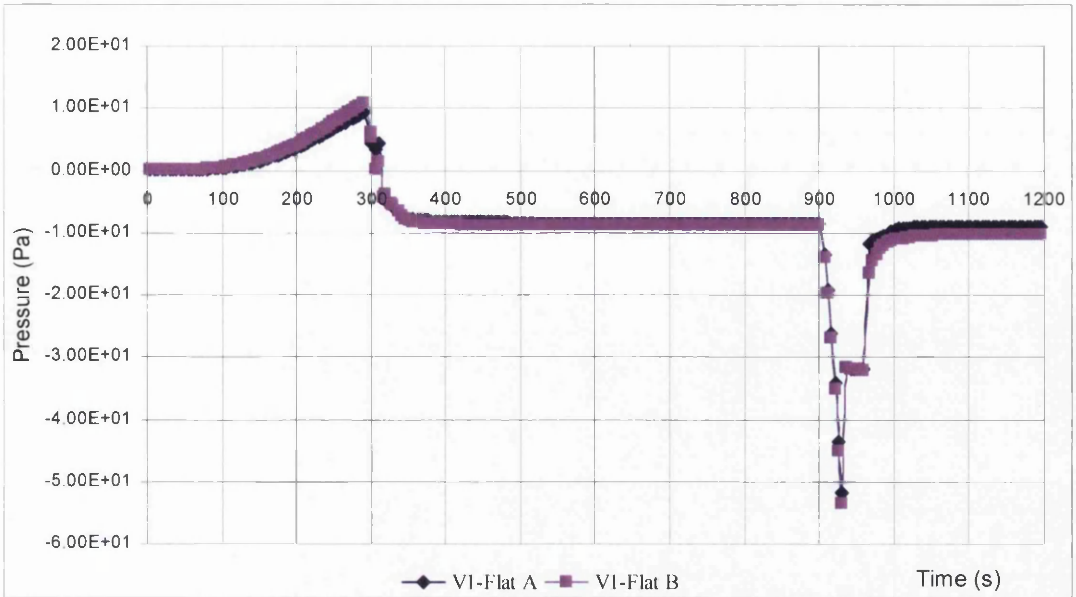



Figure 6.13 – Pressure vs time plots at ceiling vent.

During fire fighting phase, the value of smoke extracted is similar in the later part of the simulation has the results stabilised. However, the temperature varies as much as 25° with the Flat A model the higher of the two models. Since the maximum temperature observed in these two models is 530K (257°C), the extract fan fire resistance rating of 300°C is suitable for use and therefore meets Condition 3 of the acceptance criteria. The maximum pressure observed is -52Pa.

Fire door

Figure 6.14 to Figure 6.16 shows the conditions of code compliant corridor at the fire door. These figures show that very small traces of smoke enters the code compliant corridor as the fire doors are open for occupant escape. Although the hot smoke does increase the local temperature by 9°C, the visibility is not affected. This code compliant corridor therefore remains tenable for the duration of the fire event.

During fire fighting phase, a very small increase in temperature, 0.5°C, is observed at the fire doors. This may be due to the radiative heat from the hot smoke plume. The pressure is observed as -3Pa with the pressure difference across the fire door calculated as -8Pa. This suggests that the pressure difference is capable of preventing smoke from flowing into the code compliant corridor thus protecting the stair from smoke. Hence, this confirms that Condition 2 has been met.

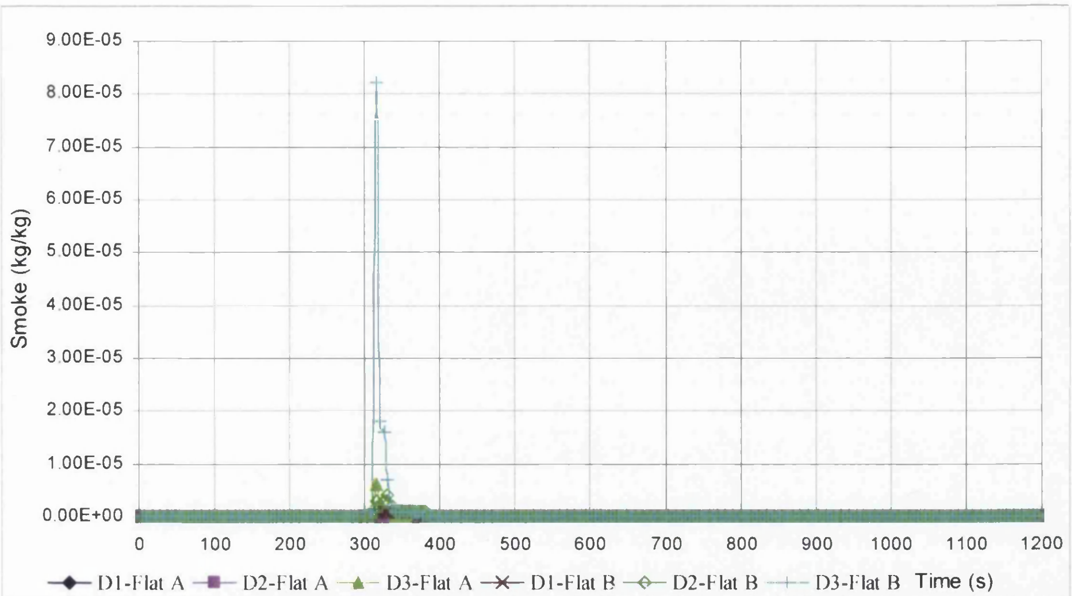



Figure 6.14 – Smoke vs time plots at fire door.

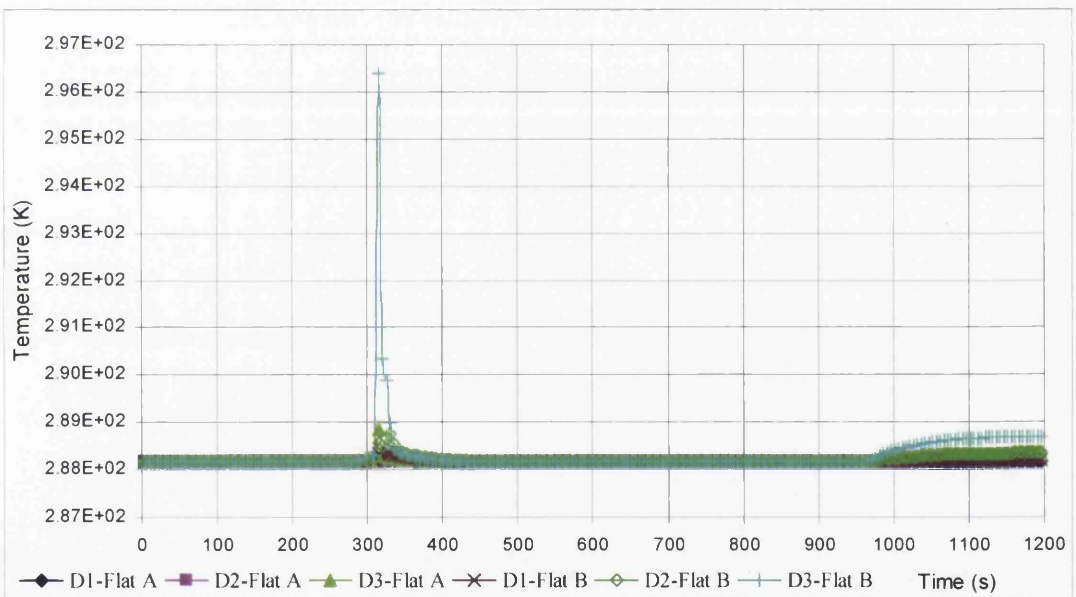



Figure 6.15 – Temperature vs time plot at fire door.

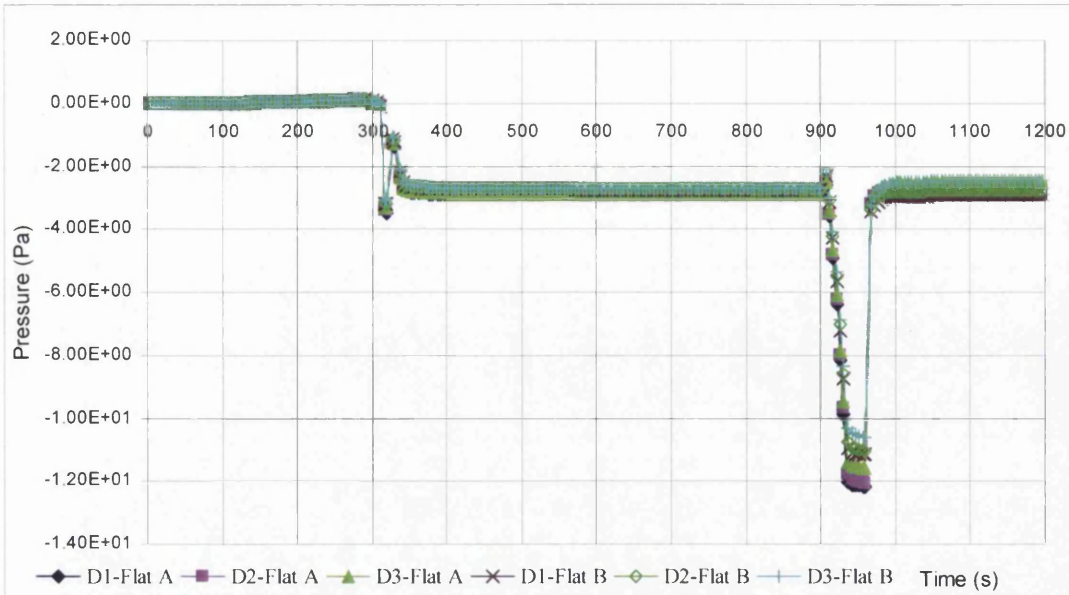



Figure 6.16 – Pressure vs time plots at fire door.

### 6.1.4.3. Mesh independence study

Like all prudent CFD analysis, a mesh independent study is carried out for both the models. Using the same points of interest as before, the mesh independent study is presented through the smoke mass fraction as this is a conserved scalar. The cell budgets of the refined mesh models, as stated in Section 6.1.3.4, are:

- Mesh independence study for Flat A: 796290 at 0.15m (length) x 0.15m (wide) x 0.17 (height).
- Mesh independence study for Flat A: 787200 at 0.16m (length) x 0.15m (wide) x 0.17 (height).

<u>Flat A model</u>

Figure 6.17 to Figure 6.19 show that the refined mesh model is comparable to the initial model. Detailed assessment found that the percentage errors between the two models are calculated as 3%. This error is sufficiently small and is therefore acceptable. Hence the solution is said to have converged to a mesh independent solution.

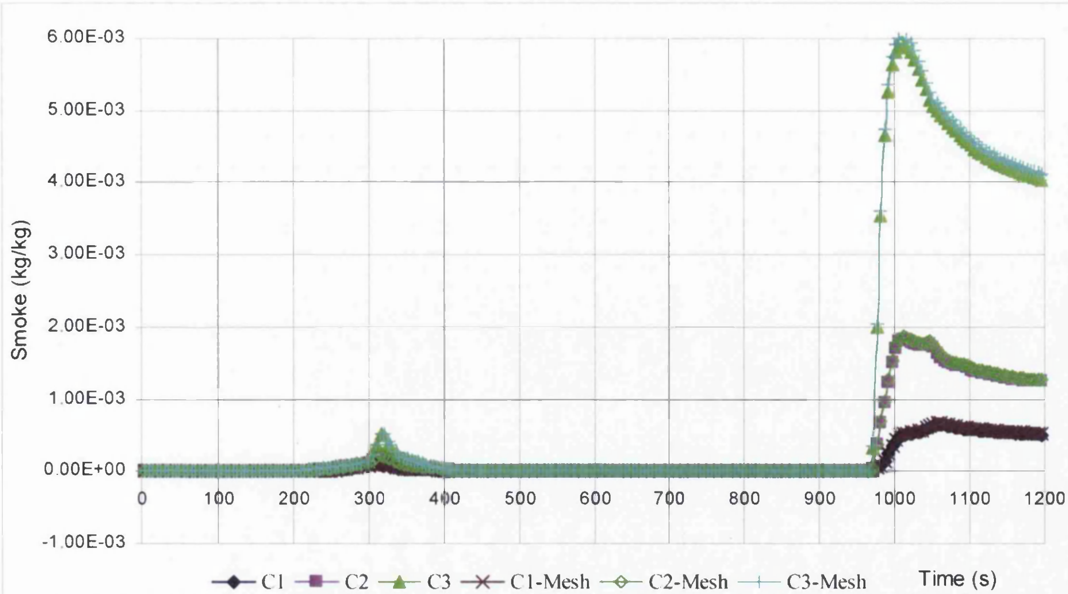



Figure 6.17 – Smoke plots in the dead end corridor.

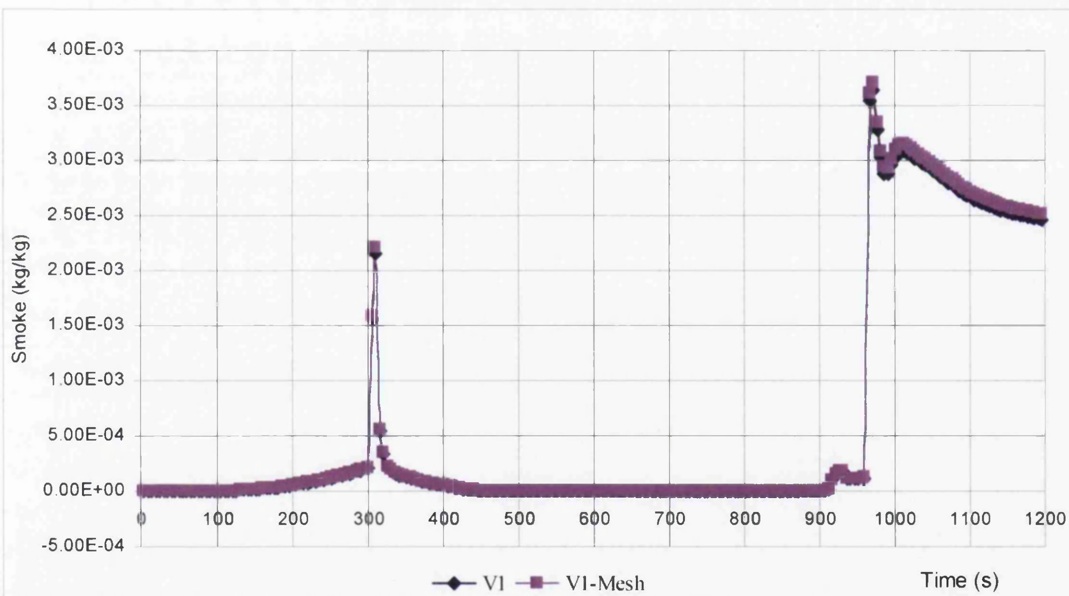



Figure 6.18 – Smoke plots in the ceiling vent.

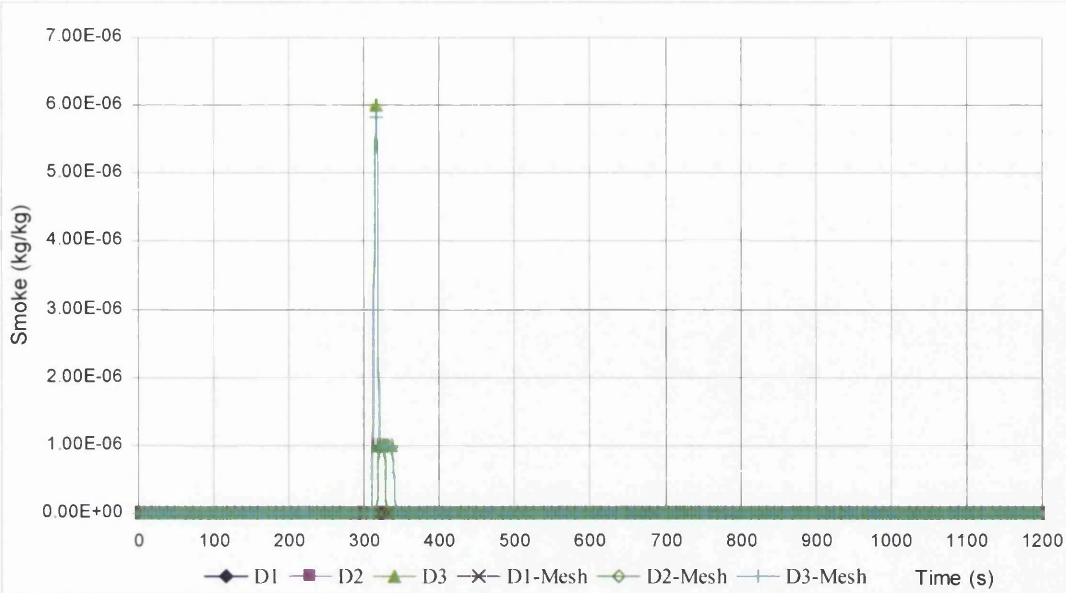



Figure 6.19 – Smoke plots at the fire door.

Flat B model

Similarly, Figure 6.20 to Figure 6.22 show that the refined mesh model for Flat B is again comparable to the initial model. The errors due to the mesh refinement are calculated as 5% which is sufficiently small and is therefore acceptable. The solution is said to have converged to a mesh independent solution.

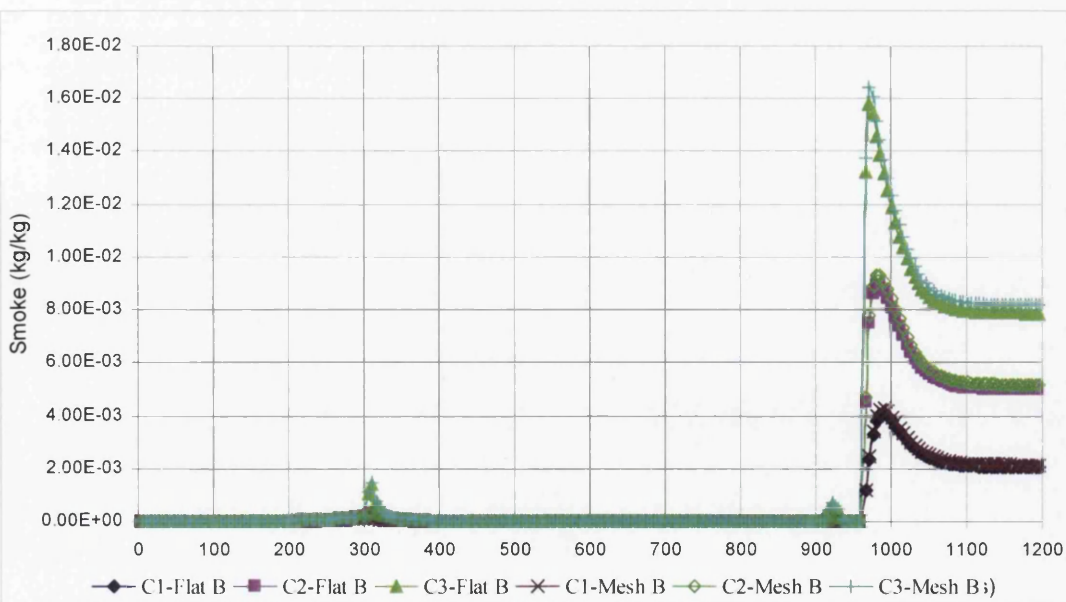



Figure 6.20 – Smoke plot in dead end corridor.

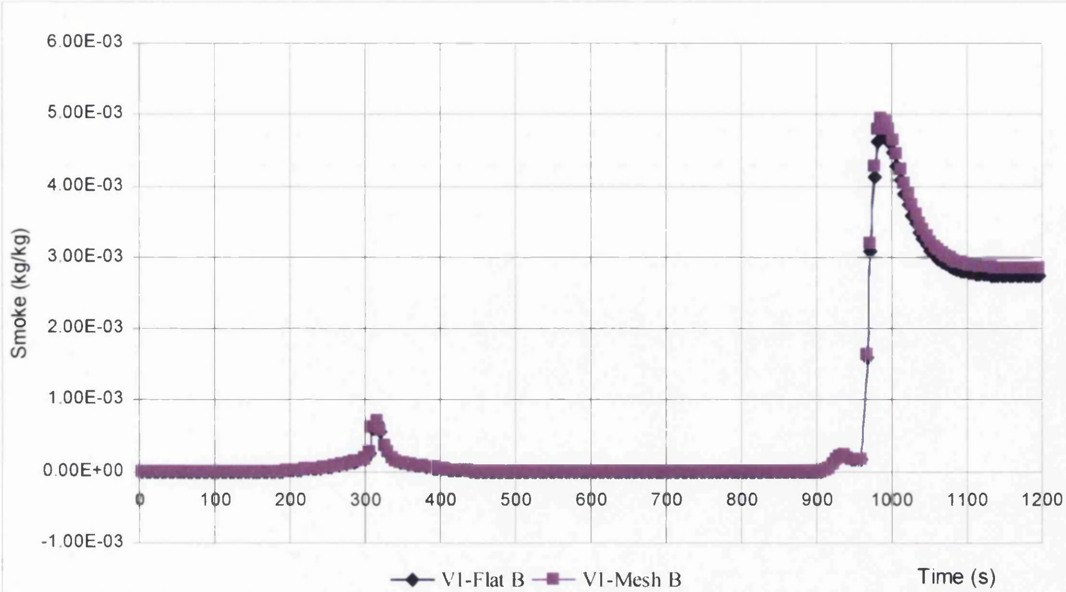



Figure 6.21 – Smoke plot in the ceiling vent.

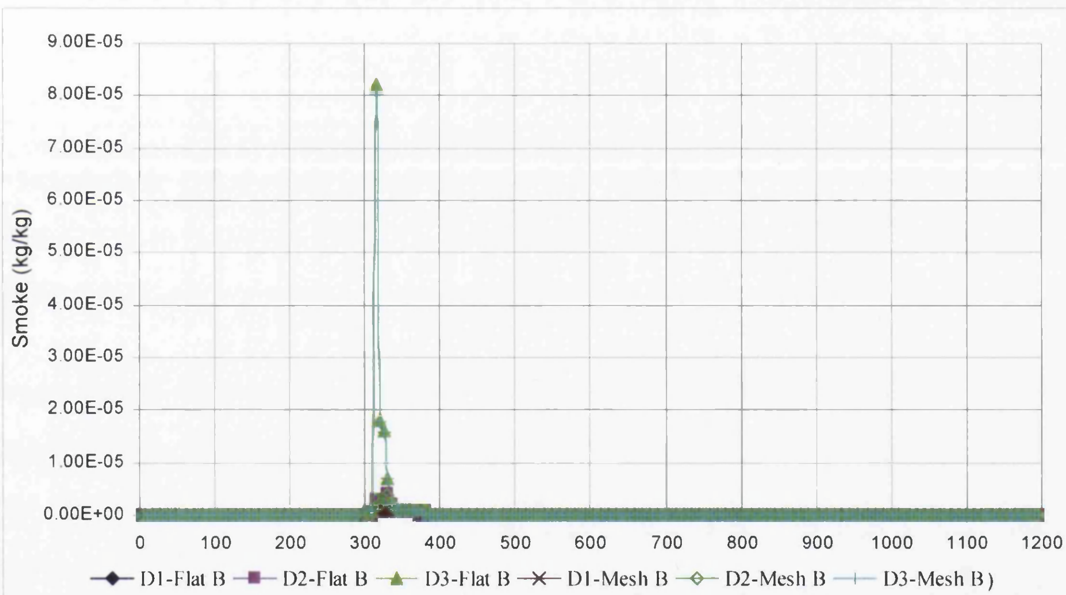



Figure 6.22 – Smoke plot at the fire door.

### 6.1.5 Conclusions

These results show that conditions within the common corridors meet the design assessment throughout the simulation. It can therefore be concluded that the proposed mechanical extract system, based on the design flow rates are acceptable and is fit for purpose:

- Means of escape: $2.0m^3/s$

- Fire fighting: $6.0m^3/s$

The system is able to effectively extract the hot smoke released while a person escape and rapidly, within 100 seconds, restore the corridor to ambient conditions.

Over-depressurization of the common corridor is avoided with the fire door acting as a pressure relief damper. The fire door, once opened is kept open to the stated arrangement behind the escaping occupant due to the pressure difference across the stair door.

In addition, the mesh independence studies have confirmed that solutions have converged to a mesh independent solution.

## 6.2 Case study B – Mechanical extract for above ground 2

### 6.2.1 Problem description

The building of interest is a residential block of apartments that consists of ground plus five storeys and includes one main escape stairs. The escape stairs are served by a protected common corridor.

The common corridor (also referred to as extended corridor) is on the first floor of the building – highlighted as of Figure 6.23, which has a maximum travel distance to the nearest exit (i.e. the stair door) of 26m that exceeds the permissible 7.5m in accordance to ADB 2006 [19]. The extended corridor has been proposed to be ventilated by the fire engineered mechanical extraction system. Figure 6.2 highlights the region of interest i.e. the extended corridor.

The adjacent common corridors that serve the rest of the building have a maximum travel distance compliant to Approved Document B [19]. These code compliant common corridors are designed to be naturally ventilated and will not be further discussed.

The proposed fire engineered mechanical system comprises of the following:

- A fire rated builders' work shaft rising the length of the building;
- Fire rated damper/door ventilator opening into the smoke shaft at each floor that requires protection;
- Run and standby extract fans rated at 300°C for 1hour positioned at the head of the smoke shaft;
- A 1.5m$^2$ Automatic Opening Vent (AOV) on each floor for dedicated inlet;
- Head of stair vent with a free area of 1m$^2$.

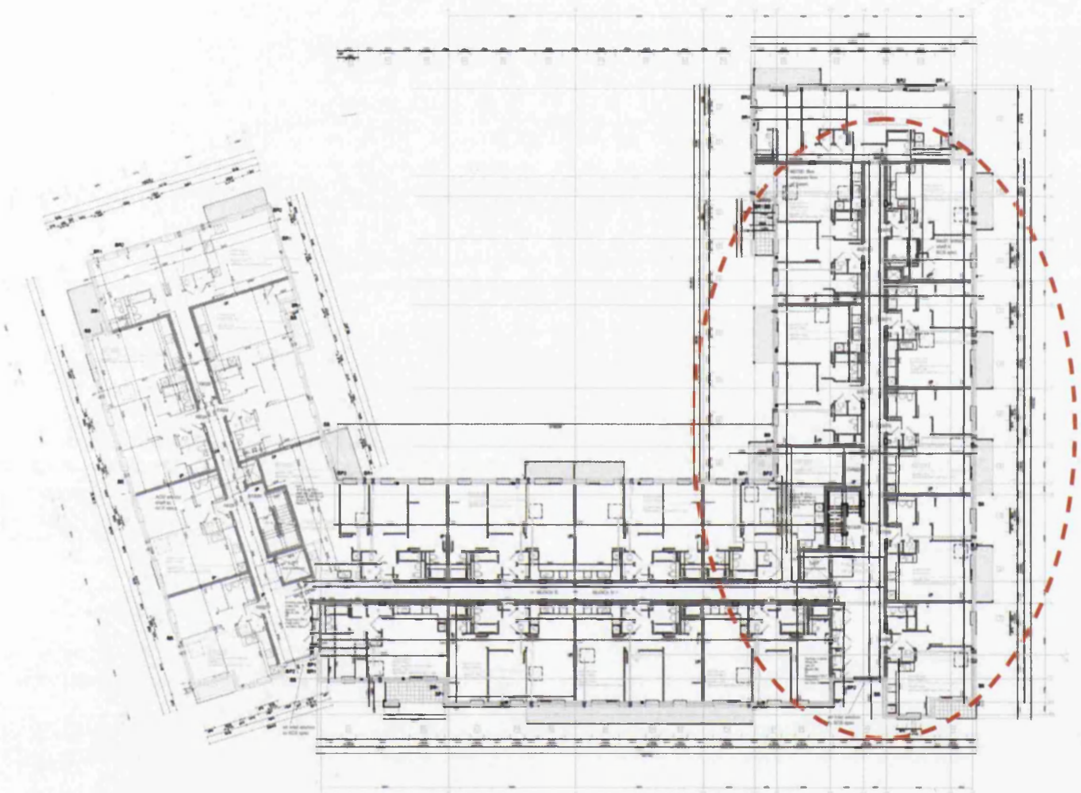


Figure 6.23 – CAD Floor plan courtesy of SCS Group [95].

Inlet replacement air is provided by the AOV. This prevents excessive depressurisation in the common corridor which, in the event of over-depressurization, prevents the stair door from opening in means of escape mode.

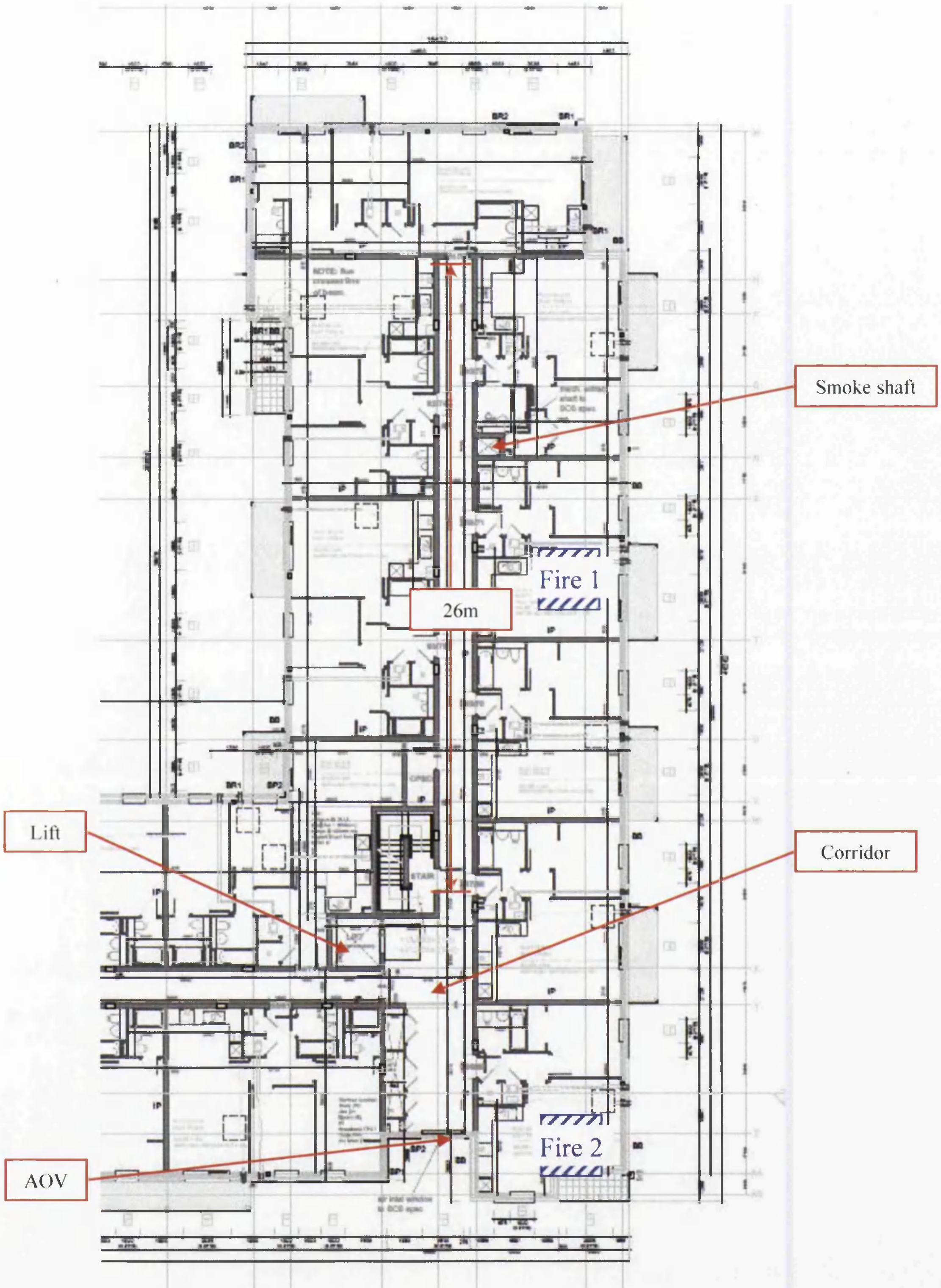



Figure 6.24 – Region of interest.

On detection of smoke in the extended common corridor, the AOV and the automatic opening damper/grill vent opening into the mechanical smoke shaft at that level open automatically. All vents on other levels remain closed.

Consideration is given to the operation of the fire service as this building falls within the requirements for fire fighting as detailed in BS 9999 [20].

### 6.2.2 QDR

The fire scenario at which the fire engineered mechanical extract system is assessed against is presented. As the fire engineered solution is intended for a residential building, the parameters identified here is broadly similar to those identified in Case Study A. The same assessment approach is also adopted.

#### 6.2.2.1. Design assessment

The proposed mechanical extract system, as requested by the fire authority, is deemed acceptable when the following deterministic conditions are met.

- Tenable conditions shall be maintained within the common corridor during the escape phase i.e. the common corridor shall be relatively cleared within two minutes of the flat door being closed (300 seconds – 320 seconds).
- The stairwell shall be clear of smoke during fire fighting phase.

#### 6.2.2.2. Scenarios modelled

Two fire scenarios will be modelled. They are

- Flat C – Fire assumed located as of Fire 1 in Figure 6.24.
- Flat D – Fire assumed located as of Fire 2.

These flats are chosen as their respective entrances are at opposite end of the extended corridor and therefore provide a full picture throughout the corridor as to the performance of the mechanical extract system when in operation.

The proposed design duties, shown in Figure 6.25, for the mechanical assisted systems are:

- Means of escape: $2.0m^3/s$
- Fire fighting: $6.0m^3/s$

The extract duties are assumed to increase linearly to aid in the stability of the simulation. The means of escape duty is assumed to increase from 0m$^3$/s to 2m$^3$/s in 5 seconds while the fire fighting duty increases from 2m$^3$/s to 6m$^3$/s in 10 seconds.

The stair door is free to close by the door closer. The 1.5m$^2$ AOV at each floor level provides a constant source of air inlet which regulates the pressure within the extended corridor avoid over depressurization.

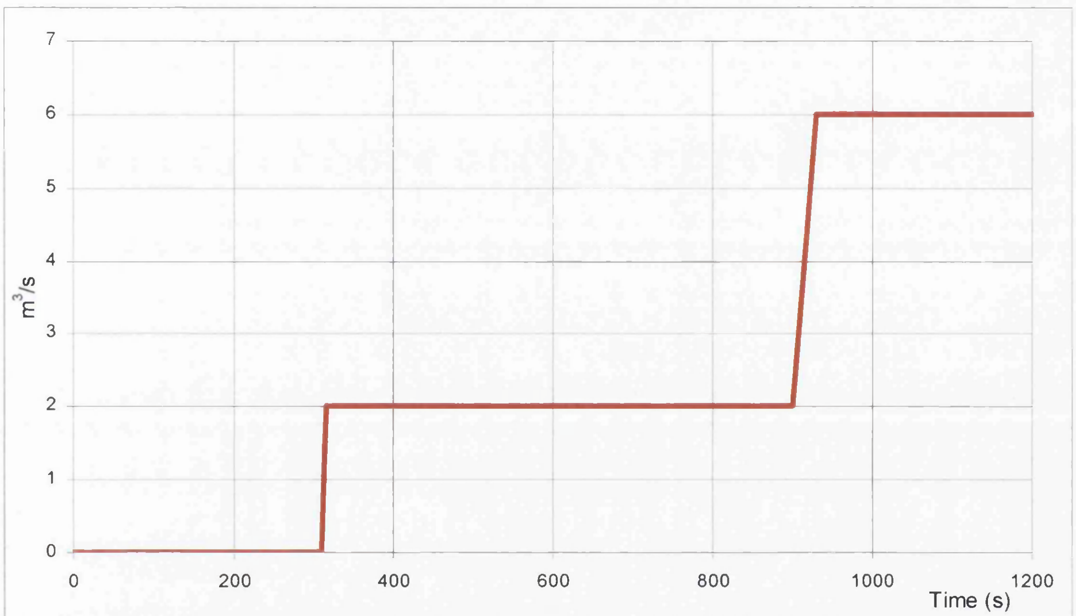



Figure 6.25 – Extract duties curve.

#### 6.2.2.3. Tenable conditions

Tenable conditions as per PD 7974 part 6:2004 [34] are classified as

- temperature of less than 120$^o$C
- Visibility of 5m for small enclosure

#### 6.2.2.4. Fire size

Similar to Case Study A, the volumetric fire model is used to represent the fire. A volume of 3.0m (wide) x 3.0m (length) x 1.3m (high) is used to represent the flaming region which theoretically be engulfed by the flame at peak output.

The design fire is assumed to be medium growing $t^2$ fire as for a residential building [29] and is assumed to peak at 4MW in 585 seconds. The severity of the fire is deemed suitable as a typical living room is assumed to be on fire. The fire is maintained once peaked output is reached.

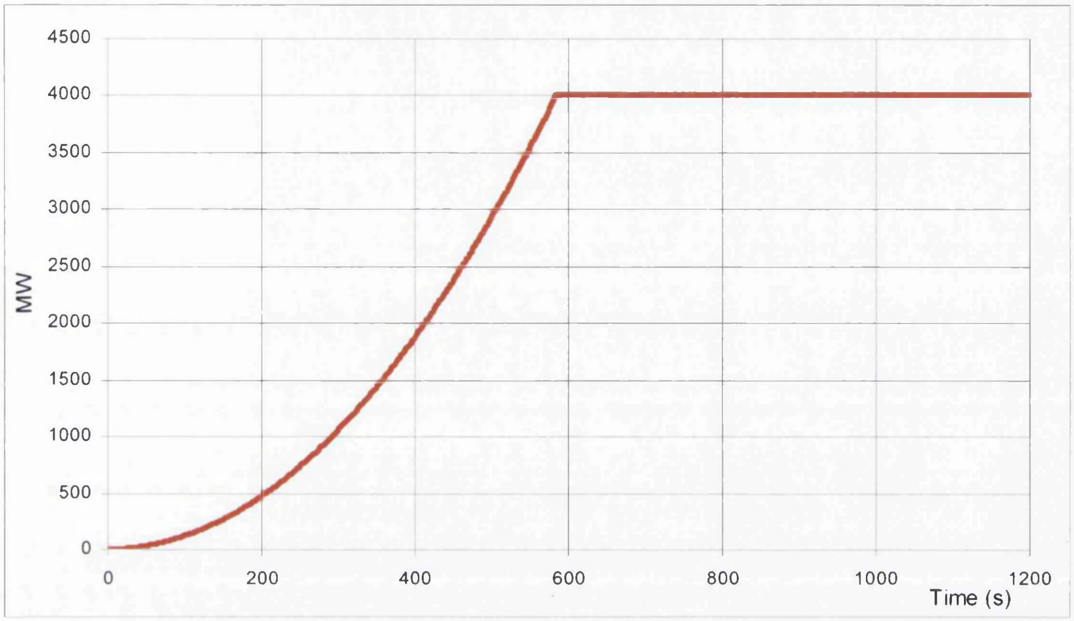



Figure 6.26 – Proposed fire curve.

### 6.2.2.5. Smoke production

Similar to before, assuming that upholstered furniture in a residential flat is on fire, the polyurethane foam correlation is used. The corresponding heat of combustion of 25MJ/kg and smoke yield of 0.1kg/kg [72] is used for the production of hot gases. Figure 6.27 gives the smoke production curve.

The smoke density, smoke absorption constant and smoke specific extinction coefficient is taken as 1800kg/m$^3$, 1200, and 7600 m$^2$/kg respectively.

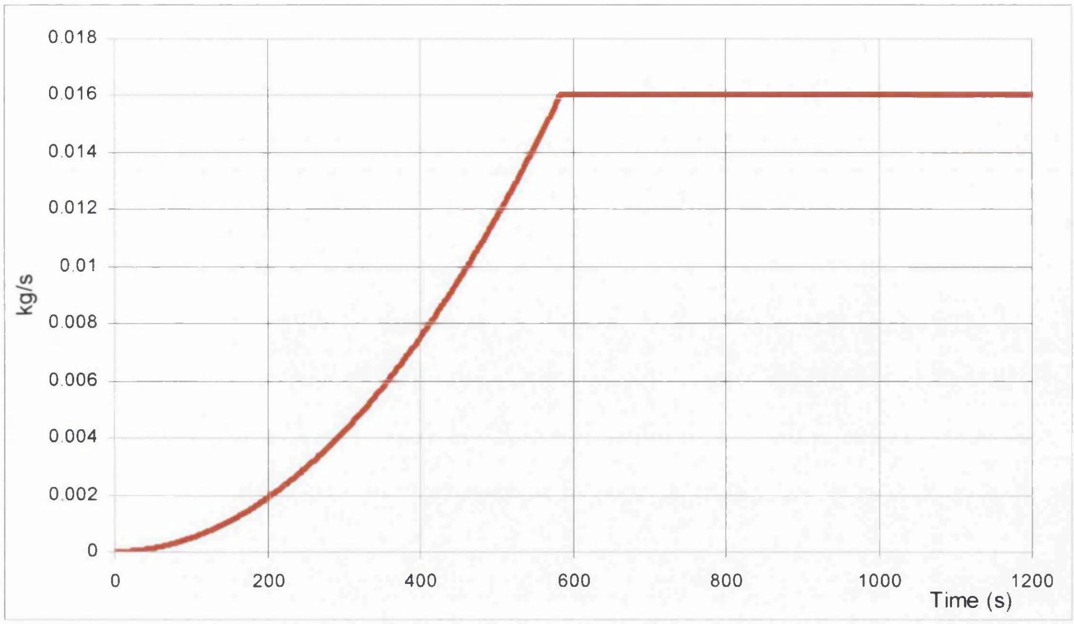



Figure 6.27 – Smoke production curve.

#### 6.2.2.6. Order of events

Based on the events stated in LDSA LFB discussion document [90] and the fire brigades' recommended time scale, the order of events are:

Means of escape

At time, t = 0 seconds the fire starts. Fire growing at design growth rate

At t = 300 seconds door to the flat on fire opens to allow for occupants escape. AOV, stair vent and automatic damper/door ventilator on the fire floor serving the smoke shaft opens.

At t = 310 seconds flat door closed by successful activation of door closer. Door serving stair opens. Main extract fans at means of escape design extract rate.

At t = 320 seconds door serving stair closed by door closer behind escaping occupants.

End of means of escape phase.

Fire Fighting

At t = 900 seconds fire service arrival. Stair door opens. Extract fans switched to fire fighting duty.

At t = 930 seconds flat door opens for firefighting access. Extract fans at fire fighting duty.
At t = 1200 seconds simulation ends.

The time at which door closer is successfully activated is 10 seconds. This gives for an effective door closing mechanism and is accepted by the fire authorities as reflected in LDSA LFB discussion document [90].

The window included in the fire compartment is assumed to break as the fire reaches 1.0MW.

### 6.2.3 Quantitative analysis

#### 6.2.3.1. Computational models

Two flats at opposite end of the extended corridor are chosen as the flats on fire for this assessment. Flat C has a floor area of $46m^2$ (6.1m wide by 7.6m long) while Flat D has a floor area of $45m^2$ (6.1m wide by 7.3m long). This provides a full picture of the extended corridor as to the performance of the proposed mechanical extract system when in operation.

The finished floor level to ceiling height of the flats is 2.4m while the ceiling to finished floor level of the storey above is 0.6m. The extended corridor has a common width of 1.4m except near the AOV where the common width is 2.8m – shown in Figure 6.28 and Figure 6.29. The AOV is $1.5m^2$ in area (1.5m wide by 1.0m high) and positioned at 1.0m above finished floor level.

The smoke shaft is taken as $0.64m^2$ with a corresponding dimension of 0.8m length x 0.8m wide. The automatic opening damper/door ventilator has an area of $0.6m^2$ (0.6m wide x 1.0m height) and positioned at high level as close to the ceiling as practically possible. An opening of $1.0m^2$ is also provided at the head of stair to account for head of stair vent. The stair is taken as 2.5m wide by 4.4m long.

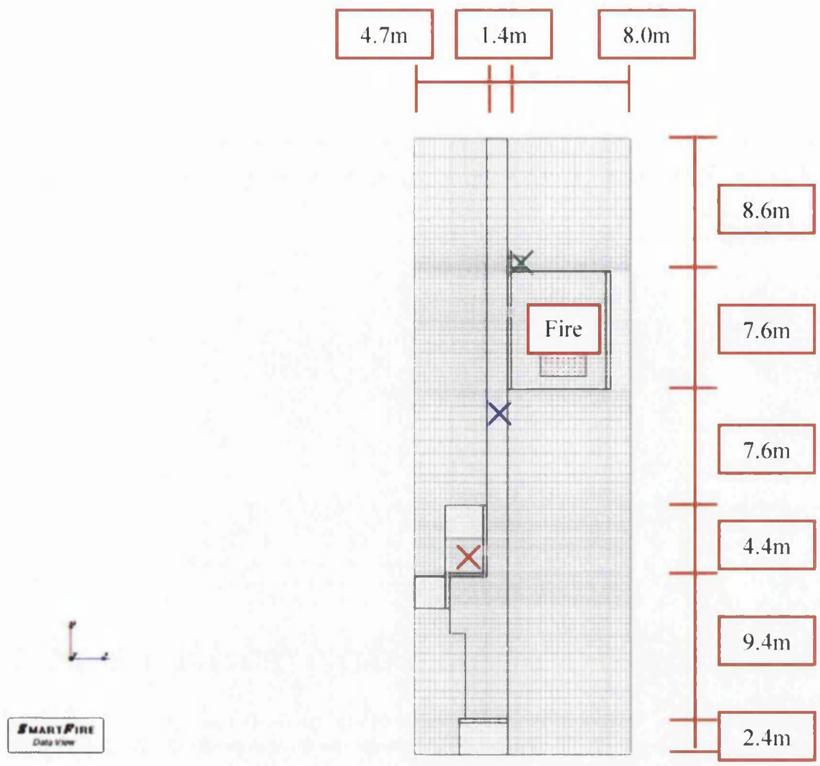



Figure 6.28 – Plan view of model for Flat C.

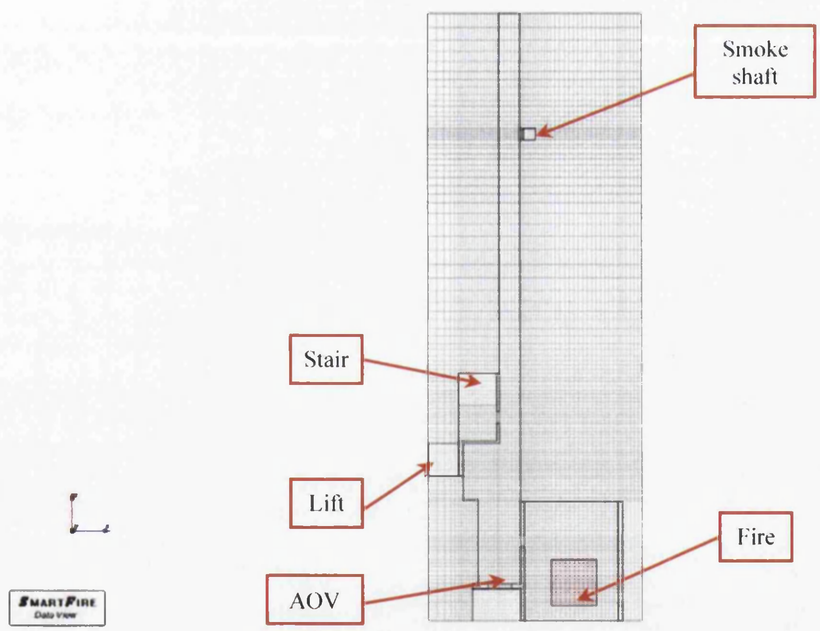



Figure 6.29 – Plan view of model for Flat D.

All doors are taken as 0.8m wide and 2.0m high. The effective leakage area through a single leaf door is taken as $0.01m^2$ [18]. The lift is taken as 2.0m wide by 2.1m long. The effective leakage area for the lift landing door is taken as $0.06m^2$ [18].

These leakage areas are prescribed at the foot of each corresponding doors by means of porosity boundary.

A 1.5m$^2$ glazed window is included in the model to account for the window breaking due to intense heat. An additional leakage area equivalent to 0.01m$^2$ (by means of porosity boundary) is prescribed at the foot of the glazed door to regulate pressure within the burning compartment prior to the glazed window being broken.

It is also assumed that fire only occur in one flat per floor and one floor per building at any one time. In the proposed system, only the doors i.e. stair door and fire flat entrance door, of the fire floor are opened and closed.

**6.2.3.2. Boundary conditions**

The same boundary conditions are adopted as in Case Study A as these are boundaries that define a residential high rise building.

Adiabatic and non slip condition is assumed for the walls surrounding the corridor and fire compartment.

Atmospheric pressure condition is assumed at the head of stair vent, head of lift shaft and any area outside of the building.

Porosity boundary condition, position at the foot of each door, is prescribed to gaps predominately present at the foot of a door. The porosity boundary allow for air to either enter or escape the corridor without modelling the details within the gaps. The effective leakage areas are taken as per BS 12101-6:2005 [18]. The porosity boundaries for single leaf doors are 0.8m wide and 0.1m high with an effective leakage area of 0.01m$^2$ (porosity factor of 0.125)

Porosity boundary prescribed at the foot of the window is 1.5m wide and 0.1m high with an effective leakage area of 0.01m$^2$ (the porosity factor is 0.0667). This is to account for all leakages around the window and walls of the fire compartment.

Porosity boundary is again used to represent the effective leakage area due to the lift door. The porosity boundary for the lift door, position at the foot of the door, is 0.8m wide and 0.1m high with an effective leakage area of $0.06m^2$ (porosity factor is 0.75).

Outlet boundary condition is prescribed to regions representing outside of the building envelop and any extended regions that would otherwise be automatically created by SMARTFIRE to allow for the flow across an opening to develop fully.

The modelling domain around the window will be extended to 2.0m to allow for sufficient room for the flow around the broken window to develop.

Wind effects are not considered.

#### 6.2.3.3. Radiation

As previous, the six-flux model is used for this simulation for the fire is large and is burning in a confined room. In addition the far field temperature is better predicted especially at the extract fans where they are in constant contact with high temperature smoke. Wall emissivity, absorption at 700K, and absorption at 1380K is taken as 0.8, 3.5 $m^{-1}$ and 7.0 $m^{-1}$ respectively.

#### 6.2.3.4. Cell budget

The number of cells used for mechanical assisted extract system is:

- Flat A: 218624 at 0.25m (length) x 0.32 (wide) x 0.20 (height).
- Flat B: 242048 at 0.25m (length) x 0.32m (wide) x 0.20 (height).
- Mesh independence study for Flat C: 439110 at 0.20m (length) x 0.26m (wide) x 0.17 (height).
- Mesh independence study for Flat D: 464202 at 0.19m (length) x 0.26m (wide) x 0.17 (height).

#### 6.2.3.5. Turbulence

SMARTFIRE v4.1 uses the buoyancy modified k-epsilon turbulence model and is part of the RANS turbulence model family.

#### 6.2.3.6. Air properties

Ambient temperature = $15^0$C

Viscosity = $1.5682 \times 10^{-5}$ Pa s

Density of air = 1.1774 $kg/m^{3s}$

#### 6.2.3.7. Simulation parameters

Time step size = 5 seconds

Sweeps per time = 50

Total simulation time = 1200 seconds

Tolerance = $1 \times 10^{-6}$

Initial pressure = 101325 Pa

Initial temperature = 15.15 $^0$C = 288.15 K

The 5s time step size is chosen as the simulation is highly stable except during the intervals where doors are opened and closed. At these intervals, the time step size is refined to 0.01s to capture the changes and ensure stability of the solution.

### 6.2.4 Assessment

#### 6.2.4.1. General

This section presents the analytical assessment of the mechanical extraction system performance. Similarly, the basis of this discussion is presented by line graphs through several strategically identified points shown in Figure 6.28 and Figure 6.29. Table 6.2 summarises the points at their respective coordinates with respect to each model.

| Reference (Colour) | Symbols | Dimension (for both Flat C and Flat D) |
|---|---|---|
| Corridor (Blue) | C1 | x=5.4 y=0.6 z=20.0 |
| | C2 | x=5.4 y=1.2 z=20.0 |
| | C3 | x=5.4 y=1.8 z=20.0 |
| Stair (Red) | L1 | x=4.0 y=0.6 z=13.3 |
| | L2 | x=4.0 y=1.2 z=13.3 |
| | L3 | x=4.0 y=1.8 z=13.3 |
| Smoke shaft (Green) | S1 | x=6.7 y=2.4 z=32.0 |
| | S2 | x=6.7 y=5.0 z=32.0 |

Table 6.2 – Location of points of interest

#### 6.2.4.2. Results

<u>Extended corridor</u>

Figure 6.30 indicates that the conditions of the extended corridors for both Flat C and Flat D. The extended corridors of both models are seen contaminated by smoke from 200 seconds up to 400 seconds. This coincides to the flat door being opened as occupants make their escape at 300 seconds. The smoke contaminate observed in the extended corridors leading up to the flat door being open is due to smoke leaking through the leakage path prescribed at the foot of the door. The visibility at this point in time is less than 3m. The period after the flat door is open represents the residual smoke in which the system is trying to clear.

Conditions peaked at 310 seconds as the flat doors are closed by the successful activation of their respective door closer. Temperature plots shown in Figure 6.31 highlight this observation where the temperature peaked at 370K in Flat C and 330K in Flat D.

Conditions improved as the flat door is closed and that the system is in operation. By 400 seconds, residual smoke is cleared with the visibility calculated as exceeding 5m and that temperature returns to ambient. The extended corridors are said to be within tenable limits. No additional smoke is seen leaking into the extended corridors of both models and continues until the Fire Service arrival. After the initial pressure variation due to the opening and closing of doors, the pressure is observed at a steady -3.8Pa – Figure 6.32. This confirms that pressure is sufficiently low to prevent smoke from leaking into the extended corridors. These observations confirmed that Condition 1 of the acceptance criteria has been met.

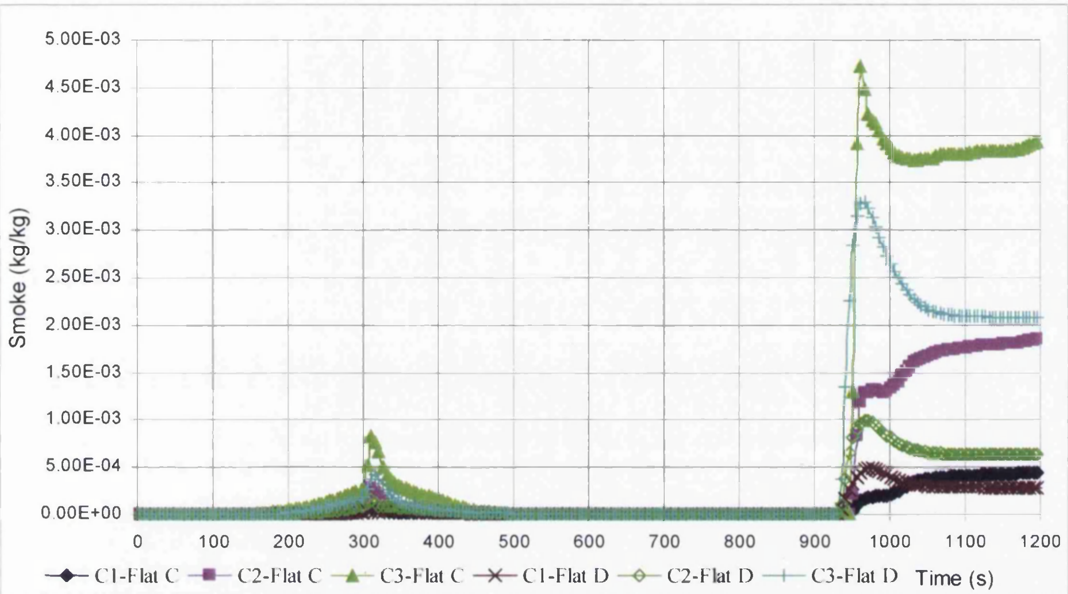



Figure 6.30 – Smoke vs time plots in the extended corridor.

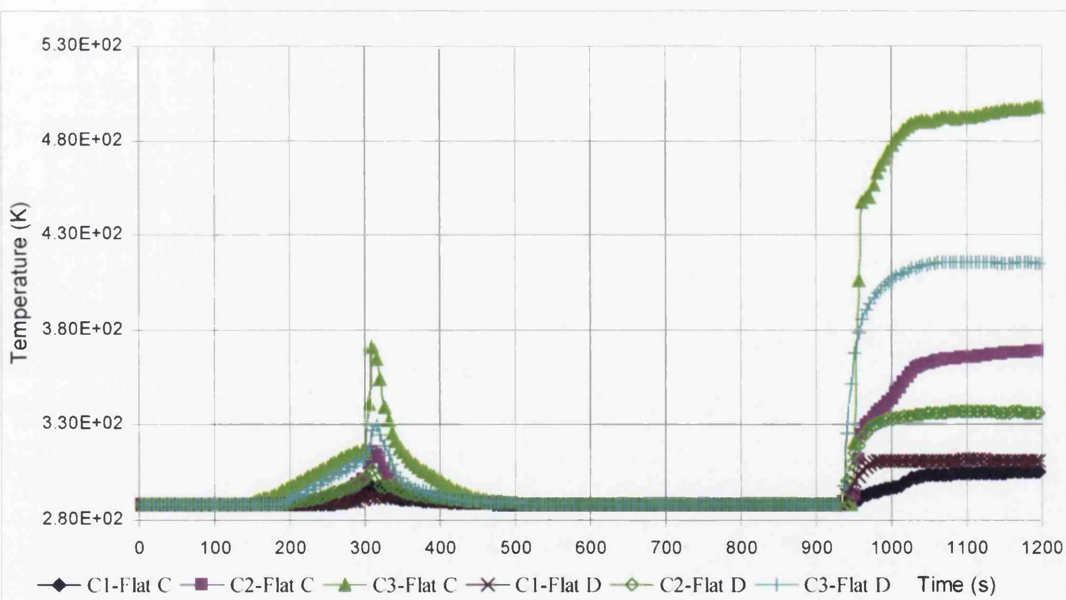



Figure 6.31 – Temperature vs time plots in the extended corridor.

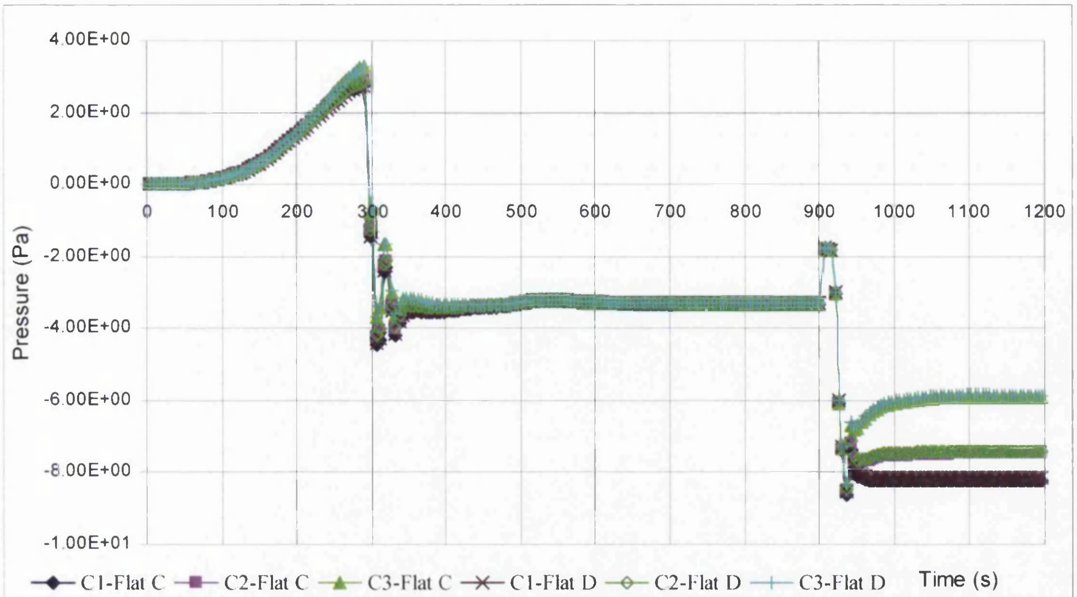



Figure 6.32 – Pressure vs time plots in the extended corridor.

As fire fighters arrive on the fire floor i.e. 900 seconds, the system is switched to fire fighting mode where the extract duty is increased to $6m^3/s$. This increase has resulted in a sudden drop in pressure to -8Pa. A drop of -6Pa as the opened $1.5m^2$ AOV provides sufficient inlet to the system.

At 930 seconds, the flat doors open to allow hot smoke to spill into their respective extended corridors thus making the corridors untenable. This is shown by the sudden increase in smoke and temperature. The conditions eventually stabilised to a stratified smoke layer.

Smoke shaft

Figure 6.33 to Figure 6.35 indicate that conditions in the smoke shafts of their respective models are fairly uniform. The Flat C model has imposed a much worse condition on the smoke shaft compared to the Flat D model. This is due to the location of entrance of Flat C which is next to the smoke shaft. This meant that the hot smoke has little time to entrain fresh air before it is exhausted which explains the high temperature observed.

In contrast, the Flat D model is furthest away from the smoke shaft where the hot smoke from the flat has time and space to entrain fresh air before it is exhausted. The location of the AOV which is adjacent to Flat D also aid in the entrainment process by providing fresh air to the smoke plume. The entrainment lowers the temperature of the hot smoke and is therefore less harsh to the extract fans.

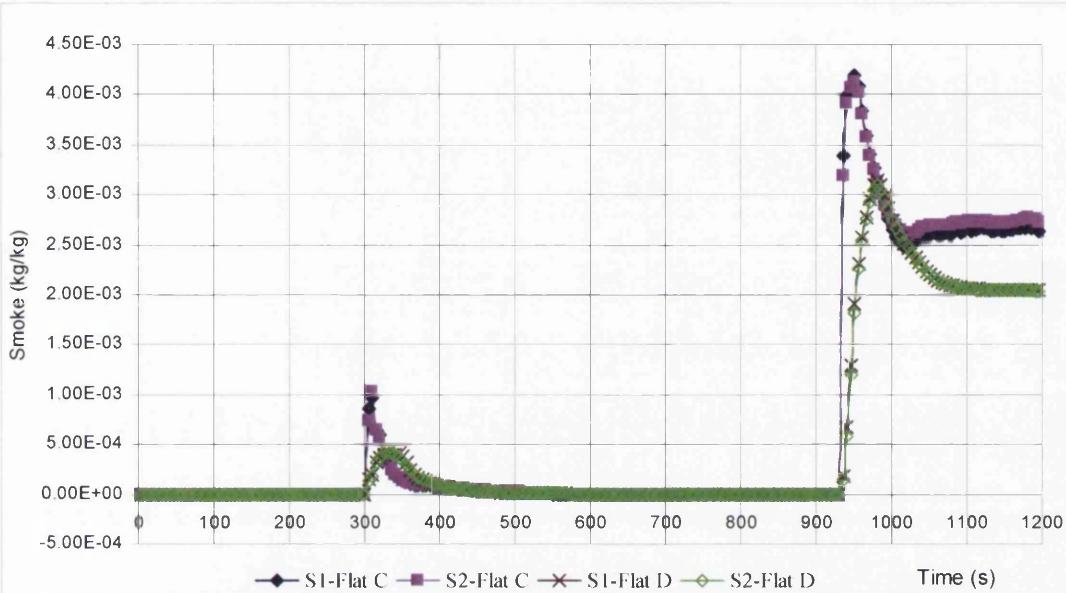



Figure 6.33 – Smoke vs time plots in the smoke shaft.

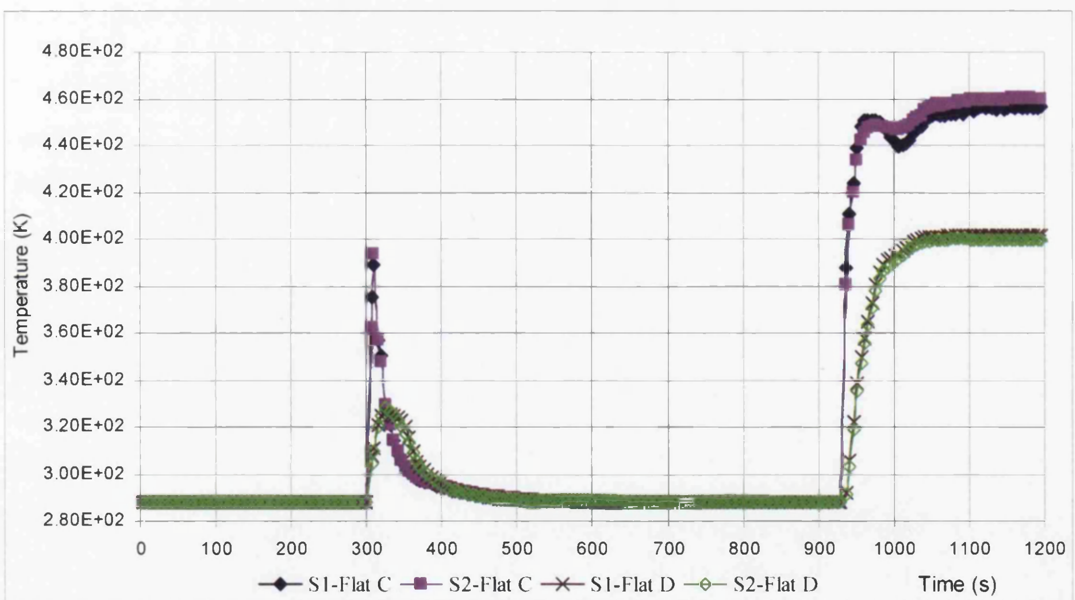



Figure 6.34 – Temperature vs time plots in the smoke shaft.

In the subsequent periods after the flat doors are closed behind escaping occupants, conditions in the smoke shafts in both models have returned to ambient where no smoke is seen extracted until 930 seconds. This is because smoke has not leaked into the extended corridor and therefore only fresh air from the opened AOV is vented. The pressure in the smoke shaft is observed at -30Pa.

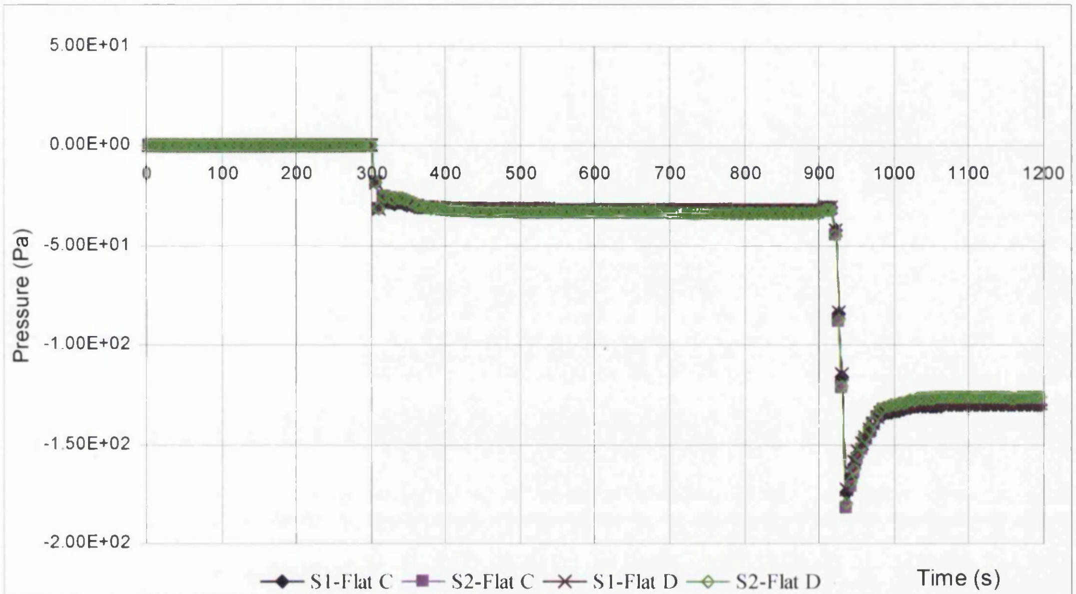



Figure 6.35 – Pressure vs time plots in the smoke shaft.

During fire fighting phase, a high concentration level of smoke is exhausted through the smoke shaft. As expected, the temperature values due to the Flat C model are higher than that of the Flat D models at 460K and 400K respectively. Since the maximum temperature values observed are 460K (187°C), the extract fan with fire resistance rating of 300°C is suitable for use in this case. The maximum pressure observed is -180Pa before rising to -130Pa. This implies that the extract fans must be able to perform at this pressure drop.

<u>Stairs</u>

Figure 6.36 to Figure 6.38 show that very small traces of smoke enter the stairs of both models as their respective stair doors are open for occupant escape. Although the hot smoke does increase the local temperature by 1K, the visibility is not affected. The stairs corridor therefore remains tenable.

During fire fighting phase, a very small increase in temperature, 0.2°C, is observed in the stairs which may be due to the radiative heat from the hot smoke plume. The pressure is observed as -4.7Pa with the pressure difference across the stair door calculated as -3.3Pa. This suggests that the pressure difference is capable of preventing smoke from flowing into the stairs thus protecting the stairs from smoke. Hence, this confirms that Condition 2 has been met.

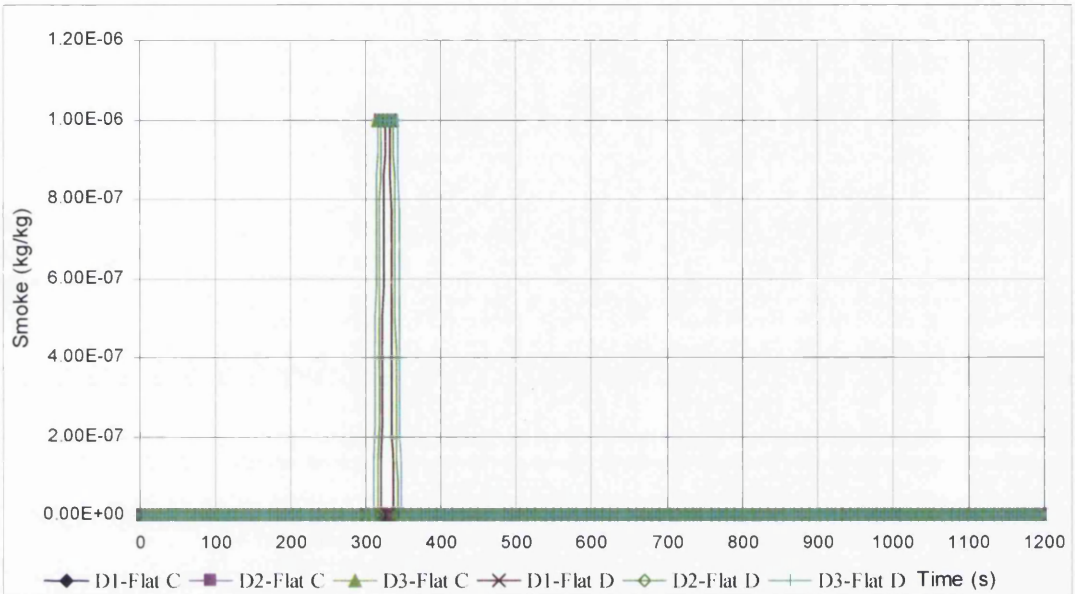



Figure 6.36 – Smoke vs time plots in the stairs.

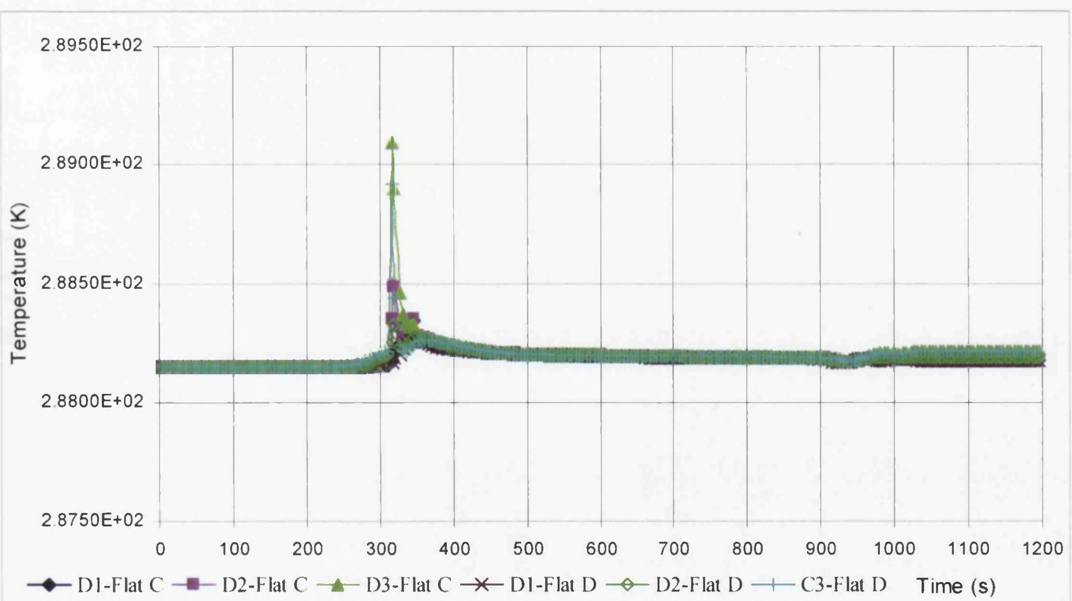



Figure 6.37 – Temperature vs time plot in the stairs.

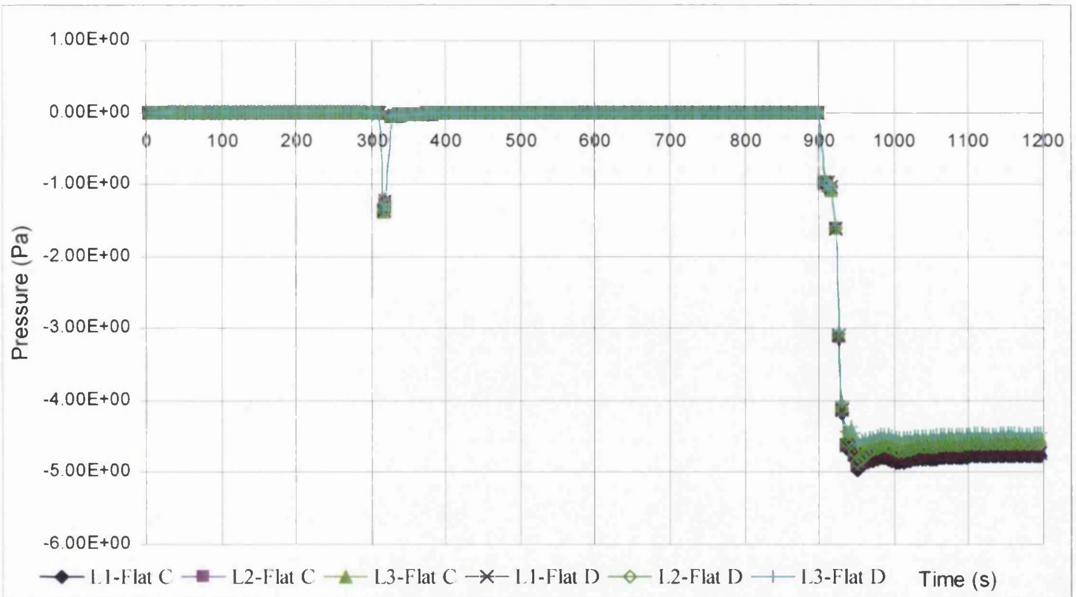



Figure 6.38 – Pressure vs time plots in the stairs.

### 6.2.4.3. Mesh independence study

Similar to before, a mesh independent study is carried out for both the models. Using the same points of interest as before, the mesh independent study is presented through the smoke mass fraction. The cell budgets of the refined mesh models, as stated in Section 6.2.3.4, are:

- Mesh independence study for Flat C: 439110 at 0.20m (length) x 0.26m (wide) x 0.17 (height).
- Mesh independence study for Flat D: 464202 at 0.19m (length) x 0.26m (wide) x 0.17 (height).

<u>Flat C model</u>

Figure 6.39 to Figure 6.41 show that the refined mesh model is comparable to the initial model. Detailed assessment found that the percentage errors between the two models are calculated as 5%. This error is sufficiently small and is therefore acceptable. Hence the solution is said to have converged to a mesh independent solution.

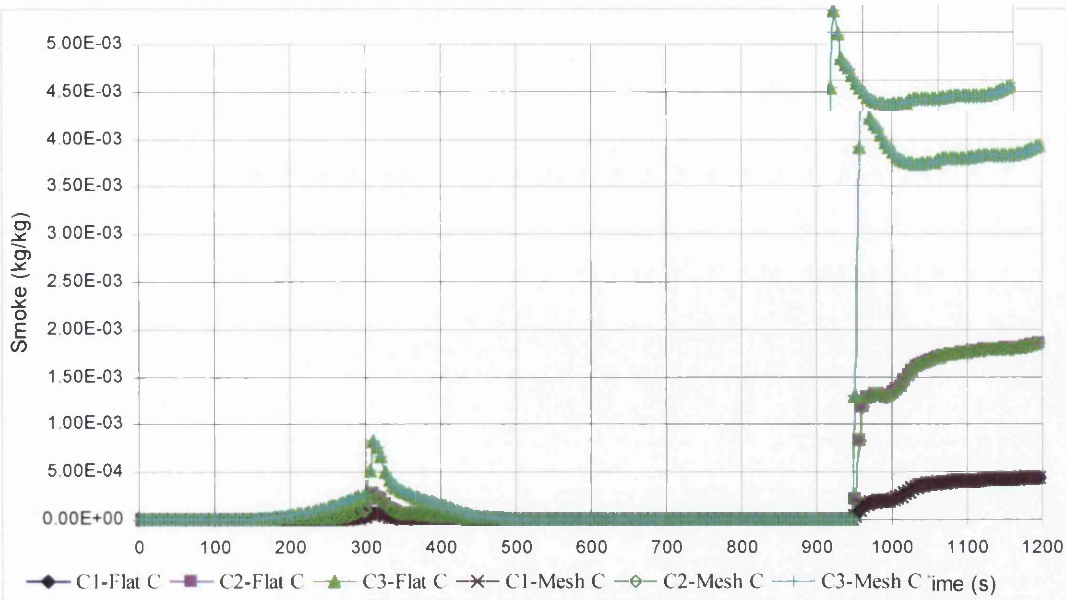



Figure 6.39 – Smoke plots in the extended corridor.

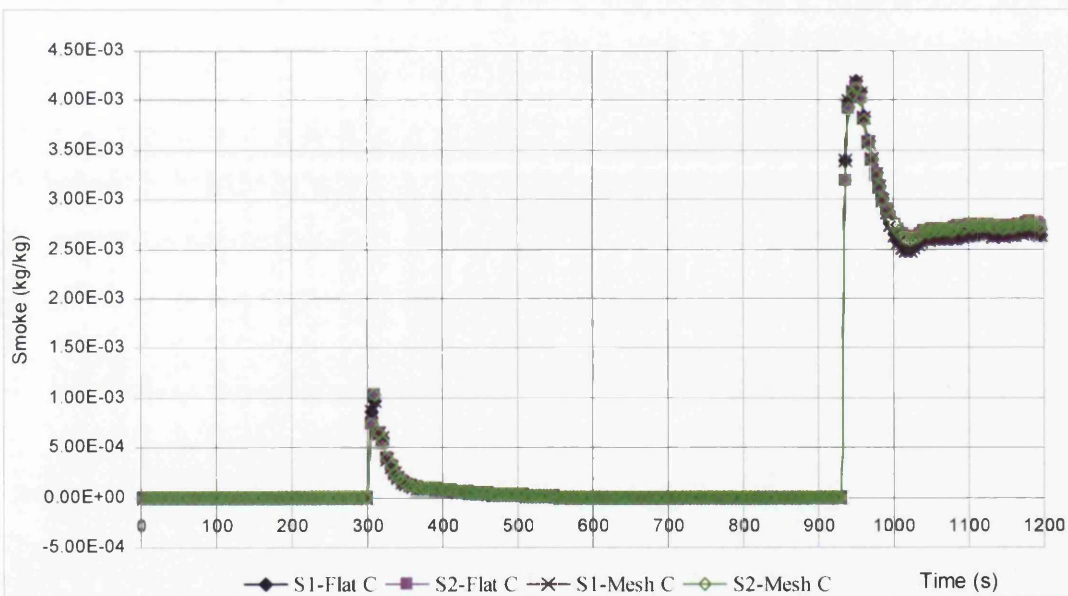



Figure 6.40 – Smoke plots in the smoke shaft.

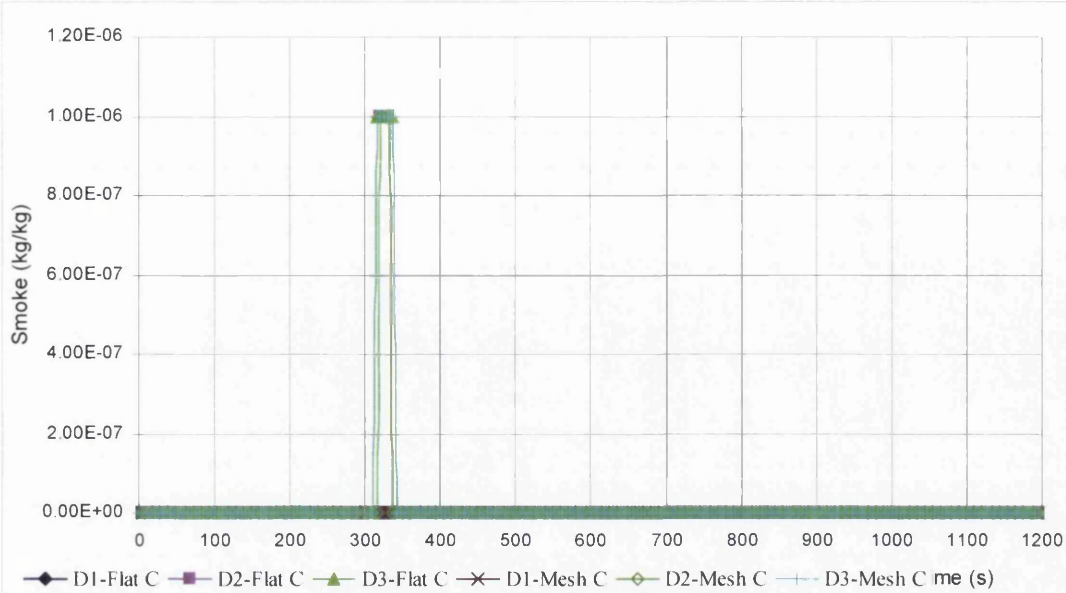



Figure 6.41 – Smoke plots in the stairs.

Flat D model

Similarly, Figure 6.42 to Figure 6.44 show that the refined mesh model for Flat D is again comparable to the initial model. The errors due to the mesh refinement are calculated as 5% which is sufficiently small and is therefore acceptable. The solution is said to have converged to a mesh independent solution.

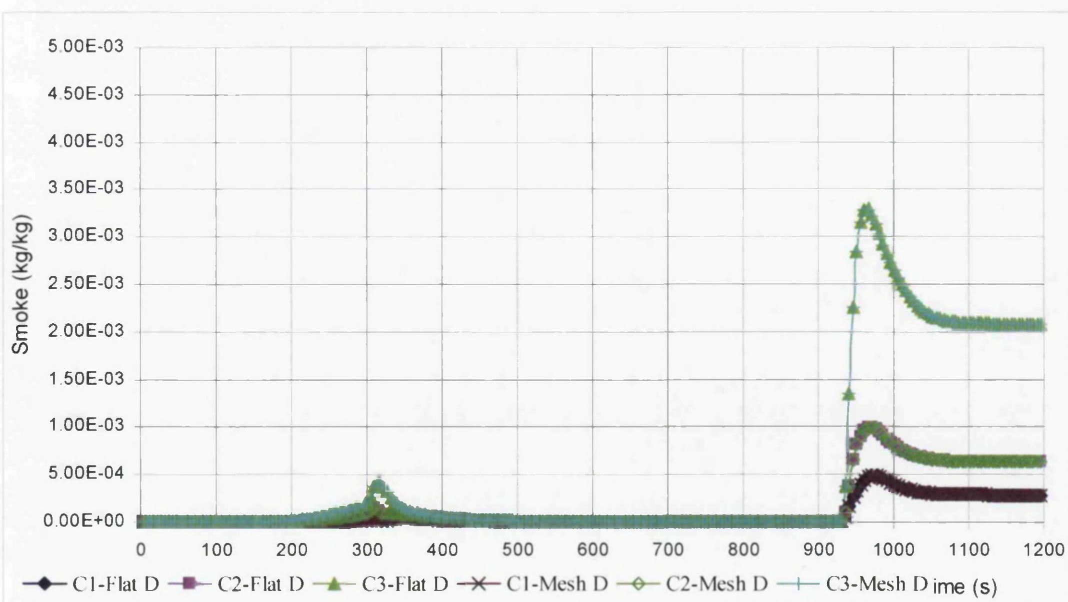



Figure 6.42 – Smoke plot in extended corridor.

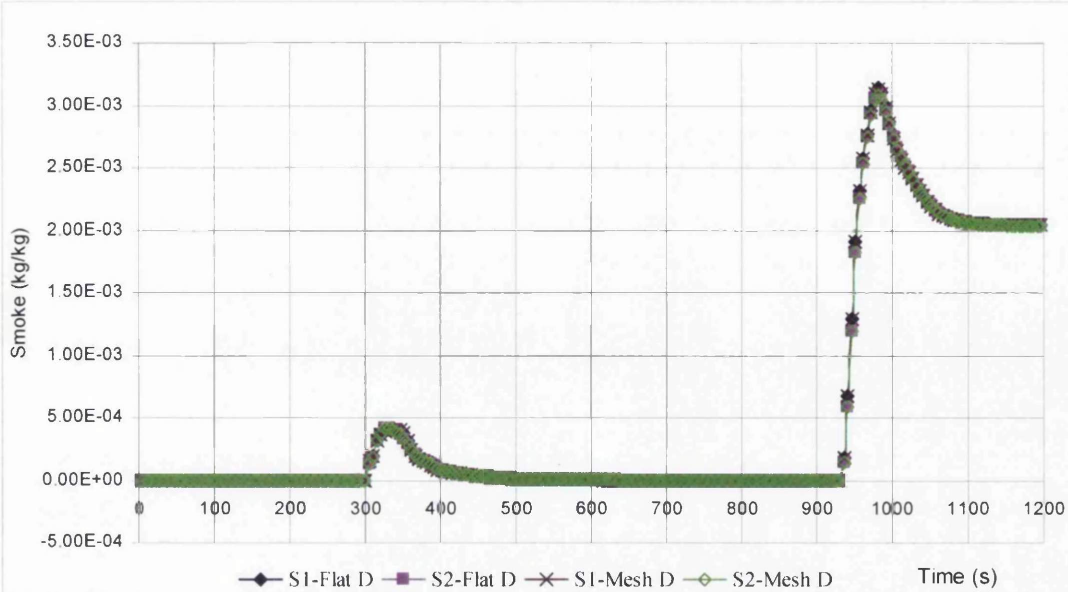



Figure 6.43 – Smoke plot in the smoke shaft.

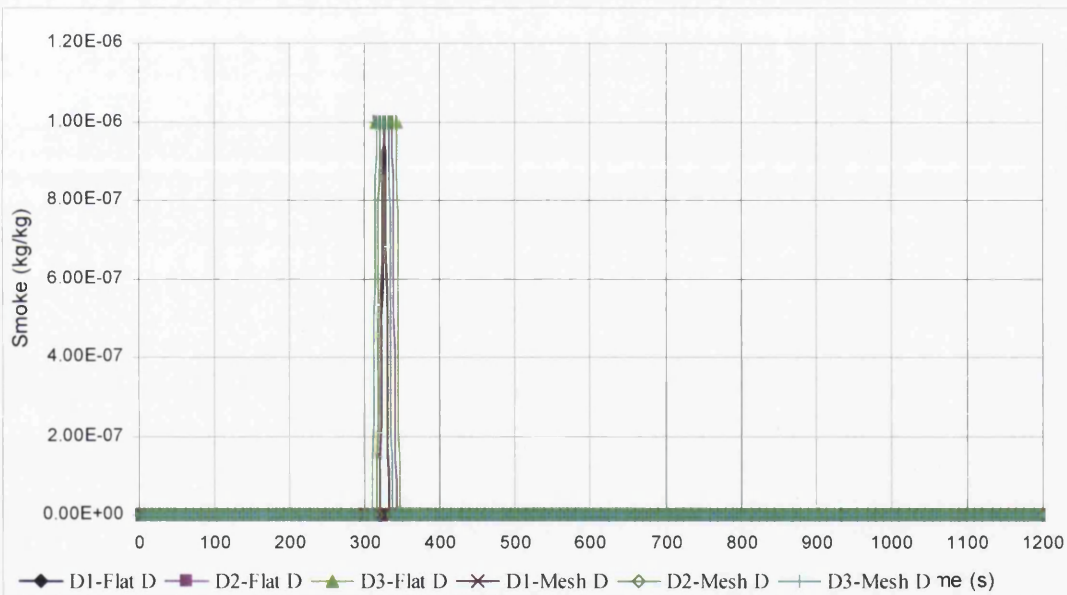



Figure 6.44 – Smoke plot in the stairs.

### 6.2.5 Conclusions

These results show that conditions within the common corridors meet the design assessment throughout the simulation. It can therefore be concluded that the proposed mechanical extract system, based on the design flow rates are acceptable:

- Means of escape: 2.0m$^3$/s
- Fire fighting: 6.0m$^3$/s

The system is able to effectively extract the hot smoke released while a person escape and rapidly, within 100 seconds, restore the corridor to ambient conditions.

Over-depressurization of the common corridor is avoided with the open AOV providing the necessary air replacement. The stair door is allowed to be fully closed so as to preserve the compartmentation of the extended corridor.

The mesh independence studies have confirmed that solutions have converged to a mesh independent solution.

## 6.3 Case study C – Mechanical extract for covered car park

### 6.3.1 Problem description

The car park of interest is a single storey covered car park and is to be ventilated mechanically with assistance from strategically positioned impulse fans. The system is designed for smoke clearance only in which the system is required to assist fire fighters in clearing smoke form the car park after the fire is under controlled.

The covered car park is mechanically ventilated as the available free area is $32.2m^2$ which is less than 2.5% of the floor area. The main extract fans are housed in a plant room which is opened to the car park through a damper or grille and is positioned at high level for effective smoke extraction.

Several impulse fans are strategically placed within the covered car park to provide air movement so as to ensure that no dead spots are present. These impulse fans direct the bulk air flow towards the extract point.

Replacement air is provided naturally via the free area made up of a ceiling vent and the main entrance to the car park.

### 6.3.2 QDR

The fire scenario at which the smoke ventilation system is assessed against is presented.

#### 6.3.2.1. Design objective

To assess the effectiveness of the proposed ventilation system capabilities in providing sufficient ventilation for post fire smoke clearance. The system and the impulse fans position is acceptable on the condition that the car park is cleared of smoke after the fire is under controlled (extinguished).

#### 6.3.2.2. Fire size

A volumetric heat source with a volume of 3.5m (wide) x 3.7m (length) x 2.8m (high) is used to represent the flaming region which theoretically be engulfed by the flame at peak output of 10MW. This fire size is chosen based on two cars burning simultaneously as prescribed by the code of practice [26].

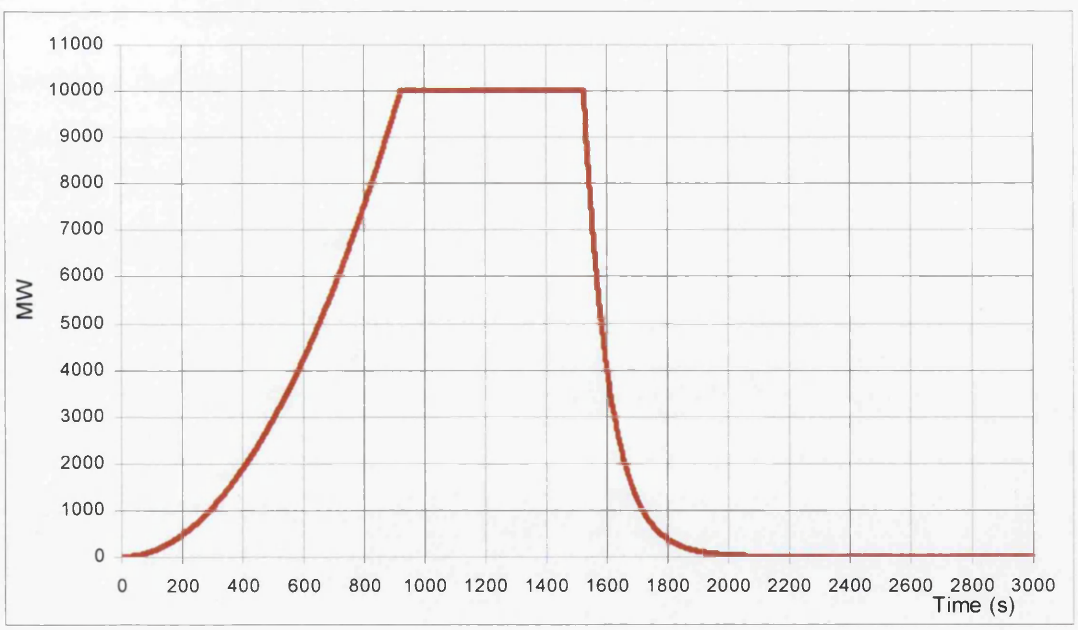



Figure 6.45 – Design fire curve.

The fire is assumed to burn in 3 stages, shown in Figure 6.45, the fire growth is assumed to be of medium growth rate which peaks at 925 seconds; the heat output is then kept constant between the times of 925 seconds to 1525 seconds; fire is assumed to decay at an exponential rate of $e^{-0.012}$ until 2400 seconds.

### 6.3.2.3. Smoke production

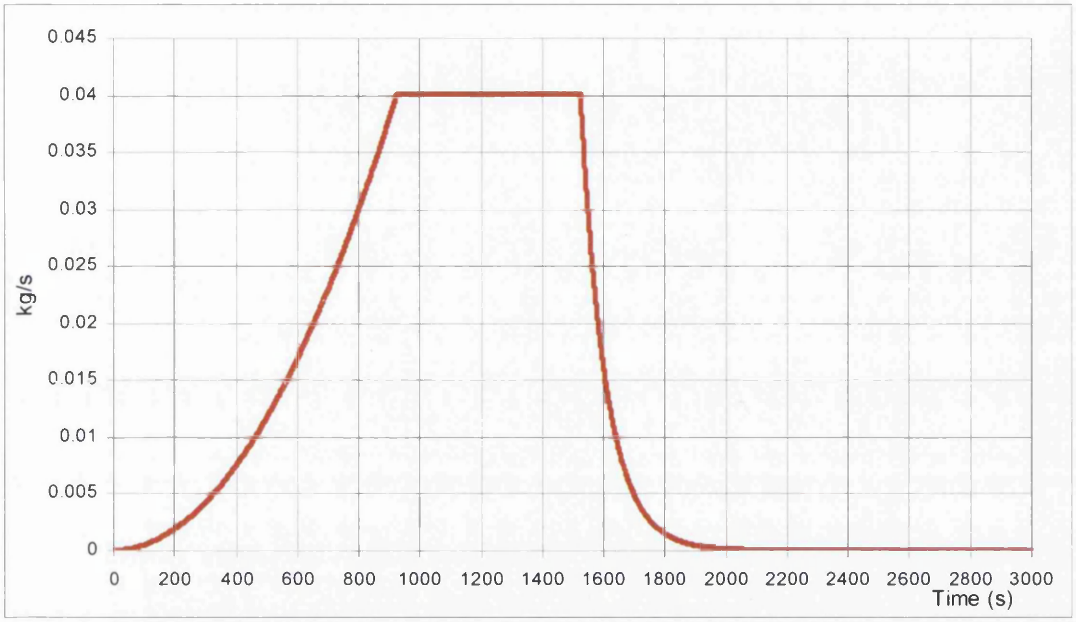



Figure 6.46 – Smoke production curve.

Assuming the seat is on fire, the polyurethane foam correlation, with corresponding Heat of Combustion of 25MJ/kg and soot yield of 0.1 kg/kg (10%) is assumed for the production of hot gases [72]. The smoke production curve due to this correlation is shown in Figure 6.46. The smoke, smoke absorption constant and smoke specific extinction coefficient is taken as 1800kg/m$^3$, 1200, and 7600 m$^2$/kg respectively.

### 6.3.2.4. Extract duty

The extract duty of the main fans is taken as 10 air changes per hour [26] – 40m$^3$/s at a volume of 14400m$^3$. The impulse fans duties are taken as 1.96m$^3$/s for fighting operation.

### 6.3.2.5. Order of events

At time t = 0 seconds the fire starts, Extract fans to provide 10 air changes per hour

At t = 300 seconds impulse fans activated at fire fighting design duty.

At t = 925 seconds fire peaked at 10MW

At t = 1525 seconds fire starts to decay

At t = 2400 seconds fire assumed to be extinguished

These events represent the duration at which a typical sedan car is burning [96] so as to fill the car park with realistic amount of hot smoke prior to complete removal.

### 6.3.3 Quantitative analysis

This section presents the computational models and the respective boundary conditions relevant to the covered car park of interest.

#### 6.3.3.1. Geometry and computational model

The covered car park has a floor area of 3300m$^2$ at an average height of 4.37m. The volume of the car park is calculated as 14400m$^3$. The entrance to the covered car park, which is at ground level, is served by a ramp. Additional parking spaces are provided under the plant room and are served by a right angles ramp as indicated in Figure 6.47. The void as shown is provided to ventilate the areas underneath the plant room. Impulse fans are positioned 2.5m above finished floor level.

Natural inlet is provided at the vent at the bottom left corner and the entrance to the covered car park. The former has a free area of 16.2m$^2$ whereas the later has a free area of 15.99m$^2$. The area of the plant room damper/grille is 6.5m$^2$ positioned at high level.

Figure 6.48 to Figure 6.52 show the detailed layout of the car park including the location of fire, the strategically placed impulse fans and the sections view to better appreciate the complexity of the car park layout.

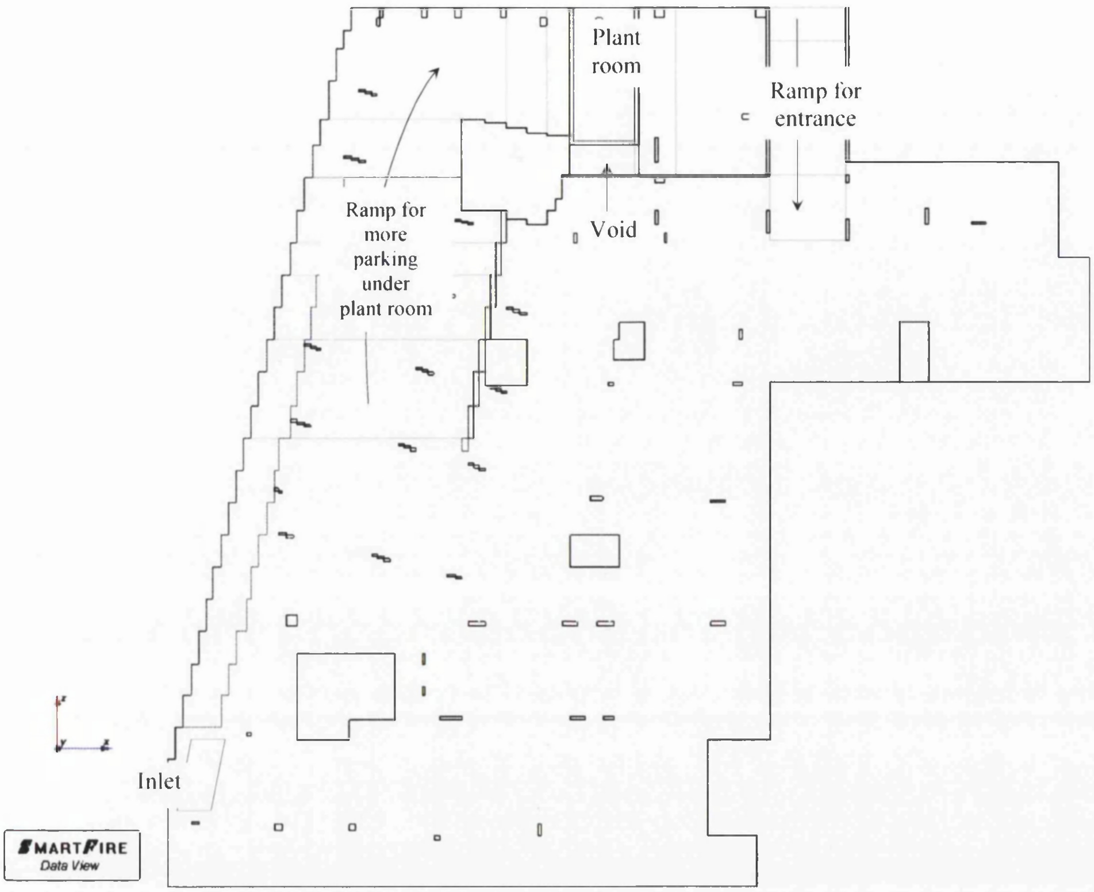



Figure 6.47 – Covered car park geometry layout.


Figure 6.48 – Plan view of the underground car park.


Figure 6.49 – Showing the directions at which impulse fans blow at.

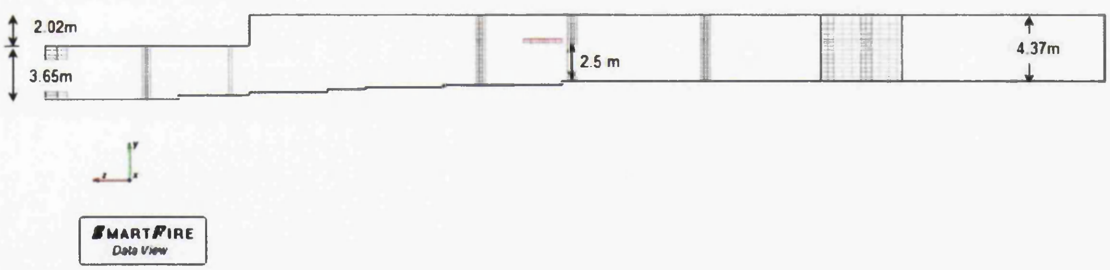



Figure 6.50 – Showing section cut through AA'

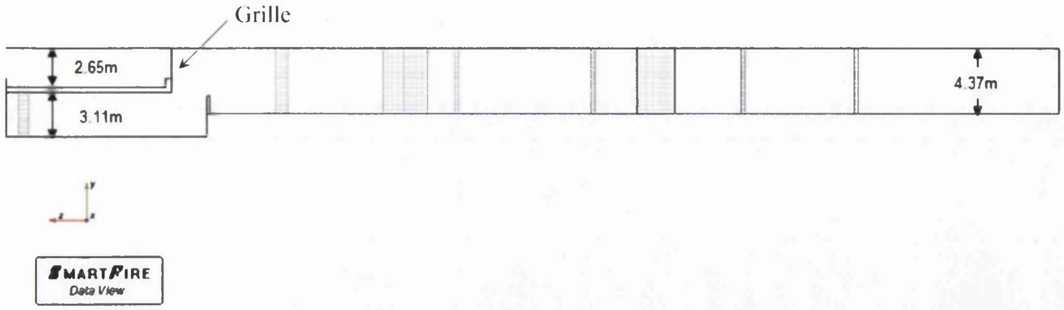



Figure 6.51 – Showing the section through plant room, BB'

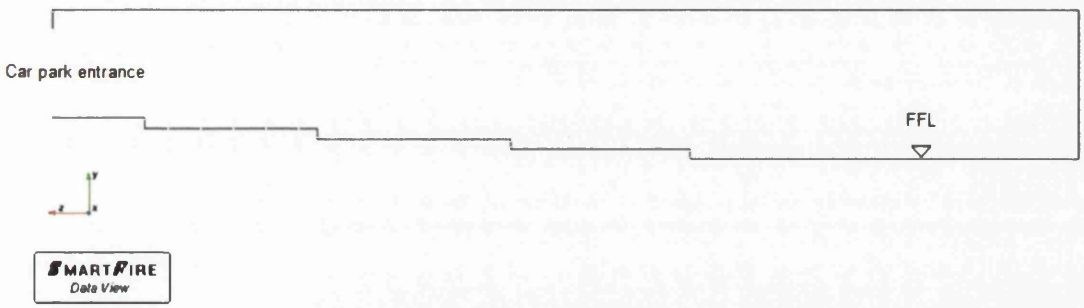



Figure 6.52 – Showing the section through the entrance ramp CC'

### 6.3.3.2. Radiation

The Radiosity model is used in this case as the fire is burning in a large open space. In addition, the far field temperature is less critical. Wall emissivity, absorption at 700K, and absorption at 1400K is taken as 0.8, 3.5 $m^{-1}$ and 7.0 $m^{-1}$ respectively.

### 6.3.3.3. Boundary conditions

Adiabatic and non slip condition is assumed for the walls surrounding the car park.

Atmospheric boundary condition is assumed at the opening at the bottom left of the ceiling and at the entrance. This is because the areas are open to external surrounding.

Wind effects are not considered as this is a covered car park.

#### 6.3.3.4. Turbulence

SMARTFIRE v4.1 uses the buoyancy modified k-epsilon turbulence model and is part of the RANS turbulence model family.

#### 6.3.3.5. Cell budget

Initial model: 816750 at 0.45m (length) x 0.35m (wide) x 0.25m (high).
Mesh independent study: 700700 at 0.48m (length) x 0.40m (wide) x 0.25m (high).

The initial model has used up the available cell budget allowance and as a results a coarse mesh is used for the mesh independent study instead of a refined mesh.

#### 6.3.3.6. Air properties

| | |
|---|---|
| Ambient temperature | = $15^0$C |
| Viscosity | = 1.5682 x $10^{-5}$ Pa s |
| Density of air | = 1.1774 kg/$m^3$ |

#### 6.3.3.7. Simulation parameters

| | |
|---|---|
| Time step size | = 10 seconds |
| Sweeps per time | = 50 |
| Total simulation time | = 3000 seconds |
| Tolerance | = $1x10^{-6}$ |
| Initial pressure | = 101325 Pa |
| Initial temperature | = 15.15 $^0$C = 288.15 K |

### 6.3.4 Assessment

#### 6.3.4.1. General

This section presents the analytical assessment of the car park ventilation system performance. Similarly, the basis of this discussion is presented by line graphs through several strategically identified points shown in Figure 6.53. The points, except at the plant room is at 1.8m above finished floor level i.e. at head height.

Table 6.3 summarises the points at their respective coordinates with respect to the model.

| Reference (Colour) | Symbols | Dimension |
|---|---|---|
| Plant Room (Purple) | P | x=35.5 y=5.0 z=58.5 |
| Fire (Red) | F | x=30.8 y=3.8 z=42.0 |
| Natural vent (Green) | V | x=4.6 y=3.8 z=10.0 |
| Entrance ramp (Blue) | R | x=52.0 y=3.8 z=51.5 |

Table 6.3 – Location of points of interest


Figure 6.53 – Point of interest.

### 6.3.4.2. Results

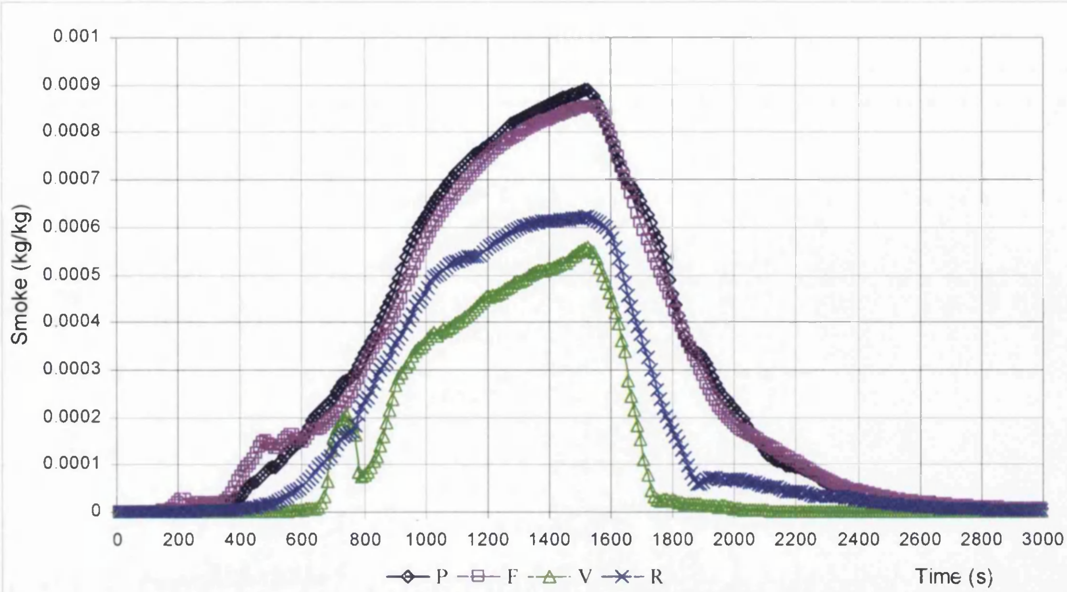



Figure 6.54 – Smoke vs time plots.

Figure 6.54 shows the smoke plots at the various points of interest. The covered car park is gradually filled with smoke as fire grows in size. By 700 seconds, the visibility in the car park has reduced to 1m as smoke takes time to fill the car park. This is relatively slow because of the large volume of the car park and the operation of the extract and impulse fans. The former enables smoke to entrain more air thus reduces the concentration and temperature of the hot smoke. The later removes smoke from the covered car park while the impulse fans encourages mixing by disturbing the stratification process. At the same time i.e. 700 seconds, smoke is seen to be ventilated from the ceiling vent.

Conditions peaked at 1525 seconds as defined in the fire scenario. The visibility at this point in time is calculated at 0.4m while the maximum temperature (Figure 6.55) is observed at 120°C. The entrance to the car park and the ceiling vent acts as the exhaust points as smoke produced at peak output overwhelm the ventilation system.

As fire is brought under controlled from 1525 seconds, conditions have improved significantly where smoke and temperature returned to ambient at 2600 seconds. The higher value of smoke observed at the plant room and near the fire is due to the impulse fans pushing the bulk air flow towards the extract point. This eventually clears at 2800 seconds which implies that the covered car park is free of smoke.

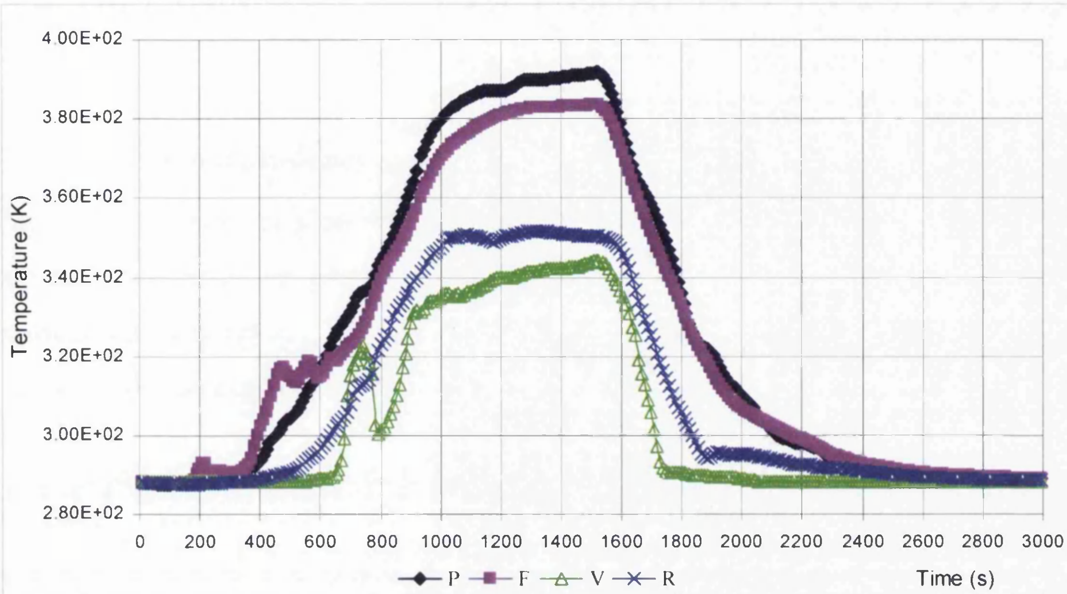



Figure 6.55 – Temperature vs time plots.

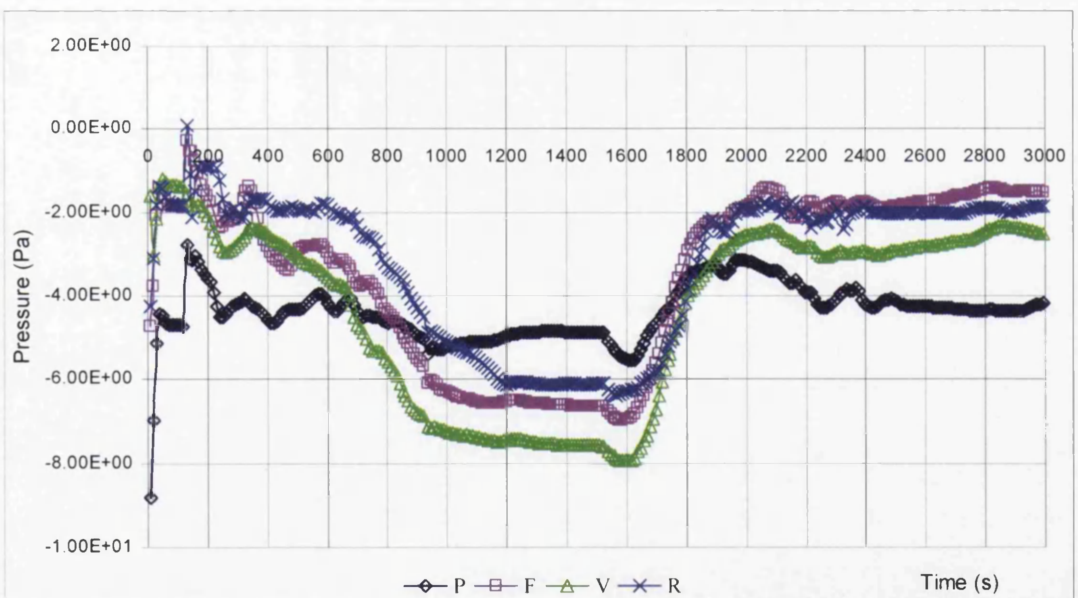



Figure 6.56 – Pressure vs time plots.

The pressure plots shown in Figure 6.56 vary in time due to the effects of impulse fans. The covered car park is constantly under negative pressure which would offer some protection to the lobbies that leads to the stair serving storeys above.

As all smoke is cleared form the covered car park, it can be certain that air flow is well distributed in the car park and that there is no dead spots. Hence, the acceptance criterion is met.

#### 6.3.4.3. Mesh independence study

Figure 6.57 shows the plots of the coarse mesh compared to the initial model. The results are seen to be comparable with detailed assessment found an 8% error between the two models. The errors are sufficiently small and is therefore accepted with the solution converged to a mesh independence solution.

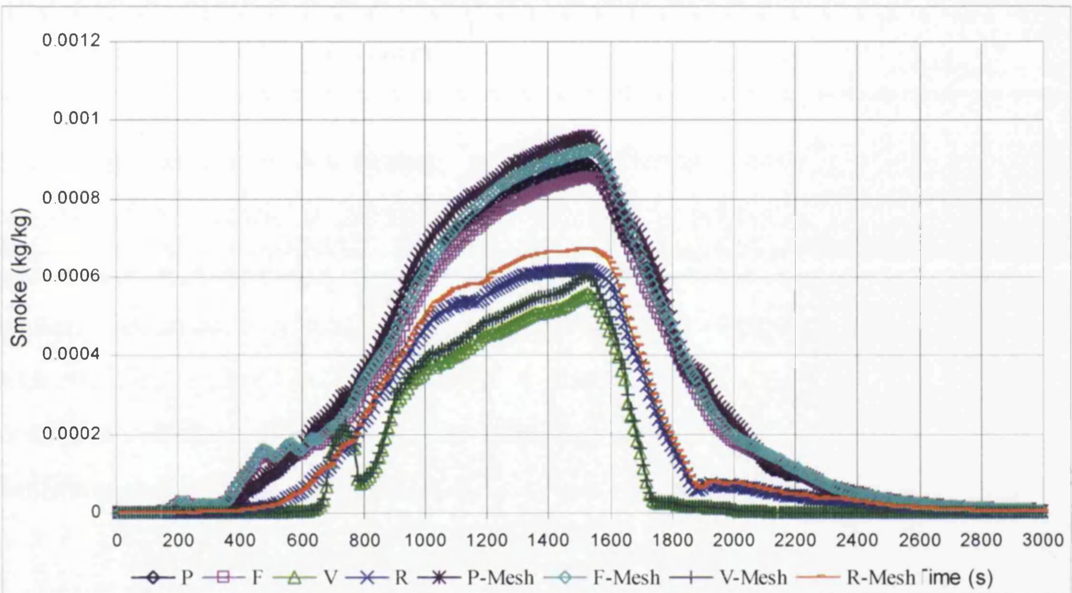



Figure 6.57 – Smoke vs time plots.

### 6.3.5 Conclusions

These results show that the position of the impulse fans is capable of clearing smoke from the covered car park, thus, confirming its suitability.

Negative pressure is maintained throughout the covered car park which provides some protection to the stair core entrances.

## 6.4 Concluding remarks

The industry challenges presented in this chapter has been submitted to the relevant fire authorities for approval. All three schemes have subsequently been approved for installation and are now protecting their respective buildings as part of their respective fire safety systems.

The proposed simulation based design strategy is shown to be flexible and yet sufficiently robust to include for the assessment of smoke control systems for above ground and covered car park. The basis of the process is similar but for some changes in the identified fire scenario. Changes include the ventilation strategy, fire size, and order of events reflecting on the problem of interest. The assessment criteria for the acceptance of the proposed designed would also have to be tailored to reflect upon the problem of interest.

The unique aspect of this strategy is the Fire Service comments where once the proposed fire scenario is determined, a proposal is submitted to the relevant fire authorities for preliminary approval prior to the simulation. This ensures that the fire scenario assumed is a representation of what might happened to the problem of interest. Fire authorities' importance is therefore reflected on determining the ventilation strategy, fire size and the estimated time of arrival of the fire service on the fire scene.

Another aspect in the capability of field modelling is to determine the conditions at which the equipment is exposed to. This can then be used to determine the fire rating of the equipment that is exposed to such conditions. For example, the fire rating of the extract fans of which the requirement is not prescribed.

# Chapter 7 Conclusions

The proposed simulation based design strategy is capable of providing a framework for the design and assessment of smoke control systems for residential high rise buildings whilst sufficiently robust to consider the design of smoke control systems for other applications such as covered car parks and atria.

Core to this strategy are the four stages namely:

- Qualitative Design Review (QDR);
- Quantitative Analysis (QA);
- Assessment process; and
- Fire Service inputs.

QDR is the initial stage where the proposed ventilation strategy, potential fire scenario and the assessment approach are identified. The information gathered in this stage is then submitted to the relevant fire authority as an initial proposal for the subsequent numerical analysis. Any changes or requests by the fire authority can then be incorporated into the design prior to the start of the analysis. The chance to agree expectations and correct any problems at this stage is much easier and cheaper than after testing upon the completion of the installation.

QA is the second stage of the process where the parameters identified in the QDR are quantified, applied to the chosen analytical approach i.e. field model and are subsequently evaluated. The measure of accuracy and validity of the analytical solution is also assessed.

The assessment stage evaluates the results of the simulation against the acceptance criteria. The proposed solution is accepted if the acceptance criteria are met. Otherwise the analytical process is repeated until the proposed solution satisfies the acceptance criteria. The findings are then submitted to the fire authorities for final approval.

Fire Service inputs are vital as it is they who would put their lives at risk before others during a fire hazard. As such, any fire safety systems would have to meet their requirements. Dialogs with relevant approving fire authorities in between processes will help in identifying the system objectives, the scenarios to be modelled, the modelling criteria, and the success criteria, which when agreed prior to commencement of the analysis will save both time and money. CFD is too expensive and time consuming a process to be carried out without this agreement.

As part of the design procedure, this thesis promotes the responsible use of CFD technology in the design of smoke control systems by several means:

- An understanding of the CFD technology, the importance of sub-models and their application in fire and smoke modelling. A short list of available software packages capable for use in fire and smoke modelling is also provided.
- Identification of the modelling requirements/parameters in the form of defining an appropriate fire scenario and the setting up of the computational model that is representative to the geometry of interest.
- Measure of the accuracy of the numerical simulations.
- Applicable approaches for the assessment of fire engineered solutions and the choice of suitable equipment for use as a result of the assessments.
- Successful use of the simulation based design strategy with acceptance of the proposed fire engineered solution being approved for installation.

On this aspect the Institution of Fire Engineers (IFE) has recently published a fire modelling process flow chart with the aims of promoting responsible use of technology and provide guidance on the use of modelling in fire engineering [97]. Most of the design process in this thesis overlaps that of the published flow chart thus giving further confidence to the proposed design strategy.

The successful implementation of the proposed simulation based design strategy has exceeded SCS Groups' expectation of a systematic and coordinated process for the design of fire engineered systems. As a result, the proposed strategy is now playing a central role in their future design and assessment of fire engineered systems for both above ground and covered car park applications.

## 7.1 Future work

One future work to be undertaken is the full scale experiment using hot smoke. As part of the commissioning process, the fire engineered system is required to be tested by means of a cold smoke test so as to give an indication on the performance of the proposed design. However, cold smoke tests and numerical analysis are not substitutes for full scale experiments when hot smoke is concerned. Data from full scale experimental set up using hot smoke would be invaluable for future assessment and the design of a fire engineered solution.

Other future work may involve the introduction of a standardised procedure for the design of smoke control system detailing the requirements, methodologies/approaches and the assessment criteria therefore providing a streamline process from design through to commissioning to the benefit of all parties e.g. fire engineers and fire authorities alike.

The main reason behind this is that fire authorities have been inundated with fire engineering proposals based on CFD analysis whilst they do not have the necessary knowhow to assess these proposals. A standardised procedure that details the requirements and approaches would be of benefit as they slowly find their feet in terms of assessing the credibility of the CFD analysis based proposals.

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