



# THE EFFECTS OF VARIATION IN SHAPE OF SMOKE RESERVOIRS AND NUMBERS AND DISTRIBUTION OF SMOKE EXTRACTION POINTS ON THE TENABILITY WITHIN A COMPARTMENT

HM Iqbal Mahmud<sup>a,b,\*</sup>, Vijay Rajaram<sup>b</sup>, Khalid Moinuddin<sup>b</sup>

<sup>a</sup> Department of Civil Engineering, Khulna University of Engineering & Technology, Khulna, Bangladesh

<sup>b</sup> Institute of Sustainable Industries and Liveable Cities, Victoria University, Melbourne, Australia

## ABSTRACT

This study has examined some important aspects of the engineered smoke control system, namely the shape of smoke reservoirs and the quantity and distribution of smoke extract points within a smoke compartment. Three different shapes of smoke reservoirs have been selected for analysis, namely square, rectangular, and T-shaped. The shape of the smoke reservoir has been varied, but the area, length and height have been kept identical. Four different configurations of extract points have been used in each shape of the reservoir: a single extract point located at the corner of the smoke reservoir, a single extract point located at the centre of the smoke reservoir, two extract points evenly distributed within the smoke reservoir and four extract points distributed within the reservoir. These configurations were implemented in three different shaped reservoirs: square, rectangular and T-shaped. The area, length and height of the reservoirs have been kept identical. In this work, the design parameters such as area and length of the reservoir, extract rate of smoke, replacement of air in the reservoir and other parameters have been stipulated from the Singapore Fire Code and Building Research Establishment Report. Fire Dynamics Simulator (FDS) model has been employed for this research, and results show that variations in the shape of smoke reservoirs or quantity and distribution of smoke extract points do have an effect on the tenability within the smoke compartment. Generally, it has been found that the untenable conditions within a square-shaped smoke reservoir increased at the slowest rate, given the fact that the smoke compartment is symmetrically shaped with equal dimensions on all four sides of the compartment. The smoke compartment with the most number of bends, i.e. the T-shaped smoke reservoir, has shown that the untenable conditions increase at the fastest rate, followed by the most elongated shaped smoke compartment (i.e. rectangular). For the other part of the research, results have shown that the provision of four extract points evenly distributed within the smoke reservoir resulted in the most favourably stable smoke layer and the untenable conditions within the smoke compartment increased at the slowest rate. However, one vent in the centre shows a better outcome than two evenly distributed points. It has been exhibited in this research that varying the shape of the smoke reservoirs, the quantity and/or the distribution of smoke extract points does affect its tenability within a smoke compartment. A sensitivity analysis has confirmed these findings.

**Keywords:** Smoke control, extract points, smoke reservoir, tenability, FDS.

## 1. INTRODUCTION

In most fire occurrences, hot smoky gases were found to be the main cause of casualties and fatalities. Thus, it is very important for designers of buildings to incorporate this safety aspect into the buildings, which not only allows building occupants for safe evacuation but also facilitates fire fighters in their operations during a fire incident.

In most modern buildings, the building owner and the team of designers would always wish to maximise the space utilisation and to have large and open spaces such as shopping malls, factories and warehouses, atriums etc. This would usually encounter restrictions to meet the required fire safety regulations, such as fire compartmentalisation. The building authority would relax the above restrictions if buildings are designed with greater emphasis on the fire safety aspect in protecting human lives and fire fighters in their call of duty. A fully integrated *Engineered Smoke Control System*, which in recent times is recognised as a *Life Safety System* (CIBSE, 2010), would allow the building owners and designers to turn their wish into reality.

Human occupancy within a shopping mall is expected to be high, especially during peak periods. Thus, a life safety system such as an *Engineered Smoke Control System* is of paramount importance in ensuring the safety of human lives in the event of a real fire situation at the mall. An engineered smoke control system shall achieve the following key objectives: (i) to maintain a tenable environment within the building for the safe evacuation of occupants by removing hot, toxic gases and smoke and at the same time, minimise the high-temperature smoke to be within a tolerable level; (ii) to ensure fire-fighters are within a tenable environment in order to carry out their fire-fighting and rescue operations effectively; (iii) to ensure that the smoke control system installations blend in with the aesthetics of the building without compromising on the integrity of the systems.

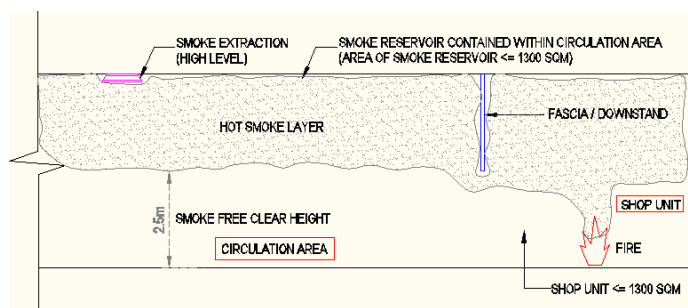
The concept of any *Engineered Smoke Control System* is typical. Buoyant smoke generated from a fire source would rise to the ceiling of the compartment and spread laterally until it reaches a wall or a vertical barrier. The smoke layer starts to deepen until it reaches a designated height, thus forming a smoke reservoir at a high level. Space from the ceiling to this designated height is known as the circulation space. Then

\* Currently in Institute of Sustainable Industries and Liveable Cities, Victoria University, Melbourne, Australia

† Corresponding author. Email: [igbal.mahmud@ce.kuet.ac.bd](mailto:igbal.mahmud@ce.kuet.ac.bd); [hm.mahmud@live.vu.edu.au](mailto:hm.mahmud@live.vu.edu.au)

smoke contained within the reservoir would be extracted to external space by smoke extract fans (mechanical system) or by fixed openings (natural system). Replaced air would be induced at a lower level to ensure that equilibrium is achieved, and turbulence at the smoke layer interface would be reduced, thus creating a smoke-free zone under the smoke layer for occupants, including fire-fighters.

For a prescriptive design, the size of the smoke reservoir needs to be kept within limits. For cases where smoke is removed from the circulation space, the area of smoke reservoir at the circulation space shall not exceed 1300 m<sup>2</sup> for a mechanical smoke ventilation system (clause 7.6.8 b of the Singapore Codes of Practice for Fire Precaution in Buildings (Singapore Fire Code, 2013) and rooms discharging smoke into the circulation space shall have a floor area not exceeding 1300 m<sup>2</sup> (clause 7.6.9 b of Singapore Fire Code, 2013) based on a fire size of 5 MW. Apart from that, the length of the smoke reservoir should not exceed 60 m. Figure 1 illustrates the above-mentioned principles collectively.



**Fig. 1** Principles of smoke control system.

Although the maximum area and length of a smoke reservoir are clearly defined by the code (Singapore Fire Code, 2013), there is no limitation on the shape of smoke reservoirs. As such, the shape of the smoke reservoir may vary and would be defined by the stakeholders, in particular, the architect and fire safety engineer. Typical shapes of smoke reservoirs include circular, square, rectangular, and T-shaped. In newer built shopping malls with a modern theme, odd-shaped smoke reservoirs could also be found. There are also no specifications of numbers and distribution of smoke extraction points.

Typical shapes of smoke reservoirs include circular, square, rectangular, and T-shaped. In newer built shopping malls with a modern theme, odd-shaped smoke reservoirs could also be found. There are also no specifications of numbers and distribution of smoke extraction points.

Therefore, the aim of this study is to establish the effects of variation in the shape of smoke reservoirs and numbers and distribution of smoke extraction points through Computational Fluid Dynamics (CFD) analysis while keeping all other design parameters constant. How would the tenability for an elongated smoke reservoir fair against a square-shaped smoke reservoir considering all other parameters in the fire scenario remain the same? Must improvements be made with regards to the quantity, location and distribution of smoke extraction points within smoke reservoirs? This study seeks to clarify certain aspects associated with smoke control designs for retail shopping malls; in particular, the shape of smoke reservoirs and how the quantity and distribution of smoke extract points would affect the overall performance of the smoke control system. In this study, Fire Dynamic Simulator (FDS) (McGrattan *et al.*, 2021a) has been used as the CFD tool as it has been validated for the modelling of temperature and smoke movement in a compartment, water-mist spray and evaporation of droplets emanated from a spray (Sikanen *et al.*, 2014; Sikanen and Hostikka, 2016; Mahmud *et al.*, 2016; Sarwar *et al.*, 2013; Janft *et al.*, 2014; Moinuddin *et al.*, 2017; Mahmud *et al.*, 2016). Furthermore, FDS has been validated and verified in a wide range of capacity by the National Institute of Standards and Technology (NIST), and the complete summary of FDS validation efforts are available in the FDS validation and verification guides (McGrattan *et al.*, 2021b; McGrattan *et al.*, 2021c). It is to be noted that fire scenarios and

mandatory design parameters considered in this study are based on Singapore Codes of Practice (Singapore Fire Code, 2013) as well as Building Research Establishment reports (Morgan and Gardner, 1990; Morgan and Hansell, 1994; Morgan *et al.*, 1999).

## 2. DESIGN OF THE STUDY

The parameters which are involved in designing and carrying out this study include: (i) examining the impact of varying the shape of smoke reservoirs while keeping all other parameters a constant, (ii) examining the impact of varying the quantity and distribution of smoke extract points within a smoke reservoir while keeping all other parameters a constant. The details of the smoke reservoir and extract points are described below.

### 2.1 Shape of Smoke Reservoirs

Three different shapes of smoke reservoirs have been selected for analysis, namely square, rectangular, and T-shaped. Circle and oval shapes would not be examined in this study as it is assumed that the results would be near similar to square and rectangular-shaped smoke reservoirs, respectively.

The shape of the smoke reservoir would be varied, but the area and length would be identical and not exceeding 1300 m<sup>2</sup> and 60 m, respectively. The height of the circulation space would be fixed at 5 m, which is the average height of a typical floor of a shopping mall. Table 1 shows the dimensions and area of the smoke reservoirs. Figure 2 shows the plan view of each smoke reservoir. To simplify the situation, the full face of each shop would be fully open, and there would be no soffit in the shops.

**Table 1** Shape and size of smoke reservoirs.

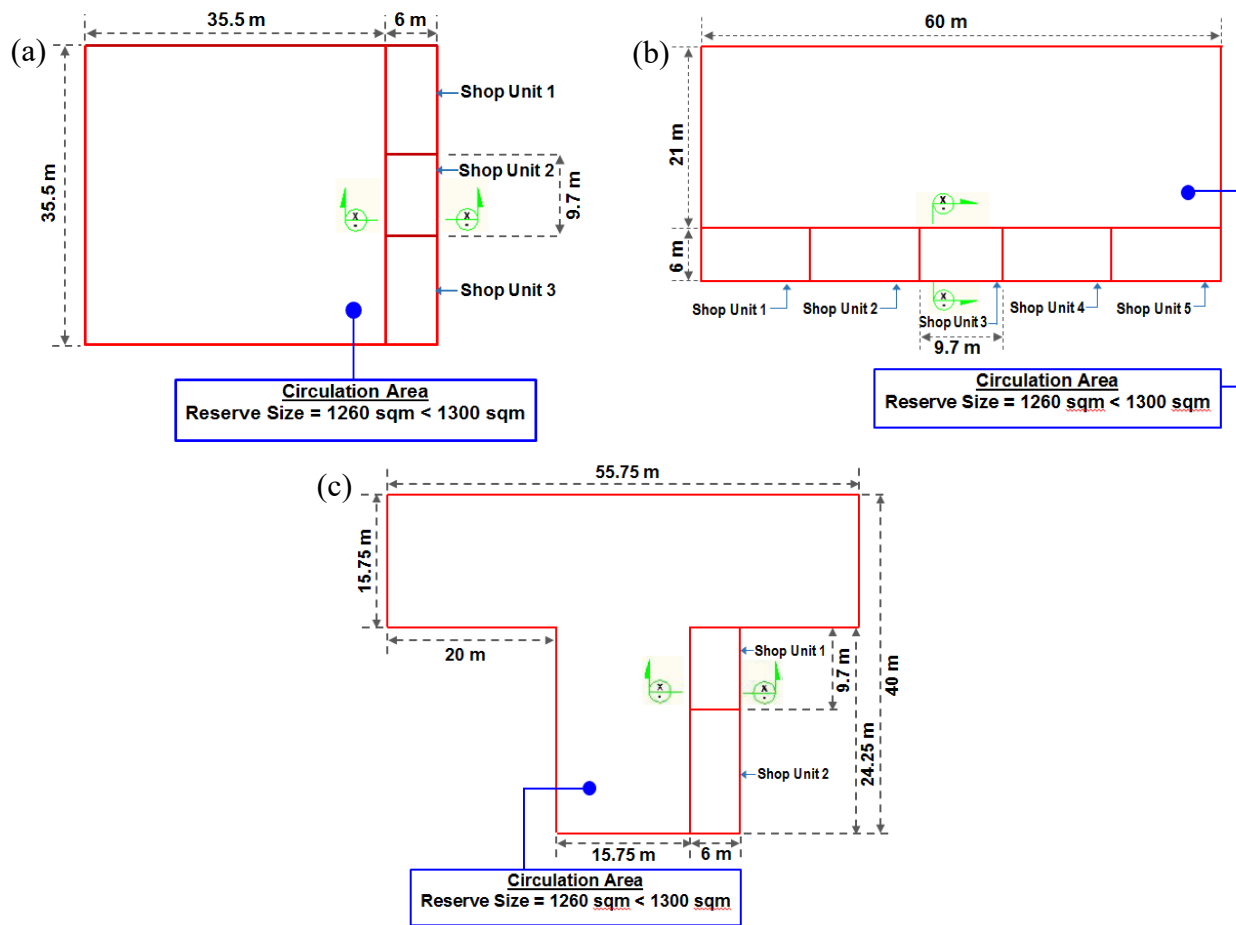
Sl. No.	Shape of the Smoke Reservoir	Dimensions of Smoke Reservoir (m) (L × W × H)	Area of Smoke Reservoir (m <sup>2</sup> )
1	Square	35.5 × 35.5 × 5	1260
2	Rectangle	60 × 21 × 5	1260
3	T-Shaped	40 × 15.75 × 5	1260
		20 × 15.75 × 5	

### 2.2 Quantity and Distribution of Smoke Extract Points

Another important design element associated with the smoke reservoir is the quantity and distribution of smoke extract points. According to the Singapore Fire Code (2013), smoke extract points shall be distributed evenly within the smoke reservoir to prevent the formation of any stagnant regions. By doing so, a smoke-free clear height of at least 2.5 m can be maintained throughout the entire smoke reservoir. The number of smoke extract points can be determined through methodologies and calculations stipulated in the Building Research Establishment report (Morgan and Gardner, 1990; Morgan and Hansell, 1994; Morgan *et al.*, 1999). The calculation in Appendix A of (Rajaram, 2014) shows that a minimum of one extract point is required. However, even though the smoke control calculations show that only one smoke extract point is required, it may not be sufficient to maintain a smoke-free clear height of at least 2.5 m throughout the smoke reservoir.

Therefore, as another objective of this research is to examine the impact of varying the quantity and distribution of smoke extract points, the number of smoke extract points has been varied from 1 to 4 within the different shapes of smoke reservoirs considering that all other parameters such as fire size and volumetric smoke exhaust rate are constant. Hence, the following quantity and distribution of smoke extract points have been modelled:

Case 1: One smoke extract point located at the most remote corner of each reservoir.



**Fig. 2** Plan view of the different shaped smoke reservoir; (a) Square shaped, (b) Rectangular shaped, and (c) T-shaped.

**Table 2** Position of the extract points in the smoke reservoir.

Number of extract point	Label of the extract point	Square		Rectangular		T-shaped	
		Distance from the left wall (m)	Distance from the wall containing opening 2 (m)	Distance from the left wall (m)	Distance from the wall containing opening 2 (m)	Distance from the left wall (m)	Distance from the wall containing opening 2 (m)
One extract point corner	—	6	17.25	6	10.5	6	32
One extract point centre	—	17.25	17.25	30	10.5	8	23.5
Two extract points	1	17.25	6	15.5	10.5	28	32
	2	17.25	29.5	44.5	10.5	8	8
Four extract points	1	6	17.25	10	10.5	10	32
	2	29.5	17.25	20	10.5	45.75	32
	3	17.25	6	40	10.5	8	23.5
	4	17.25	29.5	50	10.5	8	8

Case 2: One smoke extract point located at the centre of each reservoir.

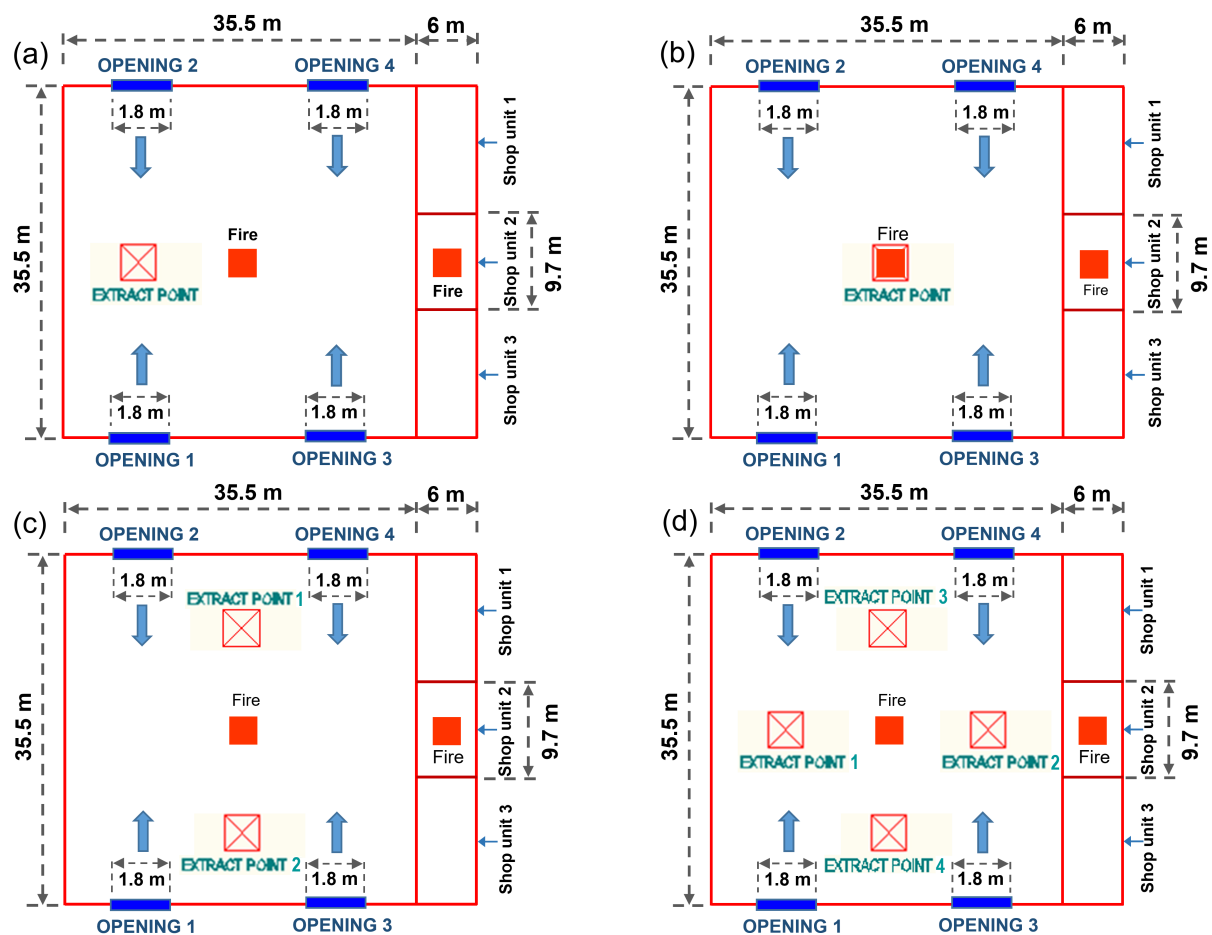
Case 3: Two smoke extract points evenly distributed within each smoke reservoir.

Case 4: Four smoke extract points evenly distributed within each smoke reservoir.

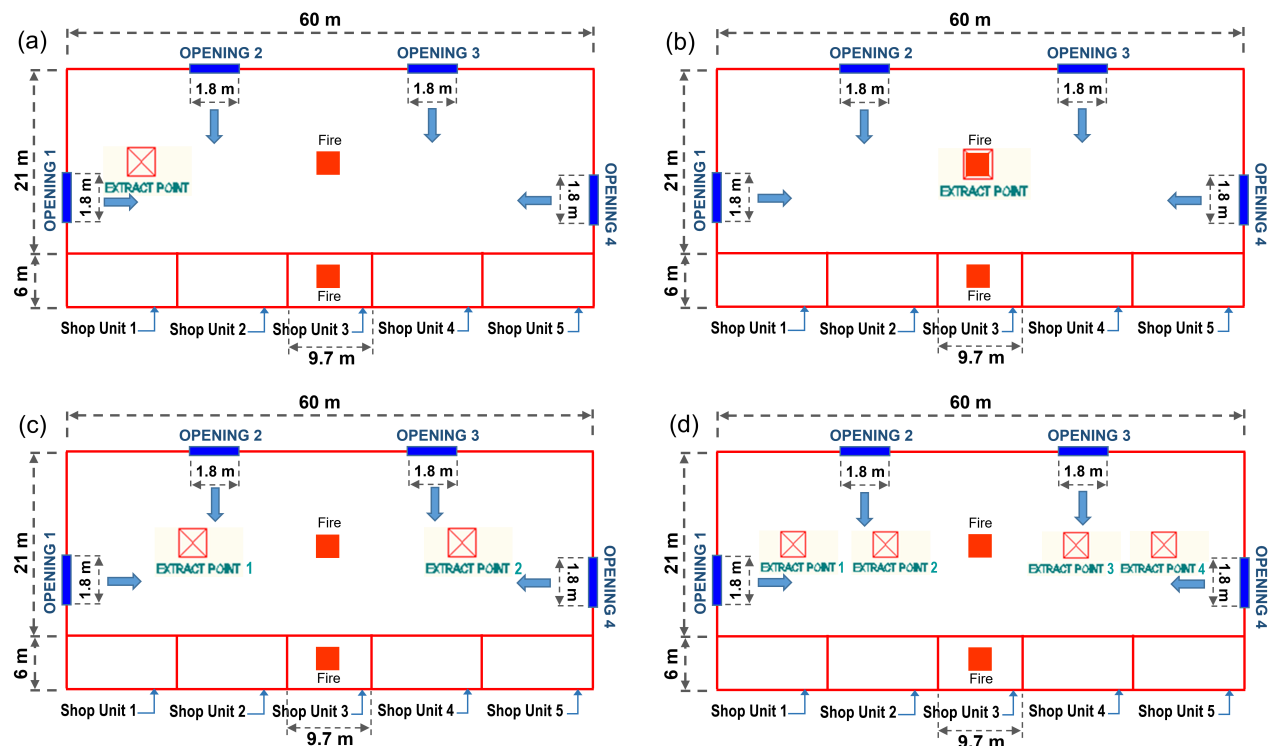
The smoke extract point(s) has been located at a high level, well within the smoke reservoir, at the height of 4.8 m from floor level, directly beneath the ceiling. This has been remained constant for all fire scenarios. Figures 3 to 5 show the location of extract points in differently shaped smoke reservoirs, and Table 2 describe their positions inside the reservoirs.

## 2.3 Replacement Air Intake

The amount of replacement has been derived from the requirements stipulated in Building Research Establishment reports (Morgan and Gardner, 1990; Morgan and Hansell, 1994; Morgan *et al.*, 1999) and Singapore Fire Code (2013). The amount of replacement air has been fixed for all scenarios and has been induced into the smoke zone through unobstructed openings located on the façade. The height of the opening is 2.1 m. In order to minimise the effects of turbulence at the smoke layer interface, the replacement air has been induced into the smoke zone at a slow rate (i.e., velocity not exceeding 5 m/s). This is in accordance with the requirements stipulated in the Building Research Establishment report (Morgan and Gardner, 1990; Morgan and Hansell, 1994; Morgan

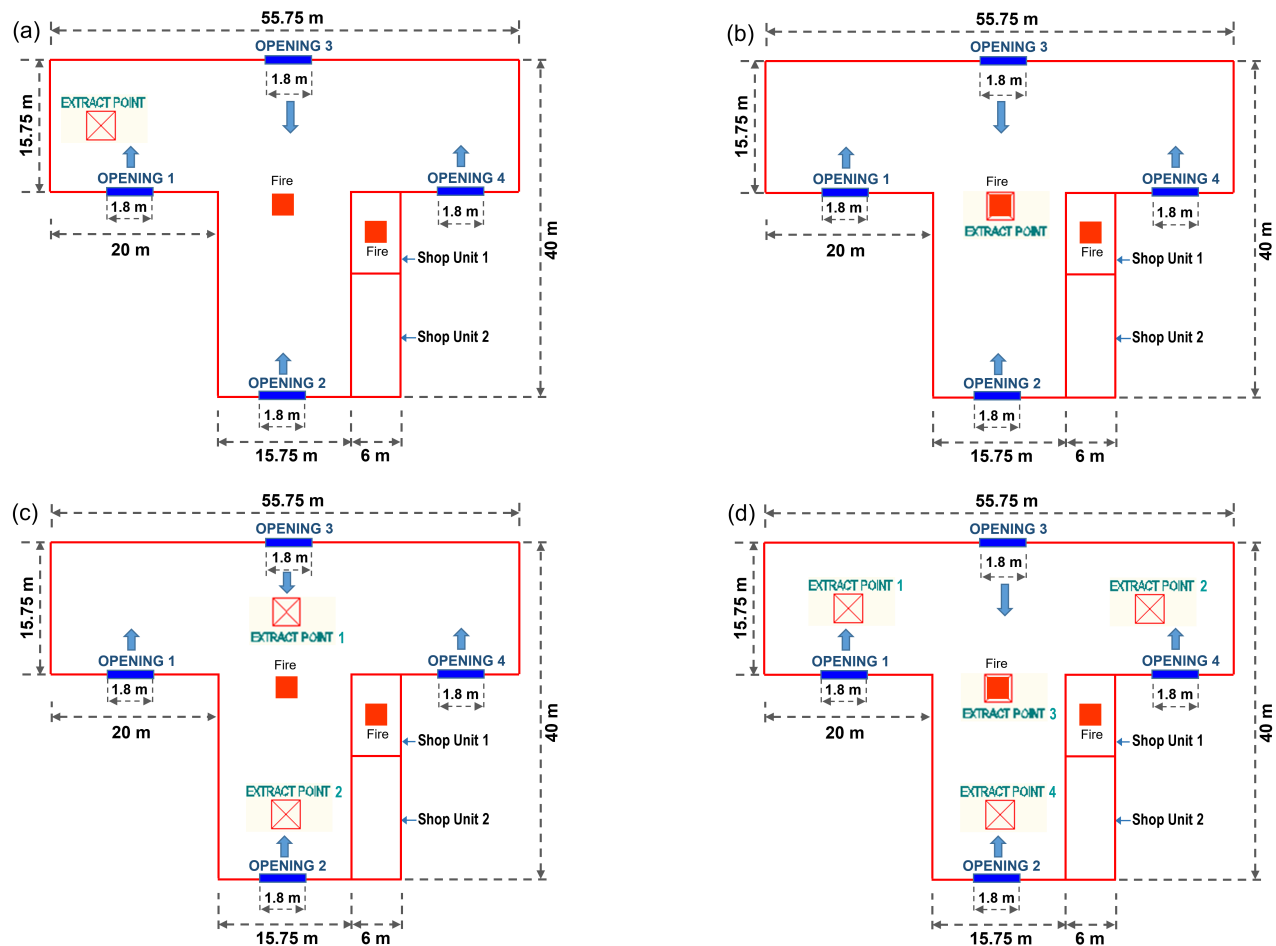


**Fig. 3** Location of extract points in the square-shaped smoke reservoir; (a) 1 extract point located at the corner, (b) 1 extract point located at the centre, (c) 2 extract points evenly distributed and (d) 4 extract points evenly distributed.



**Fig. 4** Location of extract points in the rectangular-shaped smoke reservoir; (a) 1 extract point located at the corner, (b) 1 extract point located at the centre, (c) 2 extract points evenly distributed and (d) 4 extract points evenly distributed.





**Fig. 5** Location of extract points in the T-shaped smoke reservoir; (a) 1 extract point located at the corner, (b) 1 extract point located at the centre, (c) 2 extract points evenly distributed and (d) 4 extract points evenly distributed.

*et al.*, 1999) and Singapore Fire Code (2013). However, Building Research Establishment recommends a velocity lower than 3 m/s to be used (Morgan and Gardner, 1990; Morgan and Hansell, 1994; Morgan *et al.*, 1999). For each scenario, four openings evenly distributed have been modelled on the building façade. The locations of the openings in the smoke reservoirs are shown in Figures 3-5. For the axi-symmetric fire scenario, where the fire has been located at the centre of the circulation area, air velocity through the door is  $\sim 1$  m/s. For the non axi-symmetric fire scenario, where the fire has been located within one of the shops, air velocity through the door is  $\sim 1.6$  m/s.

## 2.4 Fire Scenarios and Smoke Extraction Rates

A heat release rate of 5 MW and a fire perimeter of 12 m have been used as the design fire for a sprinkler-controlled fire. The design fire size has been obtained from Building Research Establishment report number 186 (Morgan and Gardner, 1990) and has been used for all fire scenarios. A  $t^2$ -fire has been considered with a fast rate of fire growth.

For all of the axi-symmetric cases, the fire is located at the middle of the compartment and shown with a red box as shown in Figures 3-5; in the case of a single extraction point at the centre, the fire is located underneath the extract point at the ground level. For the non axi-symmetric cases, the fire is located within a shop, as shown with a red box in Figures 3-5.

For this study, plastic (PMMA) has been used as the fire source since most of the products and packaging available in the shopping malls contains a lot of plastics. The products being sold often contain plastics as well. The soot yield for PMMA is 0.014 kg/kg (CIBSE, 2010). A soot

yield of 0.014 kg/kg would produce more stabilised results in CFD based fire model such as Fire Dynamics Simulator (FDS) (McGrattan *et al.*, 2021a) and is therefore adopted for all cases. However, it is to be noted that in shopping malls, displays and shelves are often constructed of laminate or particle board. Product packaging typically contains a lot of plastics and expanded foams. Typical soot yields for plastics are usually higher than those for wood, and therefore soot yield for PMMA has been used for all cases.

The smoke extraction rate for the mechanical smoke ventilation system has been calculated from prescriptive methodologies stipulated in the Building Research Establishment report (Morgan and Gardner, 1990; Morgan and Hansell, 1994; Morgan *et al.*, 1999). The minimum smoke layer height would be 2.5 m from floor level. For an axi-symmetric fire plume scenario, the calculated volumetric smoke extraction rate is 15  $\text{m}^3/\text{s}$ . For a non axi-symmetric fire plume scenario, the calculated volumetric smoke extract rate is 24  $\text{m}^3/\text{s}$  (Rajaram, 2014). These flow rates were implemented immediately when fans turned on without any delay or ramped function.

There have been photoelectric smoke detectors placed within the circulation space (under each extraction point 4.9 m above the floor) and within the shop unit (at the centre of each shop 4.9 m above the floor) for axi-symmetric and non axi-symmetric fire plume cases, respectively. The smoke detection system automatically detects the fire, identifies its location (i.e., whether within circulation space or shop unit) and activates the appropriate flow rate at each extract point to generate a total volumetric smoke extraction rate of either 15  $\text{m}^3/\text{s}$  or 24  $\text{m}^3/\text{s}$  within the smoke compartment for axi-symmetric and non axi-symmetric fire plume cases, respectively. Overall, 24 numbers of scenarios have been

considered. Each case has been tagged and referenced as follows in Table 3. Here, AS and NAS refer to axis-symmetric and non axis-symmetric fire plume, respectively; S, R, and T refer to square, rectangular, and T-shaped smoke reservoir, respectively; 1 refers to one smoke extract point located at the corner of the reservoir; 2 refers to one smoke extract point located at the centre of the reservoir; 3 refers to two smoke extract points evenly distributed within the reservoir; and 4 refers to four smoke extract points evenly distributed within the reservoir. As for example, AS\_T1 refers to axis-symmetric fire plume – T-shaped smoke reservoir with one smoke extract point located at the corner of the reservoir, and NAS\_R3 refers to non axis-symmetric fire plume – Rectangular-shaped smoke reservoir with two smoke extract points evenly distributed within the reservoir. The duration of the simulation for each case was 600 seconds (i.e., 10 minutes).

**Table 3** Nomenclature of 24 cases of fire scenario.

Axi-symmetric fire cases	Non axis-symmetric fire cases
AS_S1, AS_S2, AS_S3, AS_S4	NAS_S1, NAS_S2, NAS_S3, NAS_S4
AS_R1, AS_R2, AS_R3, AS_R4	NAS_R1, NAS_R2, NAS_R3, NAS_R4
AS_T1, AS_T2, AS_T3, AS_T4	NAS_T1, NAS_T2, NAS_T3, NAS_T4

## 2.5 Tenability Criteria

For the purpose of assessing the performance of the building under emergency fire conditions the occupant life safety tenability acceptance criteria from Fire Engineering Guidelines (Fire Code Reform, 1996) have been adopted. Tenability has been observed in general within the entire model and then in particular at the exit points of the model. The tenable conditions have been considered in two cases; temperature and visibility. If the smoke temperature is  $\leq 60^\circ\text{C}$  and visibility/optical density (toxicity) is  $\geq 10\text{ m} / \leq 0.1\text{ m}^{-1}$ , then the room has been considered as tenable (Fire Code Reform, 1996). According to Fire Code Reform (1996), if the optical density does not exceed  $0.1\text{ m}^{-1}$ , then the compartment would remain tenable in terms of toxicity, and if the visibility does not drop below 10m, optical density does not exceed  $0.1\text{ m}^{-1}$ .

## 2.6 CFD for Case Analyses

It is evident that full or even part scale fire tests to examine fire and smoke behaviour would require an extensive amount of resources, funds and time. In order to execute this study within a reasonable time frame and within a reasonable budget, CFD modelling has been undertaken for this research. In particular, the FDS program has been used for analysis. In FDS, there are two different fire modelling options available as mentioned: (a) prescribed fuel mass loss rate (as opposed to predicting) model and (b) pyrolysis/evaporation model. In the prescribed fuel mass loss rate (MLR) model, a fire size is prescribed, and FDS calculates volatile (gaseous form of the fuel) production rate (mass loss rate of the fuel) by dividing the prescribed fire size by heat of combustion (HoC). HoC of PMMA, which is  $22.80\text{ MJ/kg}$  (Abu-Bakar, 2019), is used in this study. The fuel bed created in FDS then acts as a pump that pumps volatiles at that production rate. Then the reaction between oxygen and volatiles are modelled by the FDS combustion model. In the pyrolysis/evaporation model, FDS calculates the volatiles production rate through the simulation of the pyrolysis (for solid fuel) or evaporation (for liquid fuel) process. The prescribed fuel MLR model is well validated by researchers, e.g. (Zou and Chow, 2005; Moinuddin and Li, 2010; Moinuddin *et al.*, 2011). This means when the fire size is prescribed FDS, it can reasonably well calculate temperatures and radiation fluxes at various locations within a compartment.

A prescribed fuel MLR model is adopted in this study rather than a pyrolysis/evaporation model. FDS version 6.7 has been (which is the latest version at the current time of the study) used, and the HVAC function (implying modelling transport of heat and combustion products through a duct network) was used in the model. As the same version is

adopted for all scenarios, it assures that program algorithms used would be identical throughout, allowing comparison to be executed without inaccuracies from using different FDS versions for a different model.

## 2.7 Limitation of the study

The following limitations are applicable to this research:

- The research examines the design parameters stipulated in Singapore Fire Code (2013) and Building Research Establishment report numbers 186, 258 and 368 only (Morgan and Gardner, 1990; Morgan and Hansell, 1994; Morgan *et al.*, 1999).
- A mechanical smoke ventilation system is examined. The results would not be applicable for smoke ventilation by natural means.
- Only three shapes of smoke reservoirs are modelled with identical sizes. The results may not be applicable for other shapes or different sizes.
- Sprinkler activation and the cooling effects of sprinklers are not modelled.
- Tenability criteria are based on visibility and temperature only. Concentrations of toxic gases such as carbon monoxide are not modelled for the reason given in Section 2.5.
- No full or reduced scale tests have been conducted to verify the CFD modelling results. This is due to the large amount of cost and time required for executing such tests. However, the outcome of this study may help to plan and design for the future study.

## 3. APPROACH TO CFD ANALYSIS

### 3.1 Operating and Boundary conditions

The operating and boundary conditions for the smoke modelling were as follows:

- The air temperature inside computational domain =  $24^\circ\text{C}$ .
- External air temperature =  $24^\circ\text{C}$ .
- The compartment floors were modelled as concrete, external walls as fire brick, internal partition walls and shop front bulk head as non-combustible gypsum board. The material properties are obtained from (Drysdale, 2011; SFPA, 2008; Manzello *et al.*, 2008), which are presented in Table 4.
- The model was surrounded by free, neutral pressure boundaries.
- No external wind conditions.

**Table 4** Thermo-physical properties of the materials.

Material	Conductivity (W/m/K)	Specific heat (kJ/kg/K)	Density (kg/m <sup>3</sup> )	Emissivity	Thickness (m)
Concrete	1.8	1.04	2280	0.9	0.2
Fire brick	0.08	1.04	880	0.8	0.1
Gypsum board	0.17	1.09	960	0.9	0.01

### 3.2 Output Analysis

The condition of visibility, temperature and smoke velocity in the compartment has been examined within the entire smoke compartment for all FDS cases. This has been done by examining a planar slice cut at 2.5 m above the floor level along the z-direction. There also have x- and y- planar slices provided for each FDS case, spaced at approximately 5m to 6m intervals to get the estimation of visibility, temperature and velocity in the x and y direction of the compartment.

Four (4) openings have been provided on the façade for each case. These openings are meant for replacement air to be naturally induced into

the smoke compartment and for occupants to evacuate premises. Thus, tenability at these openings or exit points needs to be analysed. Devices representing thermocouples (TC) have been placed near these 4 exits points, planar slices cutting across these exits and slice at 2.5 m along the z-direction (along with the height of the compartment) from floor level has been used to determine temperature and visibility at these exits.

Based on data obtained from the device and slice files, tenability at these exits/openings could be determined and compared against results obtained from other different shapes of smoke reservoirs or from different quantities and distribution of smoke extract points.

There have also been multiple numbers of visibilities, temperature and velocity devices provided within the smoke compartment. These devices have been spaced at approximately 5m to 6m intervals as well as in line with all x and y planar slices.

### 3.3 Limitation and Uncertainty Analysis of CFD analysis

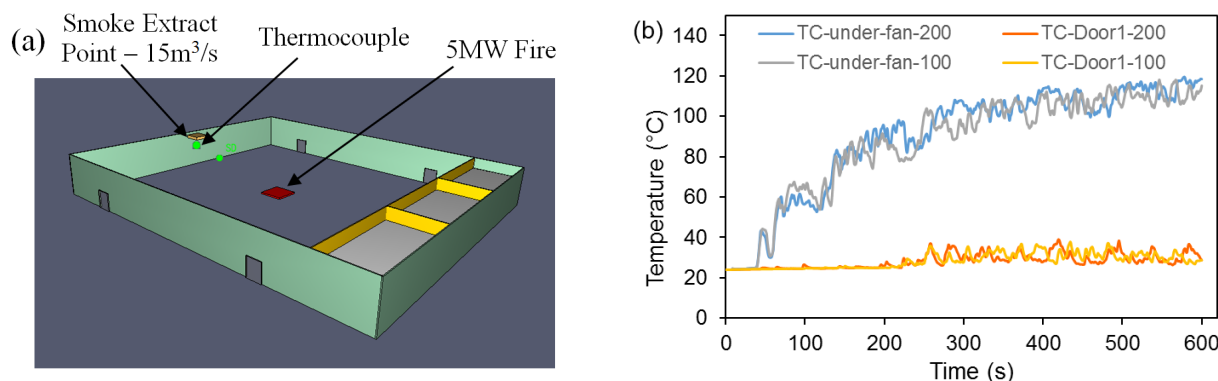
Quantifying the numerical uncertainty is important in any CFD based analysis. Freitas (2002) identified three main sources of uncertainties: (i) uncertainty generated by input variables, (ii) uncertainty generated by the model, and (iii) uncertainty in the predictions.

The uncertainty generated by input variables may introduce from input parameters into the model. For instance, specifying the wrong value of input parameters can lead to inaccurate results. The replacement air intake in the compartment prescribed in Section 2.3, soot yield of the fuel and fan extraction rate prescribed in Sections 2.4, prescribed HoC in Section 2.6, emissivity, conductivity, specific heat, density and thickness of the materials prescribed in Section 3.1 – all can be sources of error. Extreme care has been taken to prescribe them as close to reality as possible, and sources of these input parameters are provided. However, as this is a comparative study, unless there is a gross variation in these parameters, the outcome of this study is unlikely to be changed.

The uncertainties generated by the model are emanated from different formulations, structures, or implementations (Freitas, 2002). A feature of FDS is that it uses a low Mach number formulation of the Navier-Stokes equations. Fire is a variable-density, low-speed flow, and therefore this assumption is valid for this study. Secondly, the state equation is used to calculate temperature instead of solving the energy equation. However,

FDS ensures that the energy budget is correctly satisfied. Furthermore, a mixing controlled, fast chemistry combustion model is used (McGrattan *et al.*, 2021d). Despite these simplifications, FDS could predict relevant experimental results well (Zou and Chow, 2005; Moinuddin and Li, 2010). Similar to (Zou and Chow, 2005; Moinuddin and Li, 2010; Moinuddin *et al.*, 2011) prescribed fuel (MLR) model has been used in this study which eliminates a significant amount of uncertainty pyrolysis/evaporation model. While these are also limitations of the model, as the same version is adopted for all scenarios, it ensures that program algorithms used would be identical throughout, allowing comparison to be executed without inaccuracies from using different FDS versions.

Freitas (2002) suggested that numerical uncertainty in the predictions can occur due to the influence of discretisation and iterative errors. Most code has a tolerance level to reduce iterative error, and so has the FDS. The most common numerical uncertainties arise from discretisation as to obtain faithful solutions, certain turbulence and flame length scales need to be adequately resolved. That's why grid convergence study plays an important role in CFD based simulations. In conducting any CFD based simulation, the results of simulation should not be significantly changed with the change of the size of grid or cell. Therefore, grid convergence analysis has been performed to ensure that the results obtained through simulations become convergent. FDS case AS\_S1 has been used for the analysis, and cell sizes of 200 and 100 mm have been used. The fire scenario has been identical in the compartment for each of the grid sizes. Results of obscuration level from one photoelectric smoke detector, placed within the vicinity of the fire source and mounted beneath the ceiling, have been considered. Figure 6(a) shows the details of the modelled scenario. The temperature at two positions of the room was calculated – under the exhaust fan and near one of the doors, and the data has been plotted against time for all two cases. The results of the simulations are presented in Figure 6(b). Results show the change of temperature varies over a period of time. From the figure, the result of the model with 200mm and 100mm grid sizes shows very close to each other with the same level of “noise”. Therefore, the study has shown that results are grid converged, and a standard grid size of  $100 \times 100 \times 100$  mm can be used for all 24 numbers of FDS cases.



**Fig. 6** Grid convergence study; (a) FDS model, (b) Grid sensitivity analysis.

Furthermore, to have confidence in the grid size and to quantify the numerical uncertainty generated due to grid resolution, the grid convergence index (*GCI*) has been calculated. Karimi *et al.* (2012) used the *GCI* method proposed by Roache (1994) to quantify the numerical uncertainty. The *GCI* is a measure of the percentage the computed value is away from the value of the asymptotic numerical value. It indicates an error band on how far the solution is from the asymptotic value and how much the solution would change with further refinement of the grid. A small value of *GCI* indicates that the computation is within the asymptotic range (Oh *et al.*, 2009; Cheng *et al.*, 2011).

The *GCI* is based on generalised Richardson (1911) extrapolation and involves the comparison of discrete solutions at two different grids spacing. The *GCI* for the finer grid can be expressed as follow:

$$GCI_{finer} = \frac{F_s \epsilon_{rms}}{r^p - 1} \times 100 \quad (1)$$

Where,  $\epsilon_{rms}$  is the *rms* value of the relative error which provides an initial measure of grid convergence for individual point *n* as

$$\epsilon_{rms} = \left( \frac{\sum_{i=1}^n \epsilon_i^2}{n} \right)^{1/2} \quad (2)$$

Here,  $\epsilon_i$  refers to the relative error at a certain point and can be calculated as the magnitude between the coarse and fine solutions, i.e.  $\epsilon_i = (f_2 - f_1)/f_1$ ,  $f_1$  and  $f_2$  are the two individual solutions calculated from two different grid spacing,  $h_1$  and  $h_2$ , corresponding to the fine and coarse grid spacing, respectively;  $r$  is the grid refinement ratio and can be calculated as  $(h_2/h_1)$ ;  $p$  is the order of accuracy of the algorithm or the numerical scheme, for second-order scheme  $p=2$ .  $F_s$  is the factor of safety, which is a scaling factor to convert the error estimate to an uncertainty estimate. Roache (1997) suggested a range of  $1.25 \leq F_s \leq 3$  for the factor of safety.  $F_s = 3$  is recommended when a two-grid convergence study is performed, while  $F_s = 1.25$  can be used when a more rigorous grid convergence procedure has been followed involving three or more grids. However, Roache (1997) strongly recommended using  $F_s = 3$  for the sake of adequate conservatism and uniform reporting purposes.

The coarse and fine grids were 200 and 100mm, respectively, as shown in Figure 6(b). The  $GCI$ s has been computed for two grid sizes - 200 and 100 mm mesh. A second-order scheme ( $p=2$ ) with a factor of safety 3 ( $F_s = 3$ ) has been used in the calculation. The  $GCI$  has been calculated as only 8%. Brown et al. (2008) presented  $GCI$  values ranging from 15.3% to 208% for single time-averaged values of various parameters of fire scenarios, and Karimi et al. (2012) calculated  $GCI$  values ranging from 7.2% to 303% for velocity prediction of flow through a hydro-cyclone. Therefore, the  $GCI$  obtained in this study can be considered fair.

## 4. RESULTS AND DISCUSSION

### 4.1 Analysis on Shapes of Smoke Reservoirs

In this section, the comparison of the results obtained from the FDS cases has been carried out varying the shape of the smoke reservoir to examine how the tenability has been affected by the shape of the compartment while keeping all other design parameters constant. The results obtained from FDS contour plots, vector plots and devices have been used for the purpose of analysis.

The tenability within the smoke compartment has been identified by examining the visibility and temperature contour plots along the  $z$  plane. The  $z$  slice visibility and temperature contour plots for one extract point located at the corner and fire located axi-symmetrically are presented in Figures 7 and 8 for all three shapes. The  $z$  slice visibility and temperature contour plots for other types of shapes of reservoir and number and distribution of extract points are available in the supplementary document. The visibility and temperature scale at the end of Figures 7 and 8, respectively, represent the tenability criteria for assessing life safety. The visibility scale is marked from 0 m to 9.99 m, and the temperature scale is marked from room temperature 24°C to 60°C. The amount of tenable area, in terms of visibility and temperature, has been determined from the contour plots using the grid-square method of area.

The tenability in the compartment, in terms of visibility, has been quantified at a different level of time – 100, 200, 300 and 400 seconds and the results are presented graphically in Figure 9. Within 400 seconds, most of the cases reached an untenable condition. Therefore, results beyond 400 seconds are not presented. At the time of 100 seconds for axi-symmetric cases, in most of the cases, 30% area has less than 10 m visibility. The condition is best when the fire is located underneath the extract point, as seen in AS\_S2, AS\_R2, and AS\_T2. Among the three types of smoke reservoir, the visibility for square-shaped compartments with different types of extract points are better compared to rectangular and T-shaped smoke reservoir. On the other hand, the visibilities for the T-shaped reservoirs (except AS\_T2) were worst in all cases; especially, for AS\_T1 and AS\_T3, the visibilities were more than 30%. This was due to the reason that the T-shaped reservoir has a sharp bend, and the extract point was located far away from the fire source. Overall, the condition during axi-symmetrically located the fire, at 100 seconds, is better than non axi-symmetrically located fire. However, caution should be exercised within this time the fire has not grown enough, and the smoke has not spread much to affect the visibility significantly.

By 200 seconds, for axi-symmetrically located fire, the visible area is more when the single extract point has been located centrally, and among

them, especially the condition has been better for the square-shaped and rectangular-shaped reservoir compared to the T-shaped reservoir (Figure 9b). The non-visible area is more in T-shaped reservoirs; the reason is that due to bending in this reservoir, the exhaust fan positioned at one side did have less influence on smoke extraction gathered at the other side. At 300 seconds and afterward, the untenable condition has reached to about 100% for all of the cases of non axi-symmetrically located fire.

The tenability in the compartment, in terms of temperature, has been analysed and the results are presented graphically in Figure 10. The percentage of the untenable area has been considered when the temperature has crossed 60°C.

At the time of 100 seconds, it has been seen that, in most of the cases, the untenable area is less than 5 percent due to the reason that the fire has not grown enough by that time. However, at 200 seconds, the fire has grown enough that in most of the cases around 20% areas in the compartment has reached to untenable condition, where the temperature in those areas has exceeded 60°C. The least effect of temperature has been found in the cases of AS\_S2, AS\_R2, and AS\_T2, where the extract point was exactly above the fire (this has also been the case for visibility). As a result, the extraction of smoke and hot air has been most efficient compared to other cases. The most severe cases have been observed in cases of T-shaped reservoirs (except AS\_T2). In cases of the axi-symmetric location of the fire, more than 50% area has reached untenable conditions for the T-shaped smoke reservoir. In cases of the non axi-symmetric location of the fire, though the untenable condition was reached in less than 50% area, it is higher among the other shapers of the reservoir.

However, overall, the situation in the compartment for the axi-symmetric location of the fire has been found better than that of the non axi-symmetric location of the fire. This is due to the reason that for the non axi-symmetric location of the fire, the fire is partially confined in a shop resulting; as a result, the extractor takes more time to remove the smoke.

By 300 seconds, the fire in the compartment has spread out; especially, the effect has been severely observed in axi-symmetrically located fire. In those cases, except AS\_S2 to AS\_T2, the temperature has reached an untenable condition in more than 80% area of the compartment. In cases of AS\_S2 and AS\_R2, the untenable area in the compartment has been limited to only less than 5%. However, the situation is the worst in cases of the T-shaped reservoir; in all cases of the T-shaped reservoir (except AS\_T2), the area of the untenable condition has exceeded 90%.

By 400 seconds, in the cases of axi-symmetrically located fire, the untenable area in the compartment has reached almost 100%, except in two cases. Among the cases of axi-symmetrically located the fire, AS\_S2 and AS\_R2 have shown better condition within the duration of 400 sec; the untenable area in these two cases is less than 10%.

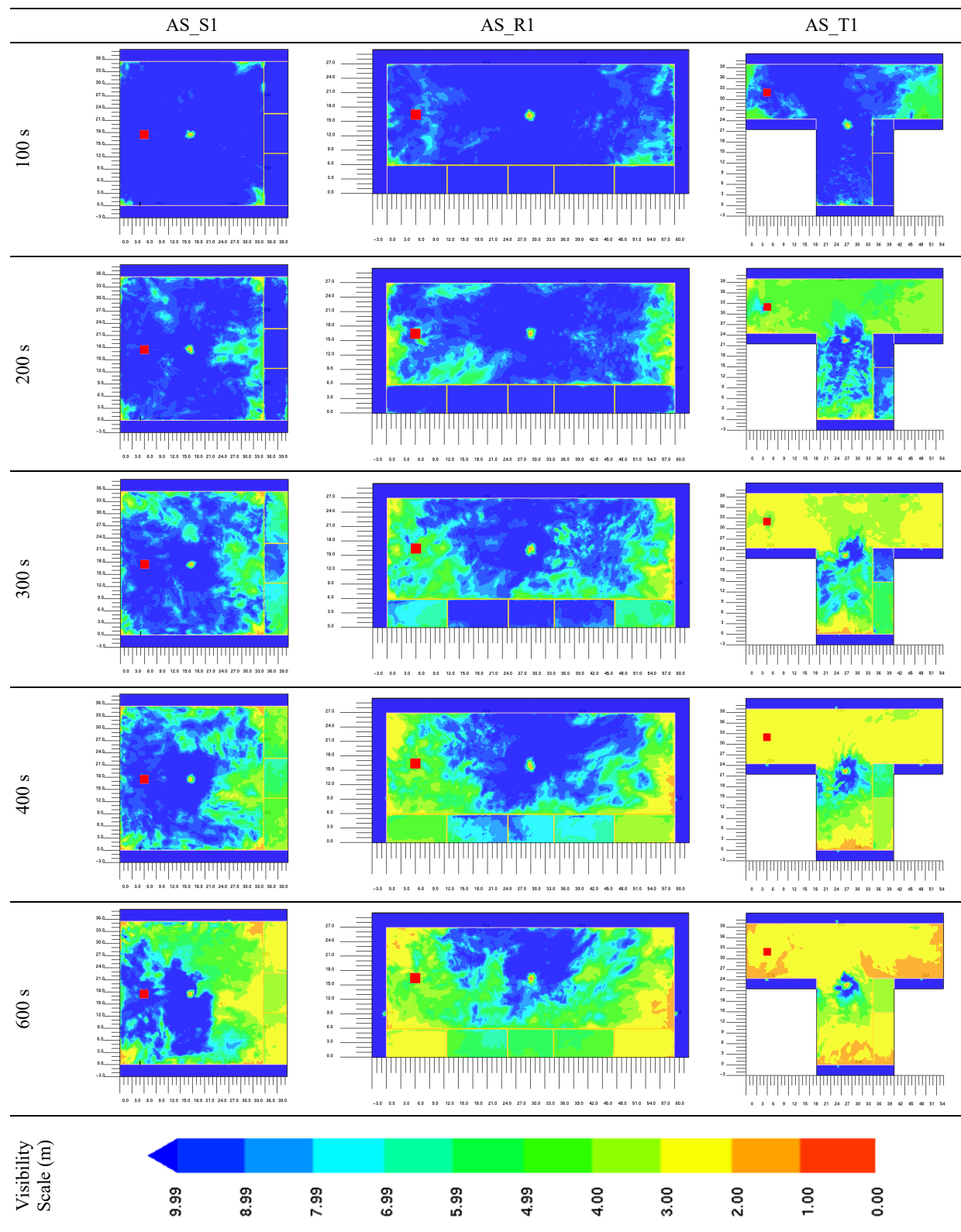
In comparison between the cases of axi-symmetrically and non axi-symmetrically located fire, overall, the latter has shown better condition. The untenable area in the compartment in the latter cases with square and rectangle shape is not less than that of the T-shaped compartment.

In comparison between temperature and visibility (Figure 9 and 10), the untenable condition in terms of visibility has reached earlier than that of the temperature. In the case of visibility, there are 15 cases where at least 50% area reached untenable condition at 200 seconds, whereas this is only for 3 cases where the temperature exceeded 60°C in 50% area of the compartment at 200 seconds. The same phenomenon was observed at 300 and 400 seconds, where the temperature situation was better than visibility within the compartment.

The visibility at different exits of the compartment for different cases has been analysed. This analysis is based on the time taken to reach a level where the visibility is less than 10 m near the exit. The duration of the visibility near the four exits are presented graphically in Figure 11.

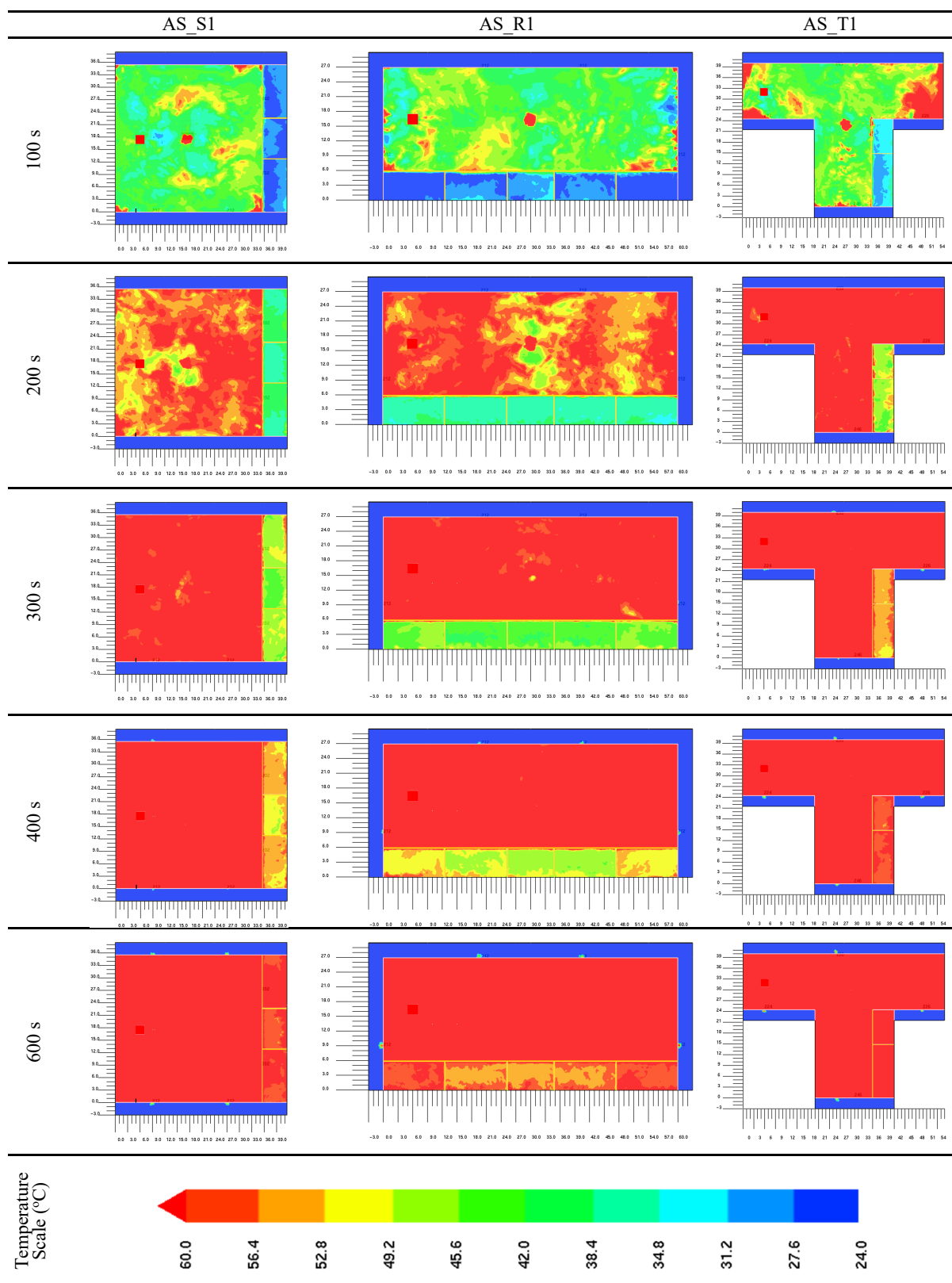
Among the four exits, overall, the untenable condition of visibility has been reached earlier in the 1st exit. On the contrary, the tenable time is the highest for the 3rd exit in overall cases. Among the 24 cases of fire scenario, in 16 cases, the untenable condition in the 1st exit has been reached within 100 seconds. On the other hand, in the 3rd exit, the tenable condition is more than 100 seconds for all of the cases; even in some

cases (nine cases), the tenable time is more than 200 seconds. Between the other two exits, the 2nd one has shown better performance compared to the 4th one.

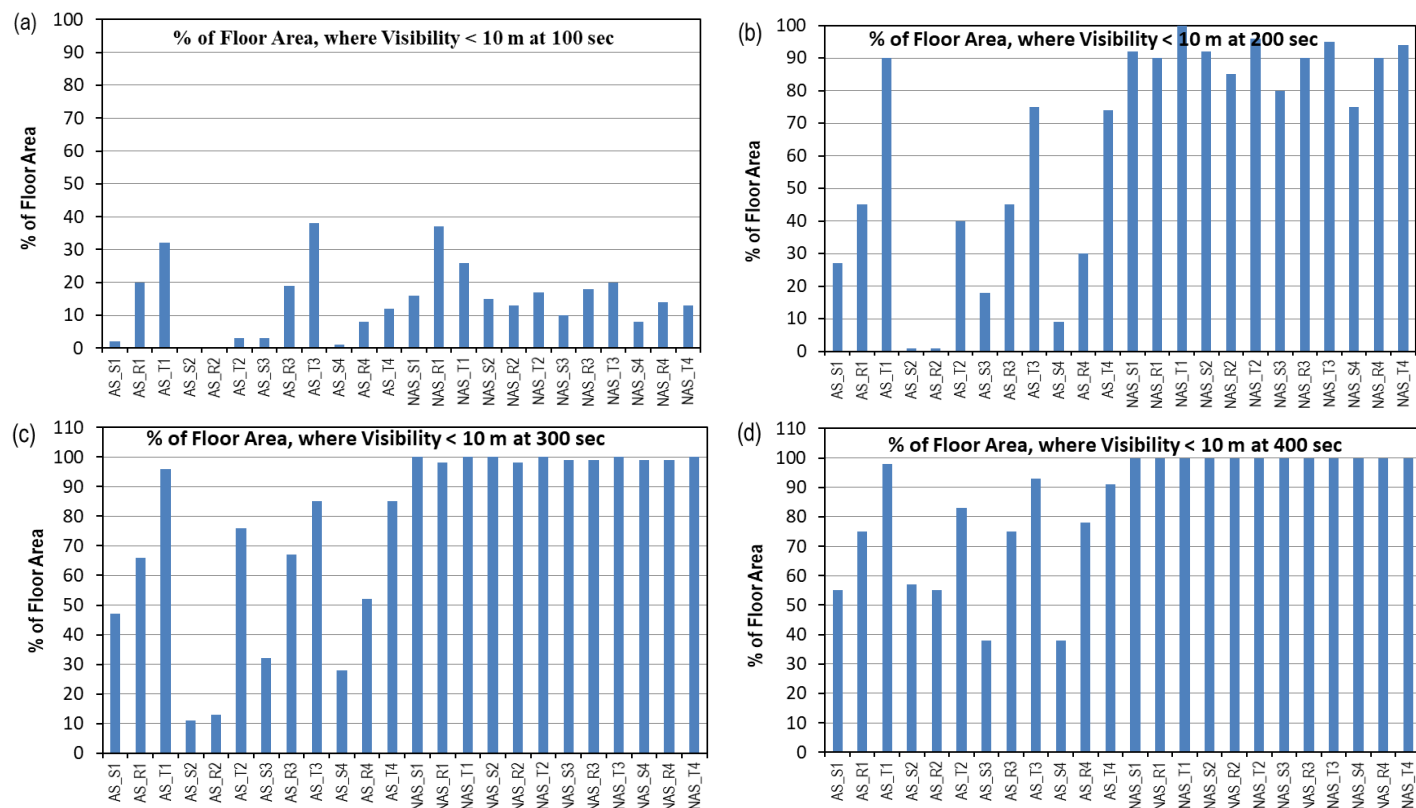


**Fig. 7** Contour plots of visibility at different time steps on the plane of z slice @ 2.5 m height with one extract point located at the corner for all three shapes and fire located axi-symmetrically.

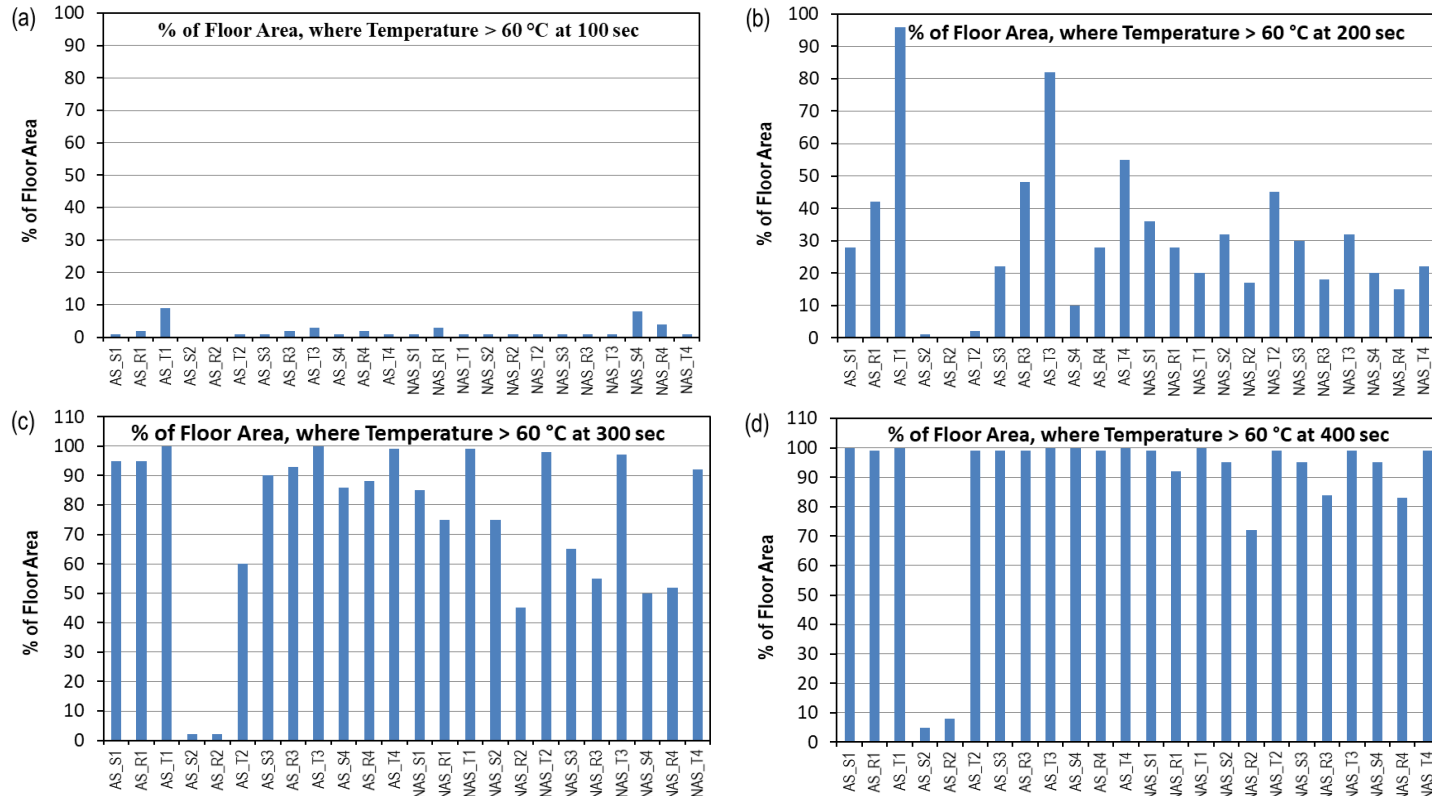




**Fig. 8** Contour plots of temperature at different time steps on the plane of z slice @ 2.5 m height with one extract point located at the corner for all three shapes and fire located axi-symmetrically.



**Fig. 9** Percent (%) of floor area where visibility < 10 m within the smoke reservoir at the time of (a) 100 s (b) 200 s (c) 300 s and (d) 400s for all 24 scenarios.



**Fig. 10** Percent (%) of floor area where temperature > 60°C within the smoke compartment at the time of (a) 100 s (b) 200 s (c) 300 s and (d) 400 s for all 24 scenarios.

In the 2nd exit, the tenable condition is more than 100 seconds for 23 cases, whereas, in the case of the 4th exit, this is for 14 cases. However, for the 4th exit, the tenable condition is more than 200 seconds for 7 cases, whereas it is only for 8 cases for the 2nd exit. A noticeable situation has occurred in the case of AS\_R2 for both in 2nd and 3rd exits. In both exits of this case, the tenable time is much higher compared to other cases, which is 350 and 600 seconds, respectively. Between the axis-symmetric and non axis-symmetric fires, the former one shows better condition as they reached the untenable situation after the latter one for the first two exits.

The tenability duration in terms of temperature in the compartment for different cases has been quantified. The room is considered to be tenable until the temperature exceeds 60°C. The duration of the tenability near the four exits are presented graphically in Figure 12.

Among the four exits, the tenable duration is comparatively higher in the 3rd exit. In 24 cases, it has been found that in 18 cases, the tenable condition is more than 200 seconds in the 3rd exit, and in 9 cases, it is more than 300 seconds in the same exit. After that, the situation was better in the 2nd exit here, 15 cases have been found where tenable duration was more than 200 seconds, and 5 cases have been found where the tenable duration was more than 300 seconds. The 4th exit has shown a similar situation to that of the 2nd exit. However, the tenable situation was worst in the 1st exit among the four exits. In this case, only 8 cases have been found where the tenable duration was more than 200 seconds, and there is no case where it was more than 300 seconds.

Among the three types of reservoirs, the tenability near the exit is better for the square-shaped reservoir. The reason is that in cases of the square-shaped reservoir, the exit points are located in equal distance from the smoke extractor, and as a result, the smoke has been drawn from equal distances and whereas with the rectangular and T-shaped reservoir, the edges have been further from the extract point compared to that of the square-shaped reservoir. As a result, these issues facilitate the square-shaped reservoir to show better condition in tenability.

## 4.2 Scoring and Ranking

### 4.2.1 Analysis on Varying Shape of Reservoir

A scoring and ranking system has been incorporated into the analysis. Out of the three different shapes of smoke compartments, the compartment which takes the slowest to reach poor visibility (i.e. visibility < 10 m) or high temperature (i.e. temperature > 60°C) will be ranked as one (1) followed by the next best compartment, which will be ranked as two (2) and so on. Scoring and ranking of smoke reservoirs for different locations and number of extract points are presented in Table 5. These are based on two sets of data: (1) along the plane of z slice @ 2.5 m height and (2) at the exits.

In the case of one extract point located at the corner of the compartment, results show that the square-shaped smoke compartment has reached untenable conditions at the slowest rate followed by the rectangular-shaped and the fastest to reach untenable conditions has been the T-shaped smoke compartment.

In the case of one extract point located at the centre of the compartment, the scoring system shows that the rectangular-shaped reservoir has reached untenable conditions at the slowest rate followed by square-shaped, and the fastest to reach untenable conditions has been the T-shaped smoke compartment.

In the case of two extract points evenly distributed within the compartment, the square-shaped reservoir has reached untenable conditions at the slowest rate followed by rectangular-shaped, and the fastest to reach untenable conditions has been the T-shaped smoke compartment.

In the case of four extract points evenly distributed within the compartment, the square-shaped reservoir has reached untenable conditions at the slowest rate followed by the rectangular-shaped, and the fastest to reach untenable conditions has been the T-shaped smoke compartment.

A general observation has shown that in most instances, visibility within the smoke compartment and at the exits has become poor (i.e. < 10 m) before temperatures exceeded 60 °C. Although poor visibility itself does not lead to injury or fatality, poor visibility is linked to toxicity, as described in section 2.5. Hence both visibility and temperature have been considered important.

### 4.2.2 Analysis on Varying Quantity and Distribution of Extract Points

The effect of the quantity and distribution of smoke extraction has been examined here, keeping all other design parameters constant. The tenability in the compartment has been quantified. The results obtained from FDS contour plots, vector plots and thermocouples have been used for the purpose of analysis. The scoring and ranking system used in the analysis has been described in the previous section, and the results are presented in Table 6.

The visibility and temperature within the smoke compartment have been analysed. This has been done by examining the visibility and temperature contour plots along the z plane @ 2.5 m height from the floor.

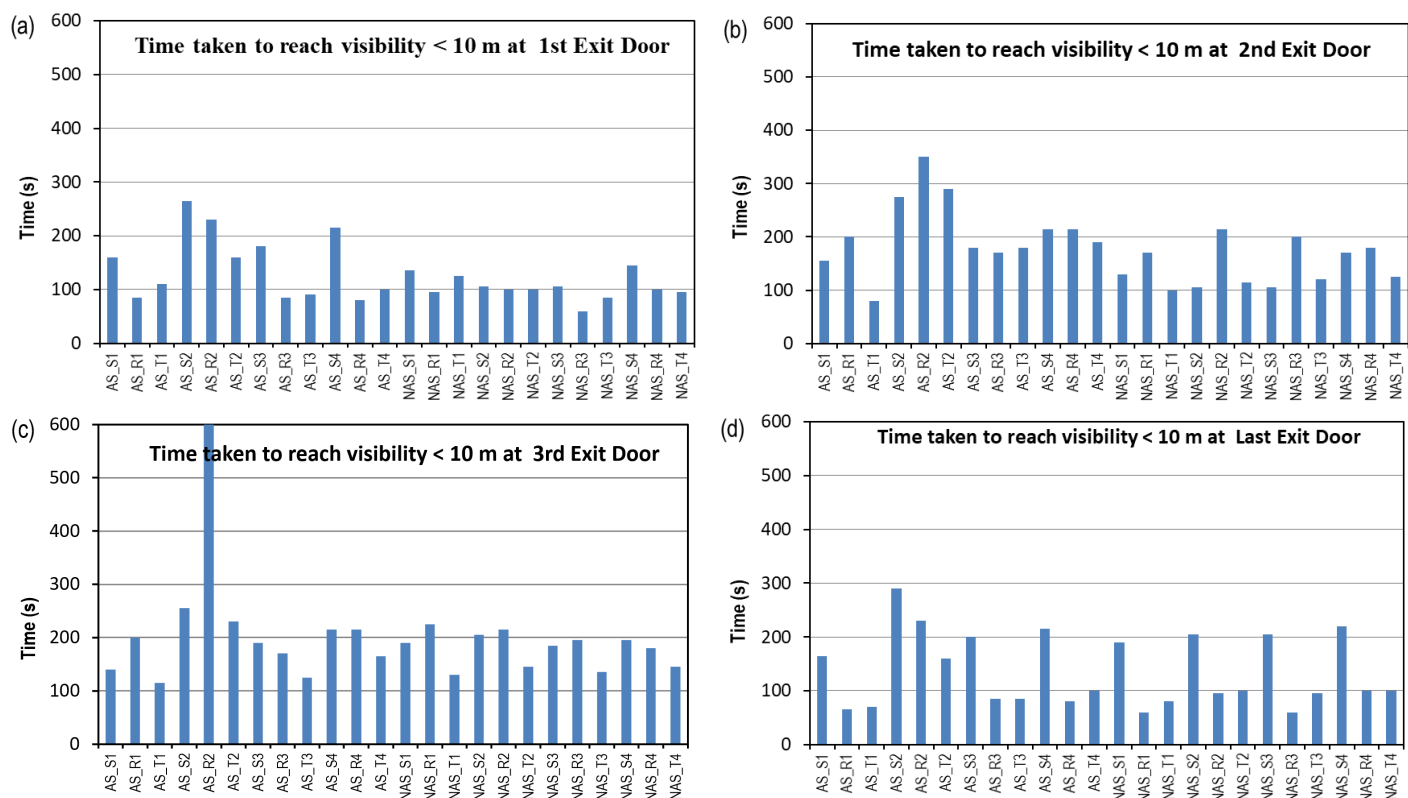
For the square and T-shaped reservoir, results of the scoring system show that the smoke compartment with 4 extract points reached untenable conditions at the slowest rate followed by the compartment with extract point located at the centre and then 2 extract points, and the fastest to reach untenable conditions is the compartment with 1 extract point located at the corner. However, in the case of the rectangular-shaped compartment, the smoke compartment with 1 extract point located at the centre reached untenable condition at the slowest rate, followed by the compartment with 4 extracts points and then 2 extract points, and the fastest to reach untenable conditions is the compartment with 1 extract point located at the corner. It is, apparently, could be attributed that in the case of the rectangular-shaped compartment, due to having a very long length (compared to the width), the position of each of the 4 extract points has been further from the fire location compared to that of the square-and T-shaped reservoir; whereas, the 1 extract point is located directly above the fire. For this reason, in the rectangular-shaped compartment, 1 extract point located at the centre showed better performance compared to the 4 extract points. Similar to the earlier analysis in the section, both visibility and temperature have been taken into account for this assessment.

### 4.2.3 Sensitivity Analysis of the scoring system

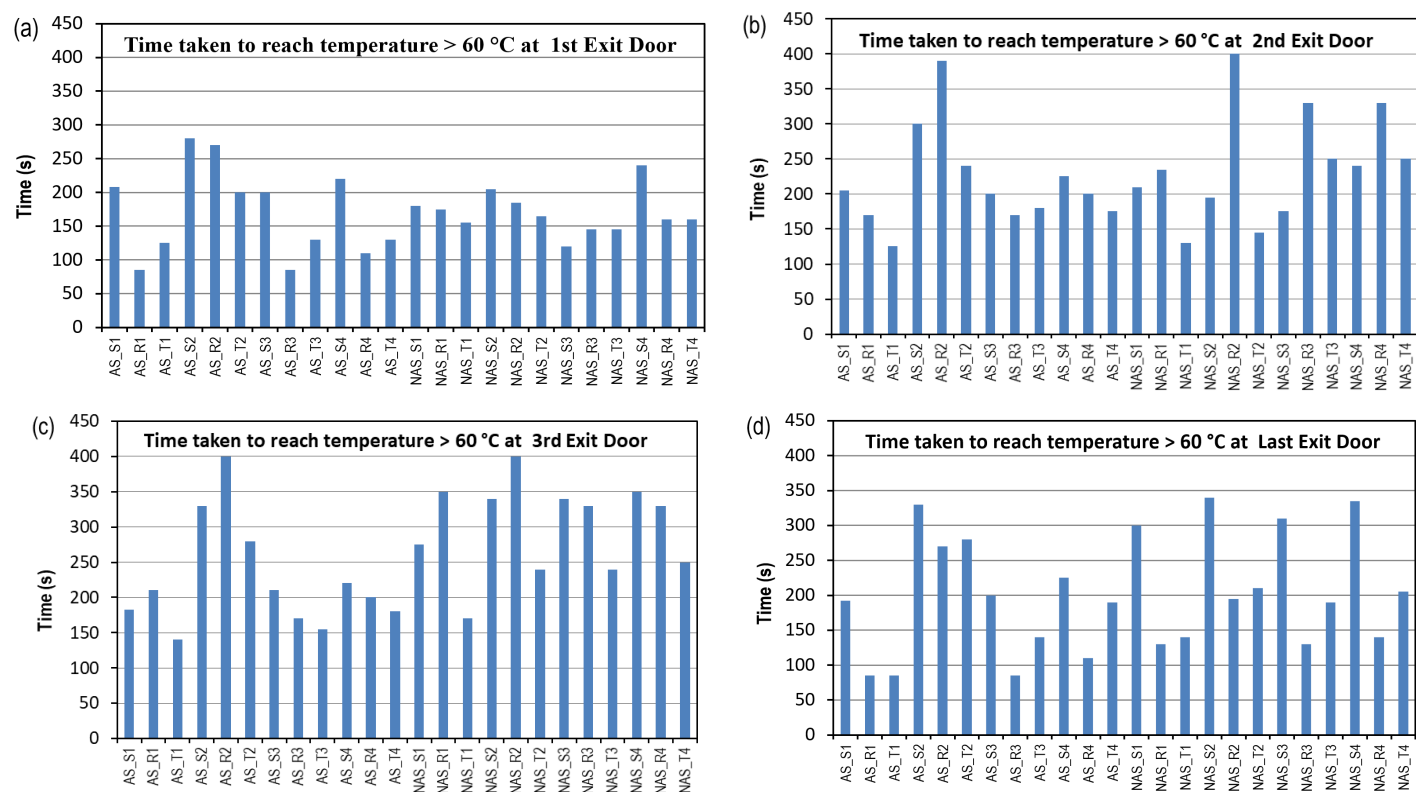
It may be argued that the scoring system adopted in Sections 4.2.1 and 4.2.2 is a subjective one. The ranking may be changed if the scoring system is changed. Hence, we have conducted a sensitivity analysis where the scoring system has been changed, and the effect of this in the ranking of the compartment has been analysed. Here we have considered five cases where five different scoring systems have been deployed. The details of the different scoring systems have been presented in Table 7.

In the base case, a scale of 1, 2, 3 has been used, where the ranking has gone up by one (1); in this scoring system, the compartment which takes the highest time to reach untenable condition has been scored by one (1), and the following one has been scored by two (2) and so on. This case has been named as the base case as it has been used in this paper to analyse the ranking of the compartments in terms of severity. In sensitivity case 1, a scale of 1, 1.5, 2 has been used where the ranking has gone up by 0.5. Similarly, in Sensitivity case 2 a scale of 1, 3, 5 has been used where the ranking has gone up by 2. In Sensitivity case 3 two separate scoring systems have been used for visibility and temperature; a scale of 1, 2, 3 has been deployed for visibility and 2, 4, 6 for temperature. As visibility is an indirect reference to toxicity whilst the temperature is a direct measure, the scoring of temperature is increased by 2 whereas the scoring of visibility has gone up by one. In sensitivity case 4, a non-linear scale of 1, 4, 9 has been used. Similarly, in sensitivity case 5, a non-linear scale with higher values has been deployed.

Here we have used the scenario of the smoke reservoirs with 4 extract points evenly distributed in the reservoir. The total score and rank of the



**Fig. 11** Time taken to reach to untenable condition (visibility) near the exit doors for all 24 scenarios, (a) 1st exit door, (b) 2nd exit door, (c) 3rd exit door and (d) 4th exit door.



**Fig. 12** Time taken to reach to untenable condition (temperature) near the exit door, (i) 1st exit door, (ii) 2nd exit door, (iii) 3rd exit door and (iv) 4th exit door.

**Table 5** Scoring and ranking of tenability in the compartment for varying the shape of the smoke compartment at different number and location of smoke extract point(s) within the compartment.

			One extract point located at the corner			One extract point located at the centre		
			Square Shaped	Rect. Shaped	T Shaped	Square Shaped	Rect. Shaped	T Shaped
Tenability Within the Compartment	Axi-symmetrical (AS)	Visibility	1	2	3	2	1	3
	Fire Plume	Temperature	1	2	3	2	1	3
	Non axi-symmetric (NAS)	Visibility	1	2	3	2	1	3
	Fire Plume	Temperature	2	1	3	2	1	3
Tenability at Exits	Axi-symmetric (AS)	Visibility	2	1	3	2	1	3
	Fire Plume	Temperature	1	2	3	2	1	3
	Non axi-symmetric (NAS)	Visibility	2	1	3	2	1	3
	Fire Plume	Temperature	2	1	3	2	1	3
	Sub-Total Score (1)		12	12	24	16	8	24
	Sub-Total Rank (1)		1	1	3	2	1	3
			Two extract points evenly distributed			Four extract points evenly distributed		
			Square Shaped	Rect. Shaped	T Shaped	Square Shaped	Rect. Shaped	T Shaped
Tenability Within the Compartment	Axi-symmetrical (AS)	Visibility	1	2	3	1	2	3
	Fire Plume	Temperature	1	2	3	1	2	3
	Non axi-symmetric (NAS)	Visibility	1	2	3	1	2	3
	Fire Plume	Temperature	2	1	3	2	1	3
Tenability at Exits	Axi-symmetric (AS)	Visibility	1	2	3	1	2	3
	Fire Plume	Temperature	1	3	2	1	2	3
	Non axi-symmetric (NAS)	Visibility	1	2	3	1	2	3
	Fire Plume	Temperature	2	1	3	1	2	3
	Sub-Total Score (1)		10	15	23	9	15	24
	Sub-Total Rank (1)		1	2	3	1	2	3

**Table 6** Scoring and ranking of tenability in the compartment for varying the quantity and distribution of smoke extract point(s) located within differently shaped of smoke reservoirs.

			Square shaped smoke reservoirs				Rectangular shaped smoke reservoirs			
			1 Point (Corner)	1 Point (Centre)	2 Points (Even)	4 Points (Even)	1 Point (Corner)	1 Point (Centre)	2 Points (Even)	4 Points (Even)
Tenability Within the Compartment	Axi-symmetrical (AS) Fire Plume	Visibility	4	3	2	1	4	1	3	2
		Temperature	4	1	3	2	4	1	3	2
	Non axi-symmetric (NAS) Fire Plume	Visibility	4	3	2	1	4	1	3	2
		Temperature	4	3	2	1	4	1	3	2
Tenability at Exits	Axi-symmetric (AS) Fire Plume	Visibility	4	1	3	2	3	1	4	2
		Temperature	4	1	3	2	3	1	4	2
	Non axi-symmetric (NAS) Fire Plume	Visibility	2	3	4	1	3	1	4	2
		Temperature	3	2	4	1	3	1	4	2
	Sub-Total Score (1)		29	17	23	11	28	8	28	16
	Sub-Total Rank (1)		4	2	3	1	4	1	3	2
			T-shaped smoke reservoirs							
			1 Point (Corner)	1 Point (Centre)	2 Points (Even)	4 Points (Even)				
Tenability Within the Compartment	Axi-symmetrical (AS) Fire Plume	Visibility	4	1	3	2				
		Temperature	4	1	3	2				
	Non axi-symmetric (NAS) Fire Plume	Visibility	4	3	2	1				
		Temperature	4	3	2	1				
Tenability at Exits	Axi-symmetric (AS) Fire Plume	Visibility	4	1	3	2				
		Temperature	4	1	3	2				
	Non axi-symmetric (NAS) Fire Plume	Visibility	4	1	3	2				
		Temperature	4	2	3	1				
	Sub-Total Score (1)		32	13	22	13				
	Sub-Total Rank (1)		4	2	3	1				



different compartments at different cases have been calculated and presented in Table 8. In the analysis, it has been seen that the total score has been increased with the increase in the scoring system. However, the overall ranking of the compartment in terms of severity has not been changed, as seen in Table 8. Therefore, it can be claimed that the ranking of the compartment is indifferent to the scale of the scoring system.

**Table 7** Different scoring systems for sensitivity analysis.

Case of Sensitivity	Scoring System	
	Visibility	Temperature
Base case	1, 2, 3	1, 2, 3
Sensitivity 1	1, 1.5, 2	1, 1.5, 2
Sensitivity 2	1, 3, 5	1, 3, 5
Sensitivity 3	1, 2, 3	2, 4, 6
Sensitivity 4	1, 4, 9	1, 4, 9
Sensitivity 5	1, 9, 25	1, 9, 25

**Table 8** Scoring and ranking of smoke reservoirs for different systems of scoring.

Case of Sensitivity	Scoring of smoke reservoirs			Ranking of smoke reservoirs		
	Square shaped	Rect. shaped	T shaped	Square shaped	Rect. shaped	T shaped
Base case	9	15	24	1	2	3
Sensitivity 1	8.5	11.5	16	1	2	3
Sensitivity 2	10	22	40	1	2	3
Sensitivity 3	14	22	36	1	2	3
Sensitivity 4	11	29	72	1	2	3
Sensitivity 5	16	58	180	1	2	3

#### 4.2.4 Final ranking

Based on the scoring and ranking tables of analysis for the variable of the shape of the reservoir (Table 5), the results obtained has been analysed and is summarised here. On average, the square-shaped smoke compartment has been ranked as one (1), showing that untenable conditions have reached the slowest rate, followed by the rectangular-shaped smoke compartment ranked as two (2), while the T-shaped smoke compartment has been ranked as three (3), showing untenable conditions was reached at the fastest rate.

For cases where the smoke extract point is located at the centre of the compartment, the rectangular-shaped compartment has been ranked as one (1), followed by the square-shaped ranked as two (2).

Based on the scoring and ranking tables of analysis for varying the quantity and distribution of extract points (Tables 6), the results obtained has been analysed and is summarised below.

Cases with 4 smoke extract points evenly distributed within the smoke compartment of square and T-shaped are ranked as one (1), which mean that it has taken more time to reach the untenable conditions within the compartment when 4 extract points were evenly distributed. This may be justified that more extract points remove toxic gases at a faster rate. As a result, it allows the compartment to be in a tenable condition for a longer time.

After the cases with 4 extract points, a single smoke extract point located at the centre of the compartment has shown better results, standing at rank two (2). The cases with fire source located directly beneath the extract point has an additional advantage as more smoke is removed within the vicinity of the fire source, minimising the spread of smoke to other parts of the compartment. Thus, if both axi-symmetric

and non axi-symmetric fire plumes scenarios are assessed together, the case with 1 extract point located at the centre would show better results, standing at rank two (2), followed by cases with 2 extract points. However, by comparing only the non axi-symmetric fire plume increased to three (3), while cases with 2 smoke extract points would be ranked two (2). However, in the case of the rectangular-shaped compartment, one extract point located directly above the fire source has shown the best performance and ranked as one (1), followed by the 4 smoke extract points within the compartment and ranked as two (2).

The scoring and ranking tables showed that all cases with a single smoke extract point located at the corner of the smoke reservoir are ranked four (4), showing untenable conditions within the smoke compartment was reached at the fastest rate as compared to other cases.

## 5. CONCLUSION AND RECOMMENDATION

The research undertaken and presented in this paper has examined how the tenability within a large compartment can be affected by varying the shape of smoke reservoirs and the quantity and distribution of smoke extract points in the reservoir. FDS has been used for the analysis. In this study, three different shapes of smoke compartments have been analysed using the results of modelling, namely, square, rectangular, and T-shaped. The effect of varying the quantity and distribution of smoke extract points within the smoke compartment has also been examined. The findings can be summarised as below:

1. In the analysis, it has been observed that within 100 seconds, the visibility and temperature within the compartment were still in good condition.
2. In comparison between temperature and visibility, the untenable condition in terms of visibility has reached earlier than that of the temperature. In the case of visibility, there are 15 cases where at least 50% area reached an untenable condition in 200 seconds, whereas this is only for 3 cases in which temperature exceeded 60°C in 50% area of the compartment in 200 seconds. The same phenomena have been observed in 300 and 400 seconds, where the temperature situation was better than visibility within the compartment. This indicates that the designer should care more about the visibility (which may be linked to toxicity) in the compartment so that the occupants can evacuate the compartment safely.
3. The overall situation in the compartment for the axi-symmetric location of the fire has been found better than that of the non axi-symmetric location of the fire. This is due to the longer distance from the fire location to the extraction points for non axi-symmetric cases.
4. In the case of tenability near the exit doors, between the axi-symmetric and non axi-symmetric fires, the tenable situation near the exit points has been found to be better for the latter cases in terms of visibility; however, an opposite phenomenon of tenability has been observed in terms of temperature. Therefore, as stated earlier, both the visibility and temperature should be considered important in designing evacuation and fire safety within a compartment.
5. The situation in the square-shaped smoke reservoir has taken a longer time to reach to untenable conditions, owing to the fact that the smoke compartment is symmetrically shaped with equal dimensions on all four sides of the compartment. Smoke compartment with the most number of bends, i.e. the T-shaped smoke reservoir, generally showed untenable conditions reached the fastest rate followed by the rectangular-shaped smoke compartment. Hence, precaution should be exercised in designing smoke control systems for long/irregular shaped compartments.
6. The provision of four extract points evenly distributed within the smoke reservoir resulted in the most favourably stable smoke layer, and the untenable conditions within the smoke compartment increased at the slowest rate. However, one vent

in the centre showed a better outcome than two evenly distributed points.

To conclude, it has been demonstrated that varying the shape of smoke reservoirs and the quantity and distribution of smoke extract points do have an effect on tenability within a smoke compartment. In designing prescriptive-based smoke control systems, where complex or elongated geometries of smoke reservoirs or smoke compartments are present, the qualified person or fire safety engineer should consider the critical situation due to the fire by undertaking fire engineering analysis to ascertain the smoke reservoir size and number and location of smoke extract points. Instead of stretching the smoke reservoir size to its limits, it may be necessary to allow for a smaller sized smoke reservoir. Apart from that, an appropriate quantity and distribution of extraction points within the smoke reservoir could be determined.

There are a few areas that could be further looked into with potential possibilities for future research. These are presented below:

1. Replacement air intake into the smoke compartment is a critical factor for any smoke control system. It would be interesting to determine the effects of providing more openings for replacement air intake such that the velocity entering the smoke compartment is less than 1 m/s. This limitation of 1.0 m/s is in line with National Fire Prevention Association and Australian Standards. In this research, the requirement for replacement air complies with Singapore and Building Standards. Furthermore, number of exhaust points can be increased keeping the total volume of smoke extraction is not changed to see the sensitivity of number of exhaust points.
2. The height of the smoke compartment is another critical factor for smoke control systems. Generally, the higher the compartment, the more time it would take for the smoke to descend. Apart from that, increasing the height of the smoke compartment would result in a more stable smoke layer since the smoke extract point(s) would be located well within the smoke reservoir and away from the smoke layer. However, on the other hand, the number of grid cells and simulation time would increase considerably. It would be interesting to vary the height of the smoke compartment and determine its effects of it on the tenability within the smoke compartment.
3. PMMA has been used as the source of fire in this study. However, there are other plastic materials that have higher soot yield, for example, nylon, polyester, polyurethane etc. A sensitivity analysis can be performed to observe the effect of the fire source on the tenability of the compartment.

## REFERENCES

Abu-Bakar, A.S., Cran, M., and Moinuddin, K.A.M., 2019, "Experimental investigation of effects of variation in heating rate, temperature and heat flux on fire properties of a non-charring polymer," *Journal of Thermal Analysis and Calorimetry*, **137**, 447-459.  
<https://doi.org/10.1007/s10973-018-7941-0>

Brown A.L., Dowding K.J., Nicolette V.F., Blanchat, T.K., 2008, "Fire model validation for gas temperatures and radiative/convective partitioned heat flux," *Proceedings of the 9th International Symposium on Fire Safety Science*, 93-104.  
<https://doi.org/10.3801/IAFSS.FSS.9-93>

Cheng S.Y., Tsubokura M., Nakashima T., Nouzawa T., Okada Y., 2011, "A numerical analysis of transient flow past road vehicles subjected to pitching oscillation," *Journal of Wind Engineering and Industrial Aerodynamics*, **99**, 511-522.  
<https://doi.org/10.1016/j.jweia.2011.02.001>

CIBSE Guide E, 2010, Fire Safety Engineering, *The Chartered Institution of Building Services Engineers*, London, 3rd Edition, 2010

Drysdale D., 2011, *An introduction to fire dynamics*, 3rd Edition, John Wiley and Sons, New York.

Fire Code Reform Centre, 1996, *Fire Engineering Guidelines*, 1st Edition, Sydney, NSW.

Freitas, C.J., 2002, "The issue of numerical uncertainty," *Applied mathematical modelling*, **26**, 237-248.  
[https://doi.org/10.1016/S0307-904X\(01\)00058-0](https://doi.org/10.1016/S0307-904X(01)00058-0)

Jenft A., Collin A., Boulet P., Pianet G., Breton A., Muller A., 2014, "Experimental and numerical study of pool fire suppression using water mist," *Fire Safety Journal*, **67**, 1-12.  
<https://doi.org/10.1016/j.firesaf.2014.05.003>

Karimi M., Akdogan G., Dellimore K.H., Bradshaw S.M., 2012, "Quantification of numerical uncertainty in computational fluid dynamics modelling of hydrocyclones," *Computers & Chemical Engineering*, **43**, 45-54.  
<https://doi.org/10.1016/j.compchemeng.2012.04.009>

Mahmud H.M.I., Moinuddin K.A.M., Thorpe G.R., 2016, "Experimental and numerical study of high-pressure water-mist nozzle sprays," *Fire Safety Journal*, **81**, 109-117.  
<https://doi.org/10.1016/j.firesaf.2016.01.015>

Mahmud H.M.I., Moinuddin K.A.M., Thorpe G.R., 2016, "Study of water-mist behaviour in hot air induced by a room fire: Model development, validation and verification," *Fire and Materials*, **40**, 190-205. doi:10.1002/fam.2279.  
<https://doi.org/10.1002/fam.2279>

Manzello S.L., Park S.H., Mizukami T., Bentz D.P., 2008, "Measurement of thermal properties of gypsum board at elevated temperatures," *Proceedings of the Fifth International Conference on Structures in Fire (SiF'08)*, 656-665.

McGrattan K., Hostikka S., Floyd J., McDermott R., Vanella M., 2021a, Fire Dynamics Simulator (Version 6), User's Guide, NIST Special Publication 1019, 6th ed.; Revision: FDS6.7.7-0-gfe0d4ef38; National Institute of Standards and Technology (NIST), U.S. Department of Commerce, Gaithersburg, MA.

McGrattan K., Hostikka S., Floyd J., McDermott R., Vanella M., 2021b, Fire Dynamics Simulator (Version 6), Technical Reference Guide, Volume 2: Verification. NIST Special Publication 1018-2, 6th ed.; Revision: FDS6.7.7-0-gfe0d4ef38; National Institute of Standards and Technology (NIST), U.S. Department of Commerce, Gaithersburg, MA.

McGrattan K., Hostikka S., Floyd J., McDermott R., Vanella M., 2021c, Fire Dynamics Simulator (Version 6), Technical Reference Guide, Volume 3: Validation. NIST Special Publication 1018-3, 6th ed.; Revision: FDS6.7.7-0-gfe0d4ef38; National Institute of Standards and Technology (NIST), U.S. Department of Commerce, Gaithersburg, MA.

McGrattan K.B., Hostikka S., Floyd J., McDermott R., Vanella M., 2021d, Fire Dynamics Simulator (Version 6), Technical Reference Guide, Volume 1: Mathematical Model, NIST Special Publication 1018-1, 6th ed.; Revision: FDS6.7.7-0-gfe0d4ef38; National Institute of Standards and Technology (NIST), U.S. Department of Commerce: Gaithersburg, MA, USA.

Moinuddin K.A.M., Al-Menhali J.S., Prasannan K., "Thomas I.R., 2011, Rise in structural steel temperatures during ISO 9705 room fires," *Fire Safety Journal*, **46**(8), 480-496.  
<https://doi.org/10.1016/j.firesaf.2011.08.001>

- Moinuddin K.A.M., Li J.D., 2010, "A new convective heat transfer model for fire dynamic simulator," *Proceedings of the 13th Asian Congress of Fluid Mechanics*, 17-21 December, Dhaka, Bangladesh.
- Moinuddin K.A.M., Nguyen T.D., Mahmud H.M.I., 2017, "Designing an experimental rig for developing a fire severity model using numerical simulation," *Fire and Materials*, **41**(7), 871-883.  
<https://doi.org/10.1002/fam.2439>
- Morgan H.P., Gardner J.P., 1990, Design principles for smoke ventilation in enclosed shopping centres. Building Research Establishment Report 186, Garston, BRE.
- Morgan H.P., Garrad G., Ghosh B.K., 1999, Design methodologies for smoke and heat exhaust ventilation, Building Research Establishment Report 368. Garston, BRE.
- Morgan H.P., Hansell G.O., 1994, Design approaches for smoke control in atrium buildings. Building Research Establishment Report 258, Garston, BRE.
- Oh C., Kim E., Sharake R., Patterson M., 2009, "Effect of channel configurations for tritium transfer in printed circuit heat exchangers," In *Proceedings of International congress on advances in nuclear power plants*, Tokyo, Japan, May 10-14, Paper-9146.
- Rajaram V., 2014, "The effects of variation in shape of smoke reservoirs and numbers and distribution of smoke extraction points," Master's Thesis, Victoria University.
- Richardson L.F., 1911, "The approximate arithmetical solution by finite differences of physical problems involving differential equations, with an application to the stresses in a Masonry Dam," *Philosophical Transactions of the Royal Society of London*, 307-357.
- Roache P.J., 1994, "Perspective: A method for uniform reporting of grid refinement studies," *Journal of Fluids Engineering*, **116**, 405-413.  
<https://doi.org/10.1115/1.2910291>
- Roache P.J., 1997, "Quantification of uncertainty in computational fluid dynamics," *Annual Review of Fluid Mechanics*, **29**, 123-160.
- Sarwar M.M., Moinuddin K.A.M., Thorpe G.R., 2013, "Large eddy simulation of flow over a backward facing step using fire dynamics simulator," *Proceedings of the 14th Asian Congress of Fluid Mechanics*, 15-19 October, Hanoi, Vietnam.
- Sikanen T., Hostikka S., 2016, "Modeling and simulation of liquid pool fires with in-depth radiation absorption and heat transfer," *Fire Safety Journal*, **80**, 95-109.  
<https://doi.org/10.1016/j.firesaf.2016.01.002>
- Sikanen T., Vaari J., Hostikka S., Paaanen A., 2014, "Modeling and simulation of high pressure water mist systems," *Fire Technology*, **50**(3), 483-504.  
<https://doi.org/10.1007/s10694-013-0335-8>
- Singapore Fire Code, 2013, "Codes of practice for fire precautions in buildings," *Singapore Civil Defence Force (SCDF)*.
- Society of Fire Protection Engineering, 2008, The SFPE Handbook of fire protection engineering, 4th edition, National Fire Protection Association, Quincy, MA.
- Zou G.W., Chow W.K., 2005, "Evaluation of the Field Model, Fire Dynamics Simulator, for a Specific Experimental Scenario," *Journal of Fire Protection Engineering*, **15**, 77- 92.  
<https://doi.org/10.1177/1042391505047304>