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MODELLING OF A SMOKE EXTRACTION DUCT SYSTEM IN A SINGLE COMPARTMENT

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International Master of Science in Fire Safety Engineering

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Abstract

In the scenario of a compartment fire, smoke is typically exhausted via natural or mechanical smoke ventilation systems. Natural smoke ventilation systems may make use of high-level smoke vents to disperse hot smoke due to its buoyancy, while mechanical smoke ventilation systems use a mechanical exhaust fan and/or duct system to exhaust smoke to the external environment.

This thesis studies the performance of a mechanical smoke ventilation system based on smoke exhaust duct (SED) systems by analysing a few key parameters which may be critical to achieving the desired life safety criteria in a single compartment office fire via computational fluid dynamics (CFD) simulations.

The CFD studies are conducted using the Fire Dynamics Simulator (FDS) software to model a single compartment office with an area of 2,500m^2 and simulate a generic office fire of which the smoke is extracted via the smoke exhaust duct (SED) system. Several key parameters of the SED system are varied and analyzed to have a broader understanding on how the factors affect the performance of the SED system and its consequential impact on the life safety criteria which is the main performance criteria when designing a smoke ventilation system for an office fire.

This thesis aims to present a general indicative guide based on CFD simulations, for the design of mechanical SED systems for a fire scenario in a single compartment which is of an office occupancy type. This design guide is produced by studying the difference between plume correlations compared to CFD simulations and how variations in key SED parameters studied may influence the simulation results. Further research is recommended to validate the results and to explore further variation of parameters in a SED system and in different fire scenarios.

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1 Introduction

In an enclosed space in a building, such as a compartment room, a fire can potentially be a life-threatening event for the occupants near the fire source. The ensuing smoke produced by the fire could fill up the compartment swiftly and greatly reduce visibility of occupants, which could reduce movement speed and delay their timely evacuation to a safe exit [1] while the toxicity and heat from the smoke may be lethal to occupants if exposed at significantly high levels for a prolonged time interval.

Active fire protection systems are increasingly popular in use due to its flexibility to implement and capability to enhance a fire safety strategy with minimal geometrical or aesthetical impact to the original compartment space as compared to passive fire protection systems such as fixed walls and barriers. A commonly applied active mitigation measure to enhance life safety of occupants during a fire is the use of smoke and heat control ventilation systems which are designed to remove smoke from the compartment on fire either naturally or mechanically. Design standards for smoke ventilation systems are provided in various regulation guidelines such as NFPA 92, BRE 368 and European Standards (TR12101-5) to provide recommendations for the optimum design of a smoke ventilation system.

The concept of natural smoke ventilation system is largely based on the fundamental knowledge of smoke and heat control and fire dynamics governing the behaviour of fire and smoke with hot smoke rising while replacement air enters through low level air inlets to keep the hot smoke layer as high as possible above the floor. Mechanical smoke ventilation systems based on smoke extraction fans are typically designed to an extraction flow rate/capacity which is sufficient to extract the hot smoke from within a fire compartment while maintaining a smoke free height which is sufficient to ensure life safety of occupants in the compartment.

Mechanical smoke ventilation systems have been in use in various buildings and tunnels as a means of extracting smoke effectively in hopes of maintaining tenable conditions for occupants in these spaces to be able to evacuate safely to an exit as defined by the NFPA 92 [2]. Additionally, mechanical smoke extraction greatly reduces the impact of unpredictable external wind conditions on the performance of the smoke ventilation system. Apart from direct extraction of smoke from exhaust fans, mechanical smoke ventilation systems can be improvised to provide better performance than natural smoke ventilation systems with the usage of smoke exhaust ducts (SED) which can be designed in extensive duct network configurations distributed throughout the ceiling space to extract smoke more effectively from large compartment spaces or from places which are remote from the exhaust fan location.

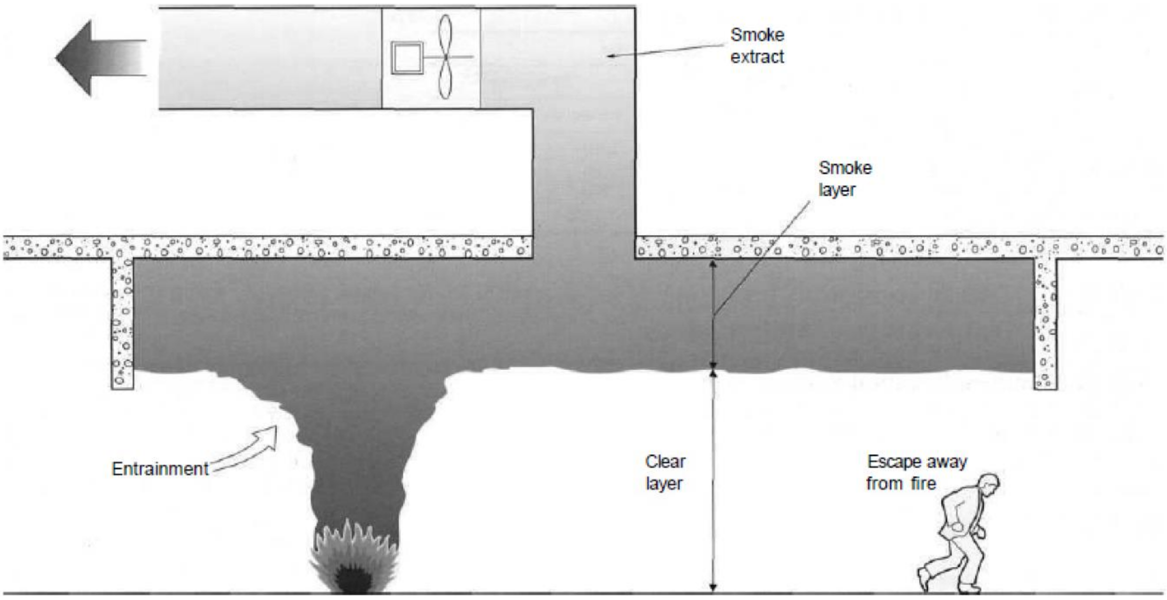


Figure 1: Illustration of a mechanical smoke ventilation system keeping the smoke layer above the height of an occupant escaping *[3]*

There have been extensive studies of mechanical smoke ventilation designs in atria and tunnels which have contributed to various findings and correlations for different parameters such as fire heat release rate (HRR) smoke extraction mass flow rates, location of exhaust and replacement air openings however, these have not involved the application of SED in the smoke ventilation design for these spaces. There are currently limited studies involving the design of a SED smoke control system in a single compartment space. It does not have the extensive smoke reservoir or smoke layer height buffer that a high ceiling atrium or a long tunnel would possess which theoretically, is favorable for smoke control solutions aimed at maintaining a safe smoke free height for the occupant escape. Single compartments such as office spaces have a greater challenge of maintaining a tenable smoke free heights due to their low ceiling height which makes it difficult to design a high performance smoke control system aimed at providing the maximum evacuation time for occupants.

This project therefore intends to explore the parameters when designing a mechanical SED system for a single compartment to understand potential impacts and correlations between various parameters and the performance of the mechanical SED system, to provide a practical insight to the fire safety design in a single compartment fire. Computational Fluid Dynamics (CFD) modelling is used to simulate the smoke flow and SED smoke extraction behaviour in a single compartment via the Fire Dynamics Simulator (FDS) software and analysis will be based on the simulation results obtained. FDS is a robust tool used in many fire and smoke computational studies to simulate CFD scenarios and provide consistent results and findings. Therefore, it serves as a reliable method of analysis compared to scaled or full model experimental setups which are often costly and more time consuming.

2 Objectives

The objectives of this thesis are as follows:

- To compare the smoke ventilation effectiveness of mechanical SED ventilation against natural SED ventilation.
- To evaluate the performance of a mechanical SED system determined based on empirical correlations and compare with CFD simulation results.
- To analyze the variation in parameters of the SED configuration, fire location, SED extraction rate, and the number of SED points and determine its impact on the performance of the SED system.

This thesis shall provide background information on existing knowledge of smoke and heat control systems implemented in tunnels and atria and previous studies on the practical application of SED extraction systems.

Subsequently, the assessment methodology is presented namely, the model, input and output parameters, followed by the results obtained from the simulations are analyzed and discussed. Further research suggestions are discussed for potential future works as well.

3 Background Review of Smoke and Heat Control (SHC) Systems and SED Designs

This chapter provides an overview of SHC systems applied in atrium spaces and tunnels for insight on notable information of smoke flow patterns, impact of different model parameters or any ventilation related effects on the smoke extraction performance. It should be noted that the research material availability for conventional air duct ventilation design is more extensive than the research material for design of SED systems in fire related incidents. However, this background review shall focus only on the research information available with respect to SED designs in fire incidents.

3.1 SHC design in atrium spaces

In cases of atrium smoke extraction via mechanical means, Lougheed et.al [4] compared experimental results against numerical simulations data derived from the standard plume equations and another data set based on computational fluid dynamics model (CFD) suitable for incompressible laminar or turbulent flows with a nonorthogonal grid feature. However, the solver for the model was not identified.

The challenges with designing for an atrium space are the provision of a high ceiling height which may create large fire sizes due to the increased distance from sprinkler to fire source, and interconnectivity of the atrium with several other habitable floor spaces above [4]. A fire in the atrium could potentially smoke fill other floor spaces above as the atrium would violate floor to floor fire separation thus enabling smoke plume to spread upwards.

The experiment involved replacement air supply into the atrium compartment through openings on the floor and walls while 32 exhaust inlets were distributed evenly throughout the atrium ceiling as part of a distributed SED layout [4].

The results reveal good correlations between the equations in NFPA 92B (1995) and experimental data and that exhaust systems are most effective in extraction smoke from the hot smoke layer when it is designed to near or slightly below the design capacity [4]. An overdesign of the capacity may instead result in extraction of fresh air from the lower layer in a situation known as plug-holing. A comparison of the CFD model predictions with experimental data reveals that the temperature and carbon-dioxide output data were not consistent however, the model was successful in accurately predicting the smoke layer height and the average conditions within the layer [4].

3.2 SED design for SHC system in an underground compartment

Wegrzynski et. al [5] studied on the hypothetical application of a smart smoke control "SSC" in confined spaces in a historical building such as underground cellar areas. SSC is essentially a SHEVS system with adaptive performance design of the smoke exhaust fan to improve performance at elevated temperatures without necessarily generating additional forces on the systems in use. The challenge of the implementation in an underground cellar is its limited compartment size and smoke reservoir area which presents space constraints to design large ducts in the compartment. While conventional SHEVS systems are designed for constant volumetric exhaust capacity based on operating pressure in ambient conditions, the SSC enables the system to adapt its volumetric extraction capacity dependent on the density of the hot smoke such that the mass flow rate of the smoke through the exhaust remains constant as temperature rises [5].

The idea of application of the use of SSC comes from the discovery that the performance of a smoke exhaust system at ambient conditions may be noticeably different than if it were operating in higher temperature environments. In high temperature environments, having a lower mass flow rate also means a lower operating power which benefits the system by imposing a lower strain on the system components and elements thus, the system is able to operate below its default operating design parameters in an elevated temperature environment. Following an increase in the temperature of smoke, the volumetric capacity of the system must be increased to maintain a constant mass flow rate. This results in the system maintaining a constant operating pressure and power of the fan which can operate with a similar strain in elevated temperatures as it does in ambient conditions.

As the fire grows, the SSC is expected to allow for an increase in volume flow rate of smoke removed from the cellar compartment. Contrary to a conventional smoke control solution, the increased volume flow rate in a SSC system may be achieved with smaller ducts than conventional smoke control systems due to the change in air density with temperature. When the constraint of space for ducts become an issue for the design of the system, the SSC is able to extract more smoke than a traditional smoke control solution using the same ductwork size.

The results discover the ability of the SSC system to remove significantly more smoke (approx. 50% more) than a conventional SHEVS system thus demonstrating its favourable use for compartments with limited smoke reservoir such as an underground historical cellar, where SED have size and capacity constraints if based on a traditional SHEVS design. The use of the SSC has extended the available safe egress time (ASET) from a range 3 to 5 mins, up to 10 mins or more. This significant extension in ASET time was made possible thanks to the increased extraction rate of the SSC in the simulation model which was able to maintain the smoke layer in the reservoir high above the floor level of the compartment.

3.3 SED design for SHC system in an enclosed car park

Wegrzynski [6] explored an alternative approach to an optimal SHC design which refers to the transient characteristics of a fire. Fundamentally, his approach derives on a system that can dynamically adapt to change in environment during a fire such as the change in density as smoke is produced and the expansion of gases in the fire. In a typical SHC system during fire, the higher the temperature, the lower the pressure exerted on mechanical installations of the system such as ducts, dampers and other elements. The objective of this paper is to envision a SHC system which is designed based on existing methodologies for ambient conditions but could outperform its rated performance in elevated temperature environments without causing any additional strains on the system. The new concept is known as the dynamic, transient adaptation of the Smoke and Heat Exhaust System (SHEVS) which utilizes the thermal expansion of hot air to boost the performance efficiency of the existing SHEVS.

Traditionally, smoke control systems are in use in many building designs such as malls, convention centers, atria and warehouses [7]. The purpose of having a SHEVS system in a building is primarily to remove smoke and heat from a space on fire such that it is able to meet or exceed the tenability criteria for occupant life safety to allow for a safe path for evacuation. The conventional design of a SHEVS system beings with the choice of a design fire, subsequently followed by an estimation of the volume of smoke entrained in the enclosure or space concerned, estimation of required system parameters that are needed to include in the SHEVS design to overcome potential fire hazards. The replacement air supply was also key design criteria for a SHEVS system as it works to remove hot smoke from the reservoir and also prevent mixing of cold air layer and upper hot smoke layer.

For the dynamic and transient SHEVS system investigated the fan in use is supposedly operates based on the change of air and pressure along the duct. The fan capacity can change dynamically with the change of density and pressure in the ductwork. In a high temperature environment, an adaptive SHEVS system tries to maintain constant pressure in the ductwork and shafts and a fixed constant mass flow rate of air but increase the volume of smoke exhausted from the compartment. Due to changes in the density of air, the system is able to operate at a higher operating capacity while using the same amount of power as in during ambient conditions and remove considerably more smoke. The dynamic adaptation of the system allows for a continuous change of volumetric and mass flow of smoke. When used correctly, this approach enables the use of a higher capacity extraction fan without needing any other changes to the system i.e; an increase in performance against high energy fires and also the use of smaller shafts reducing the cost of installation in the building but at the same time maintain the capacity using a conventional design approach.

The fire size used in the study is based on a single vehicle fire with a specified HRR curve with the addition of two surrounding vehicles partially on fire. The fire reaches 1.4MW in the initial phase and burns for prolonged period at a constant rate. As it enters the rapid fire growth phase, the fire grows rapidly and eventually peaks at a HRR of approximately 10MW and stays at the peak HRR for a short duration of time until the onset of the decay phase where the HRR slowly reduces as the fuel load on the vehicle burns out. Soot yield was chosen as 0.1g/g and the heat combustion was set as 25MJ/kg.

Results of this study reveals that an adaptive smoke control system can achieve the same performance efficiency of a conventional smoke exhaust system. The findings indicate that the adaptive system capacity improved by 25-41% based on the same ductwork and design goals as a conventional SHEVS design.

4 Assessment Methodology, Inputs and Outputs

4.1 Fire Dynamics Simulator (FDS)

FDS version 6.7.4 is used for the simulations in this thesis. Developed by the National Institute of Standards and Technology (NIST), FDS is a CFD software package which numerically computes a simplified form of the Navier-Stokes equations. It is suitable to be used for simulations of low speed thermally driven fluid flows (Ma <0.3) such as smoke plumes and heat transport from fires with second order accuracy in space and time [8]. FDS uses cartesian mesh structured grids and therefore converts all geometric obstructions into blocks to fit in the rectilinear grid.

Turbulence is represented using the large-eddy simulation (LES) code by default. Although the option to use Direct Numerical Simulation (DNS) is available subject to underlying fine mesh configurations, this is a computationally expensive option and is not feasible for the study in this thesis due to time constraints.

The combustion process in FDS is solved based on a single step chemical reaction which is mixing-controlled, representing the complex chemical species present in a typical combustion process such as air, fuel and products. Products of the combustion process are tracked using a two-parameter mixture fraction model. Droplet particles that can be captured in FDS models, such as sprinkler discharge, fuel sprays and smoke movement, are represented using Lagrangian particles.

Radiative heat transfer is solved using the radiation transport equation for a grey gas and in limited cases via a wide band model. The finite volume technique is used to compute thermal radiation on the same grid as the flow solver. Liquid droplets in the simulation have the capability of absorbing and scattering thermal radiation in the computation domain.

Prior to utilizing FDS, which functions as the solver of the CFD code, a pre-processor software called Pyrosim, is used for the modelling of the computational domain and input settings. Developed by Thunderhead Engineering, Pyrosim acts as a graphical user interface for the FDS software which provides an immediate graphical representation of all user feedback and ensures the FDS input file is formatted correctly [9].

Upon completion of the computational process in FDS, a visualization tool, also known as Smokeview, is then used to produce quantitative outputs for measurements and diagnostics. Smokeview is able to produce data files for quantities of temperature, visibility, velocity, 3D soot visualization and pressure contours which is used to analyse temperature changes, the smoke layer development and the fluid flow of air and smoke in the computation domain as the fire grows over time.

FDS has been widely adopted for academic research in the field of fire safety engineering and is commonly accepted as a validated software to model fire scenarios in all types of compartment spaces such as buildings, tunnels and car parks.

4.2 Tenability Criteria

An escape route is deemed safe when it is protected from the effects of fire such as smoke, heat or toxic gases. A safe escape route can be achieved by provision of passive fire protection systems such as compartmentation, or active fire protection systems such as SHC or a combination of both active and passive systems.

Establishing the tenability criteria gives clarity on the benchmark of the SED performance in the compartment to determine the impact whether its positive or negative, of a specific perimeter when varied. The tenability criteria proposed for the compartment assessed in this thesis shall be based on the British Standards PD7974-6 [10] as follows:

a. Temperature

i. The upper layer smoke temperature shall not exceed 200°C measured at 2.5m height from finished floor level.

b. Visibility

i. Visibility at 2.5m above the floor level shall be greater than 10m.

The effects of radiative heat flux and toxic gases are not assessed in this thesis.

4.3 Model Geometry

This thesis shall focus on a single compartment room with SED ventilation which is representative of a large office floor space. The compartment is modelled as 50m (W) x 50m (L) with a ceiling height of 5m. The area of the compartment of 2,500m^2 and with a maximum smoke reservoir length not exceeding 60m, this is within the compliance to design recommendations of the BRE 368 for mechanical smoke ventilation systems.

The compartment is assumed to have 6 exit doors which act as the replacement air openings, with each opening measuring 2m (W) x 2m (H). The exit doors are distributed evenly on either side of the compartment as shown in Figure 2 below:

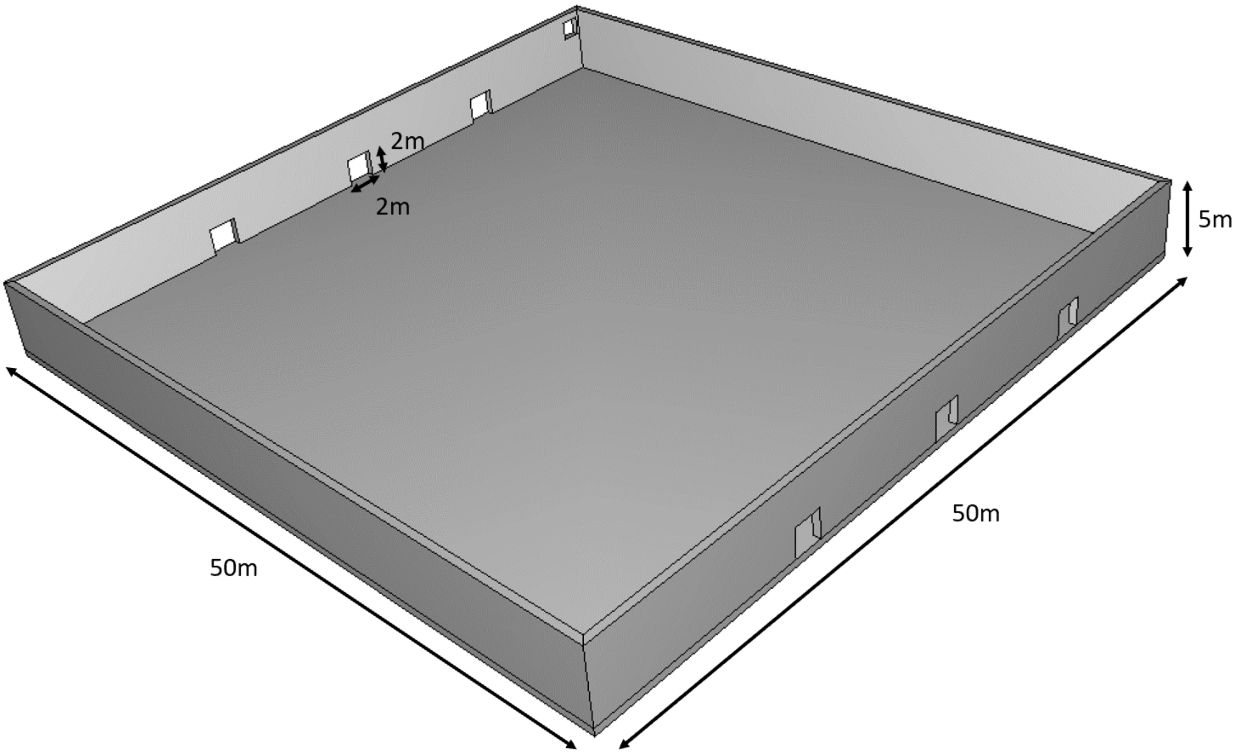


***Figure 2**: Geometry of compartment in CFD Model*

4.4 Input Parameters

A baseline result is needed for an approximate calibration of the exhaust flow rate to be assigned to the mechanical extraction in the CFD simulation to determine a reasonable flow rate prior to deeper analysis. An initial calculation is made using empirical correlations derived from the Thomas plume equations as detailed in the Annexes of TR12101-5 [11] as shown below:

$$M_f = C_e P Y^{3/2}$$

where;

- M_f is the mass flow rate of smoke plume entrained
- C_e is 0.19, assuming the compartment size of 2,500m^2 as a large compartment
- P is the fire perimeter which is set as 16m based on the area of an office fire of 16m^2 [11]
- Y is the smoke free height defined by the tenability criteria which is set at 2.5m

Based on the values provided, the mass flow rate of smoke entrainment (M_f) is determined to be 12kg/s. From the M_f value obtained, the rise in temperature is then calculated with the following formula [11]:

$$M_f = \frac{Q_f}{c\Theta_1}$$

Based on the M_f value calculated above, the rise in temperature is determined to be 240K, and the hot smoke temperature is 533K considering the ambient temperature to be 293K. Applying the ideal gas law, the density of the hot smoke is calculated to be 0.66kg/m^3. Based on the conservation of mass principle, the mass flow rate of smoke to be extracted shall be equal to M_f to ensure the smoke layer is achieved at the desired smoke free height of 2.5m. This assumption yields a required volumetric mechanical extraction flow rate of 18.2m^3/s. The extraction flow rate calculated shall be tested in the CFD model to determine if the calculated flow rate based on the plume equations is sufficient to maintain the smoke free height of 2.5m.

Subsequently, the dimension of the SED is to be determined. The SED is first assumed to be a low-pressure system based on CIBSE Guide B2 [12], which corresponds to a maximum air velocity of 10m/s in the duct. Based on the volume flow rate calculated (18.2m^3/s), the free area of the SED shall be 1.82m^2. Applying a square duct ratio of 1:1, the cross-sectional free area of the SED shall be 1.35m x 1.35m. It should be noted that due to limitations with the size of the grid coordinates in FDS, the cross-sectional free area of the SED shall be rounded up to 1.4m x 1.4m.

As a precaution to prevent reduced extraction efficiency due to plug-holing, the event where the extraction rate through a SED point is in excess such that it draws fresh air from below the smoke layer into the SED point instead of smoke, the number of SED extraction points shall be determined based on the following equations [11]:

$$M_{\mathrm{crit}} = \frac{2{,}05\,\rho_{\mathrm{amb}}\left(g\,T_{\mathrm{amb}}\,\Theta_1\right)^{0,5} d_{\mathrm{n}}^2\,D_{\mathrm{v}}^{\;0,5}}{T_1}$$

$$N \geq \frac{M_1}{M_{\mathrm{crit}}}$$

The critical exhaust flow rate, M_{crit} is first calculated and from the value obtained, the recommended number of exhaust points can be determined by dividing it with the mass flow rate of smoke entrainment calculated previously. From the values obtained, the number of SED points required to prevent plug-holing is at least 2 points. Therefore, the base case CFD simulation scenario shall have 3 SED points.

The input details for the CFD model are summarized in the Table as shown below:

Input parameters for CFD Model		Remarks
Design Fire Size	3,600 kW	Based on HRRPUA x A_f
Area of fire (A_f)	$16m^2$	Based on TR12101-5 [11] for office equipped with standard response sprinklers
Fire Growth Rate	$225 kW/m^2$	Based on TR12101-5 [11] for office equipped with standard response sprinklers
Heat Release Rate per unit area (HRRPUA)	Steady-state	N/A
Temperature	20°C (Outdoor)	N/A
	20°C (Indoor)	N/A
Radiative Fraction	30%	Assumption of 30% radiative losses [13]
Air inlet area	$24m^2$	Total 6 openings with $4m^2$ free area per opening
Smoke Extraction Rate	$18.2m^3/s$	Base case calculated as per Thomas plume equation
SED Cross sectional free area dimensions (Assuming square aspect ratio of 1:1)	1.4m x 1.4m	Based on calculations, cross-sectional area required is 1.35m x 1.35m. To overcome grid size limitations in FDS, the cross-sectional area is rounded up to 1.4m x 1.4m
Number of SED points	3 nos.	Min. 2 SED points are required to prevent plug-holing
Heat of Combustion	23,200 kJ/kg	Based on SFPE Handbook [7] for polyurethane GM27 combustible material
Soot Yield	$0.03\ kg_{soot}/kg_{fuel}$	Based on office occupancy [14]
Boundary Conditions	Open	External Domain
	Concrete	Wall, Floor, Ceiling
	Steel	Smoke Extraction Duct (SED)

Table 1: *FDS Input Parameters for the CFD Model*

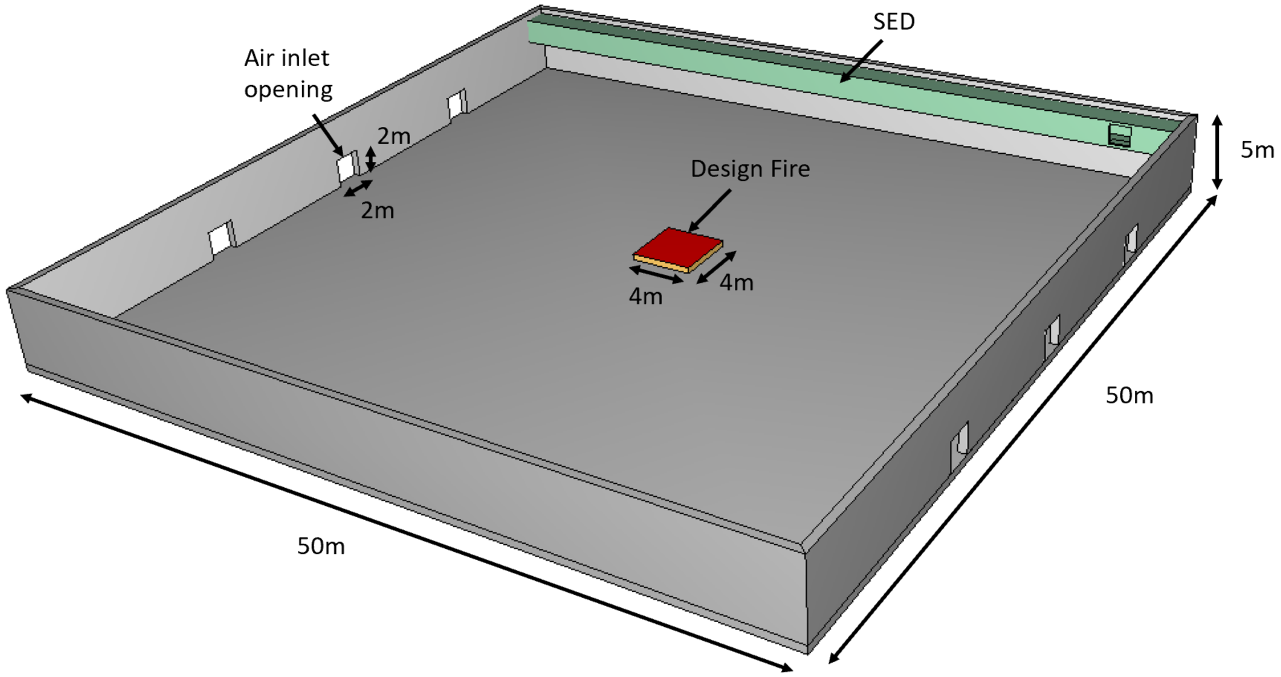


***Figure 3**: CFD Model with input parameters*

4.5 SHC System (SED + Air Supply Inlet)

A SHC system as defined by Klote, [15] is an engineered system that includes all methods that can be used individually or in a combination to modify smoke movement. A fully operational SHC system may comprise of components such as compartmentation, pressurization, buoyancy, airflow, detection and dilution.

The SHC system proposed for this thesis is a mechanical smoke extraction which serves the purpose of removing smoke from the compartment area via the SED and accompanying smoke extraction fans while simultaneously supplementing replacement air into the compartment via low level air inlet ventilation openings. The primary goal of the SHC system is to ensure occupants in the compartment are able to evacuate safely by maintaining the defined life safety tenability criteria throughout the period of evacuation.

While there are many standards and guiding principles to designing a SHC system, this thesis shall focus on the design principles defined in the European Standards, TR12101-5 [11]. Essentially, the following parameters will need to be established for a SHC design to work effectively:

- Design fire size
- Type of occupancy
- Compartment dimensions
- Smoke temperature
- Mass of smoke produced in the compartment
- Location and number of exhaust points
- Replacement air inlet size

Air inlet openings shall be supplied through the exit/entrance doors of the compartment of which 6 of them are included in the CFD model. The working principle of the replacement air is that it should be positioned as low as possible to prevent mixing of the cold air with the hot smoke layer which could cause smoke logging and compromise a smoke free evacuation path. There shall also be sufficient area of openings for replacement air to complement the mechanical extraction rate to keep the velocity of the air inlet low and prevent turbulence in the smoke layer [16].

The SED is modeled with steel as its boundary material based on FDS databases, which is representative of the properties of galvanized steel commonly used to construct SED in the industry [17]. The effect of corrosion or rusting due to lack of a zinc coating from galvanized steel is not relevant for this thesis study.

***Figure 4**: Conventional SED construction made of galvanized steel* [17]

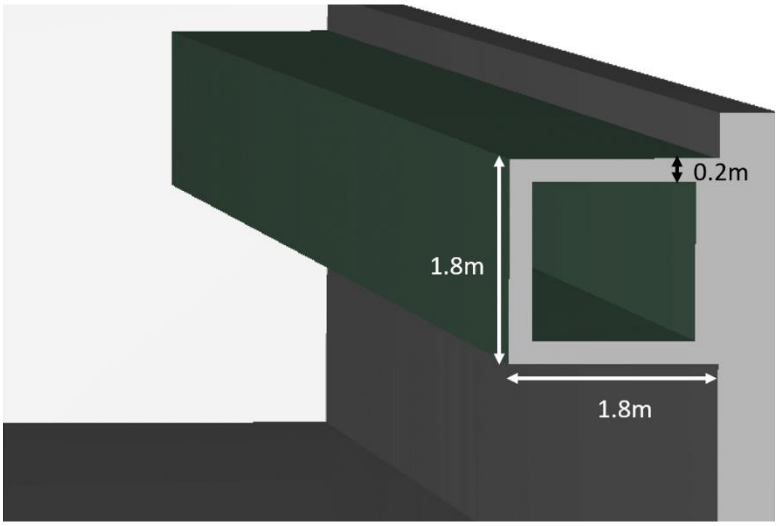


***Figure 5**: Cross Section view of SED in CFD Model with exhaust fan (SURF) at the end of the SED*

4.6 Grid Resolution

The accuracy of a CFD simulation result is dependent on the mesh quality of the computational domain. The more refined the cell resolution of the mesh is, the more precise is the calculation from one mesh to another, delivering an accurate result of the simulation. Since FDS is solved with the LES model, turbulence is a highly sensitive parameter to the mesh quality. The finer the cell resolution, the better resolved is the turbulence flow produced in the simulation. However, careful consideration is taken to ensure the best compromise between mesh quality and simulation runtime as an extra fine quality mesh would result in exponentially longer computation time which is not feasible for the project timeline.

The FDS user guide [8] provides users with a formula to calculate the optimal mesh resolution for simulations involving buoyant plumes as follows:

$$D^* = \left(\frac{\dot{Q}}{\rho_\infty c_p T_\infty \sqrt{g}}\right)^{\frac{2}{5}}$$

With:

D^* : Characteristic dimensionless fire diameter [m]
Q : Total heat release rate [kW]
ρ_∞ : Ambient air density [kg/m³]
c_p : Heat capacity of air [kJ/kgK]
T_∞ : Ambient temperature [K]
g : Gravitational acceleration [m/s²]

The relation D*/δx is the number of grid cells of length δx that span the characteristic diameter of the fire. The D*/δx should ideally range between a value of 4 to 16 with D*/δx = 4 deemed as a coarse mesh, D*/δx = 10 as moderate, and D*/δx = 16 as fine. Areas of interest in the simulation will involve several locations such as the fire vicinity, the hot smoke layer, SED extraction points and the replacement air inlet openings.

Considering the compartment size is relatively small at 50m (W) x 50m (L) x 5m (H), with all the areas of interest involved, a single mesh quality with a square box grid (ratio 1:1) is applied to the entire computational domain. This approach was made to simplify the mesh splitting process to accelerate the computation time and not produce excessive imbalances in cell distribution between one mesh to another. The computational domain was also extended 5m beyond the compartment boundary to allow for a more accurate resolved flow field entering through the air inlet openings.

A consideration was made for the cell size in the z-axis with respect to the air inlet height of 2.0 m. As the minimum number of cells in the z-axis is recommended to be at least 10, this rule yielded a mesh cell size not exceeding 20 cm at the replacement air inlet height, which corresponds, to D*/δx = 8, making it close to a moderate mesh resolution with a total of approximately 2.5 million cells for the entire computational domain. There is a limitation in the attempt to simulate a fine mesh resolution of 10 cm where D*/δx = 16, as it would have increased the total mesh cells of the domain to 20 million which exponentially increases the computational time required.

As the SED free area measures only 1.4m in its cross-sectional height, the mesh size of 20cm for the duct is insufficient for a critical region of interest as it would contain only 7 mesh cells along its height. Therefore, a special set of mesh with a refined size of 10cm is imposed specifically on the SED region of the computational domain to ensure sufficient mesh cells are included in the simulation of flow inside the SED.

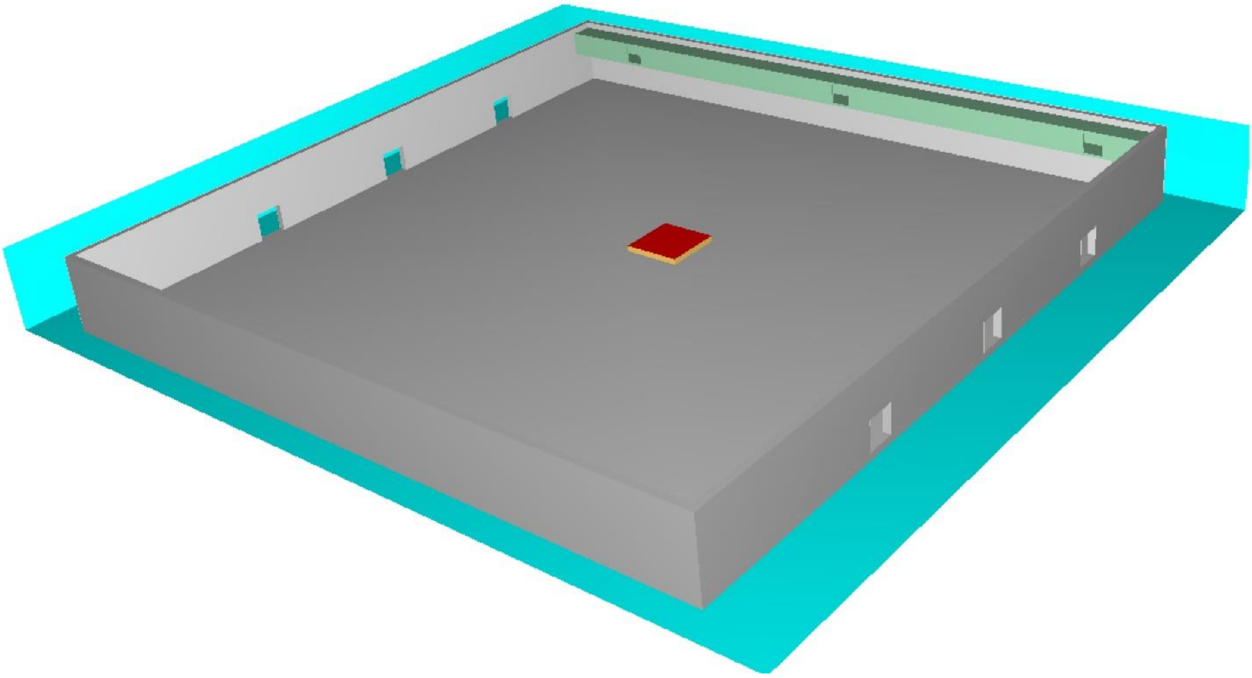


***Figure 6**: Overall Computational Domain of the CFD Model in blue outline*

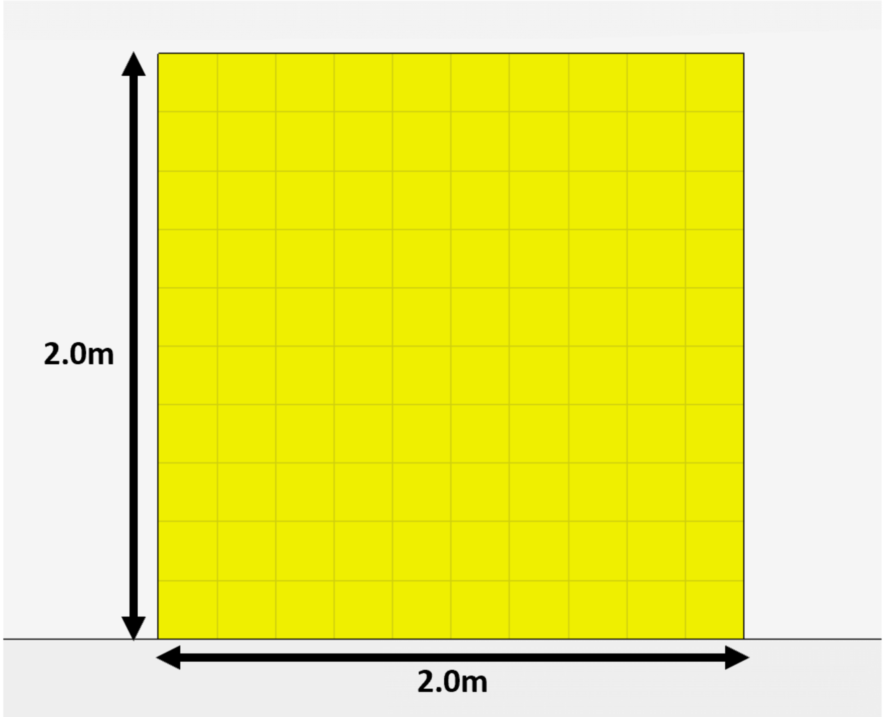


***Figure 7**: A close-up view of the replacement air inlet opening with a min. of 10 mesh cells along its height of 2.0m*

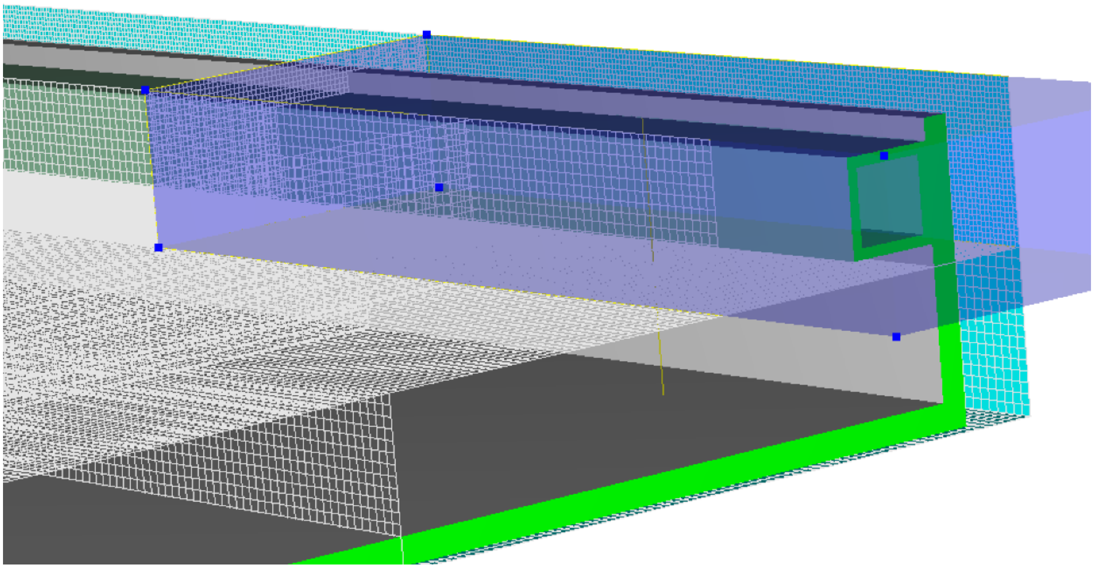


***Figure 8**: A section view showing the refined 10cm mesh resolution cells enclosing the boundary of the SED in the upper half of the compartment*

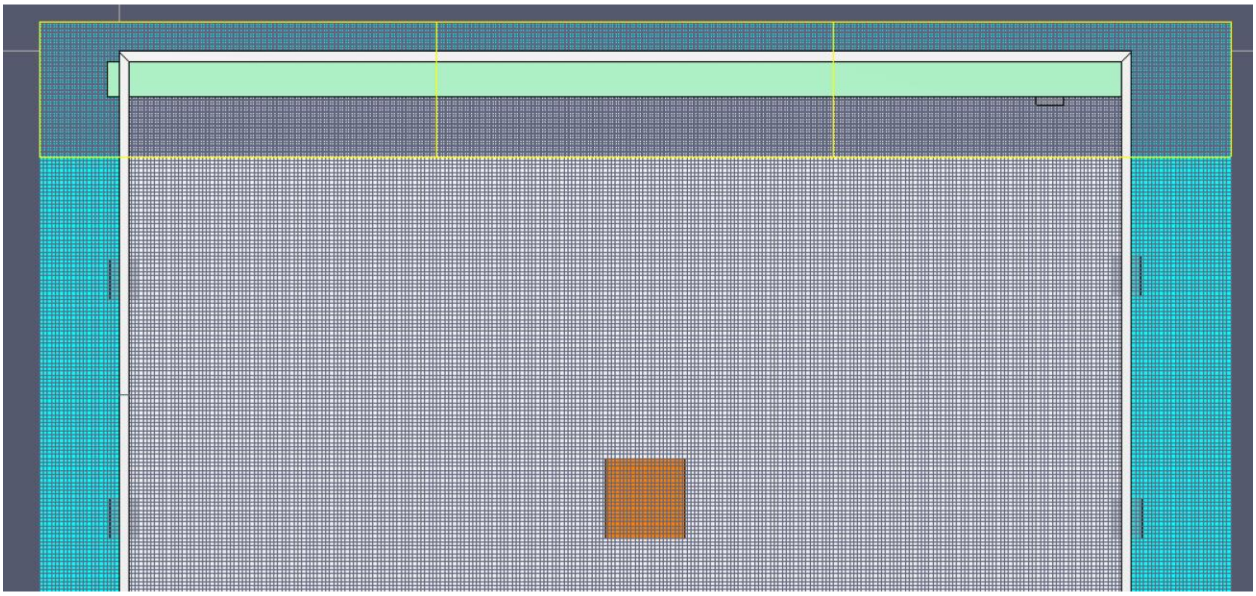


***Figure 9**: Top view of the coverage of the refined 10cm mesh along the entire length of SED*

4.7 Output

As the transient process of the CFD simulation is not of interest since the result of interest is upon achieving steady state conditions, the fire has been assumed to be in a steady state, neglecting typical fire growth rates associated with a developing fire. The time delay for the detection of fire and the subsequent time required for the activation of the SED system are also not considered in the simulation to save on the computation time needed for the simulation to achieve steady-state conditions. The CFD simulation is set to run for maximum 900 seconds or until steady state conditions are achieved.

The most critical output to be assessed is the soot concentration in the compartment which will significantly impact visibility. The smoke layer shall be measured in several ways through FDS with the use of visibility slices and 3D smoke visualization in Smokeview. This gives a overall compartment view of the visibility during the simulation period as the smoke layer develops and deepens until it achieves a stabilized smoke layer height.

A more precise averaged measurement of smoke layer is also implemented in the compartment model using smoke layer measurement devices as detailed in Section 16.9 of the FDS User Guide [8]. A total of nine smoke layer measurement devices are distributed in all sections of the compartment as shown in Figure 8 below. This eliminates any inaccuracies in the visual representation of black soot in 3D smoke or visibility slices. The smoke layer measurement devices also record the smoke layer temperature simultaneously to observe the average smoke layer temperature in the compartment.

The SED extraction rate shall be measured through flow measuring devices placed at the individual SED extraction point(s) along the SED itself to determine the extraction flow rate imposed on the extraction fan itself and the distribution of the extraction rate across the SED point(s) along the duct. The replacement air inlet flow rate shall also be measured through flow rate measuring devices placed at the air inlet openings.

Several other diagnostic measurements are recorded along the SED length such as pressure to determine the pressure loss at various points of potential interest along the duct as well as internal velocities along the duct to observe the velocity changes along the duct across the SED extraction points.

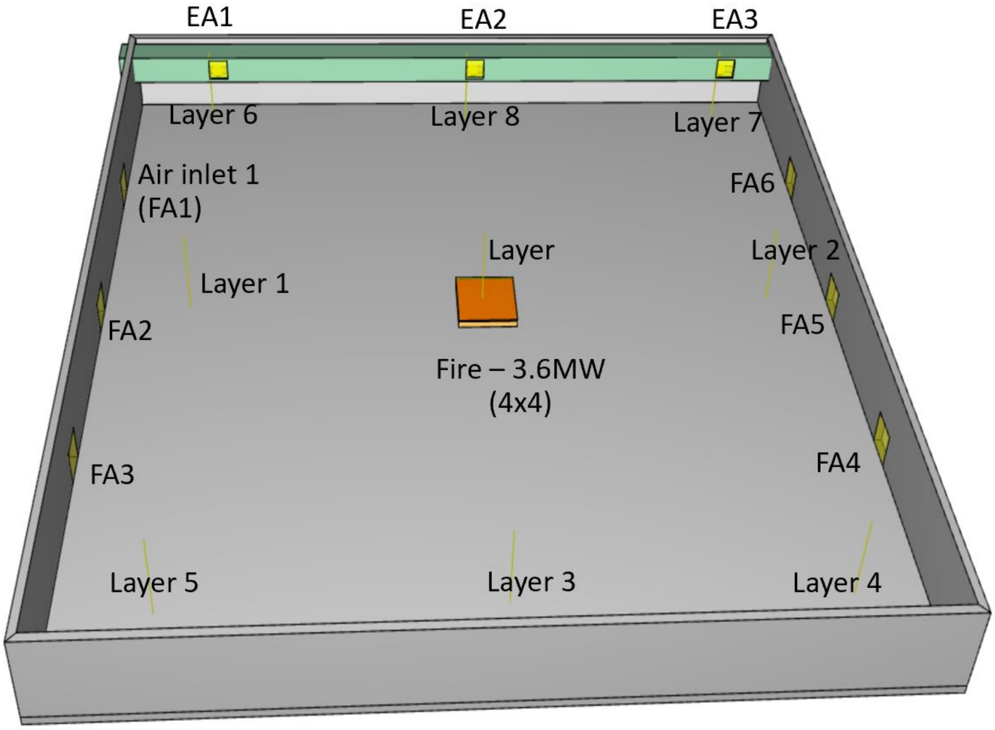


Figure 10*: Output Measuring Devices in the CFD Model; EA for SED extraction point device, Layer for Smoke & Temp devices, FA for air inlet device*

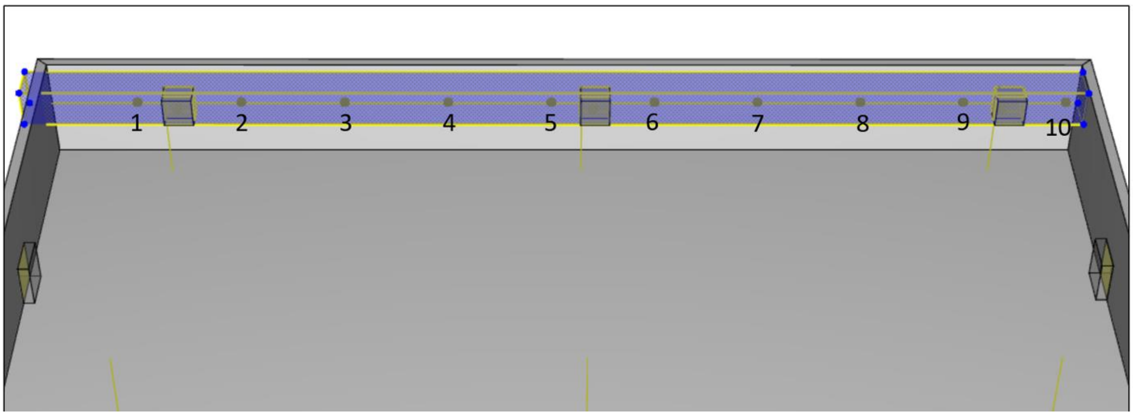


Figure 11*: Output Measuring Devices (1-10) inside the duct for pressure and velocity*

4.8 CFD Simulation Scenarios

The simulations to be conducted can be divided into four separate case studies:

1) **Case Study 1**: Test the base case scenario where the SED system is running but without the fire to determine the air flow properties at ambient conditions i.e, without the fire. This provides information for how the air flow patterns and data for normal ventilation without the influence of smoke and heat from the fire.

2) **Case Study 2**: Test the base case scenario without SED system but having the fire with natural ventilation through the SED instead. This shall provide information on the smoke flow characteristics in natural conditions without the influence of mechanical extraction.

3) **Case Study 3**: Test the base case scenario with the activation of the SED system and the fire in all default perimeters as listed below:

Parameter	Value
SED Configuration	Single SED
Fire Location	Centre of Compartment
SED Extraction Capacity	$18.2m^3/s$
No. of SED extraction points	3 points

Table 2: *Base case simulation default parameters*

4) **Case Study 4**: Sensitivity test of the base case scenario with varying parameters to determine how each parameter change affects the performance of the SED system. The parameters that are varied include the SED distribution (whether a single SED or two SED are used), the fire location, the SED extraction rate and the total number of SED extraction points.

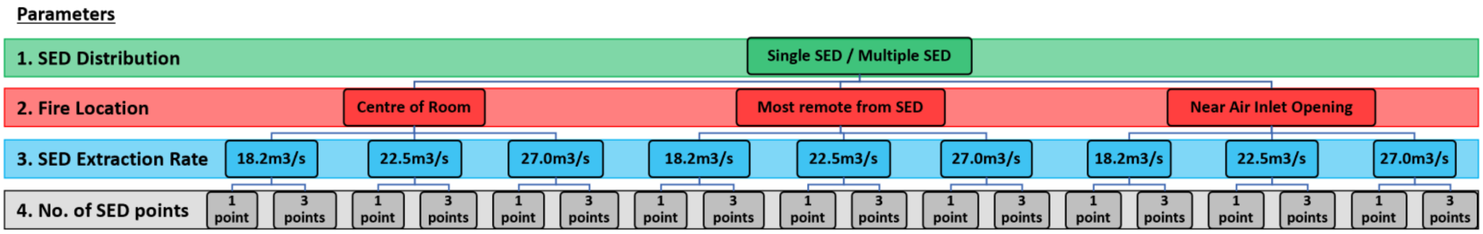


Table 3: *Sensitivity Study with varying parameters*

5 Results and Discussion

This chapter is organized based on the various sections of simulation cases as detailed in Chapter 4.8 previously and discussions are included in the respective subchapters of simulation case studies for clarity in presentation of information and findings. It should be noted that all results presented in this chapter are taken at steady state conditions unless otherwise stated.

A conclusion shall be made thereafter to summarize and draw inferences based on all the simulation results obtained. Finally, a proposal of future works shall be presented with suggestions for expanding the scope of research further based on the results obtained in this thesis study.

5.1 Case Study 1: Scenario without Fire (SED ventilation only)

The first set of results to be presented here is the scenario of the compartment without fire with the SED system activated to analyse and observe the ventilation flow patterns and results primarily focusing on the volume flow rates, mass flow rates, pressure drops and velocity data since there is no smoke or heat produced in this scenario.

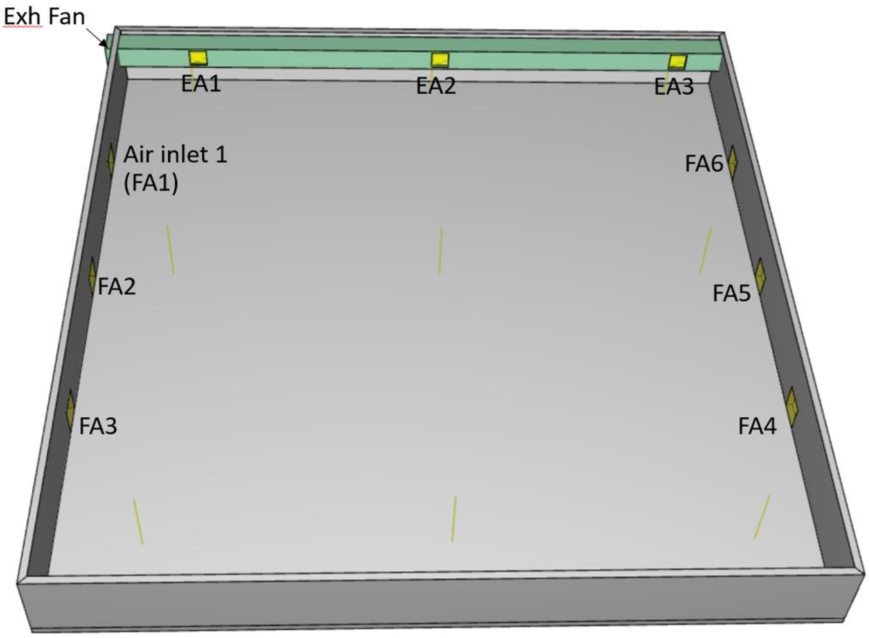


Figure 12: *CFD Model for Case Study 1 (No Fire, SED only)*

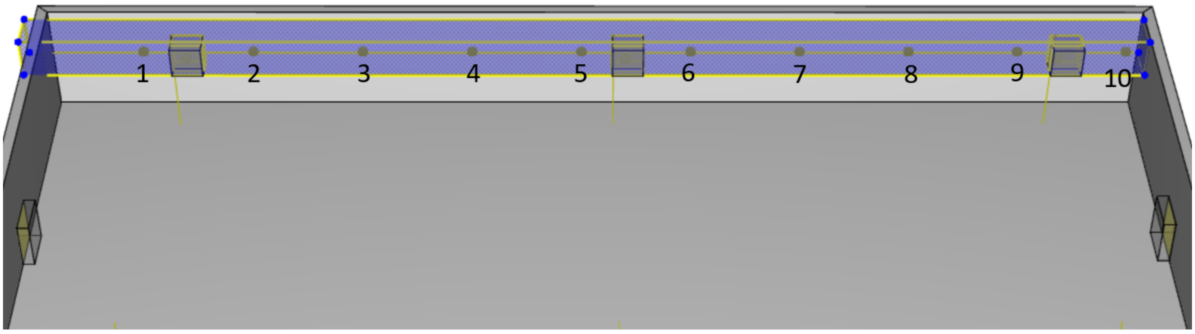


***Figure 13**: Measurement intervals along SED duct (1-10)*

The velocity slice taken at mid-height of the air inlet opening level, i.e; z=1.6m, shows relatively stable air inlet velocities of approximately 1 m/s through all air inlet openings. The influence of the SED point extraction on the nearest air inlet opening at the top of the compartment is not significant as there is no noticeable pulling force induced by the SED point on the air flow through the air inlet opening.

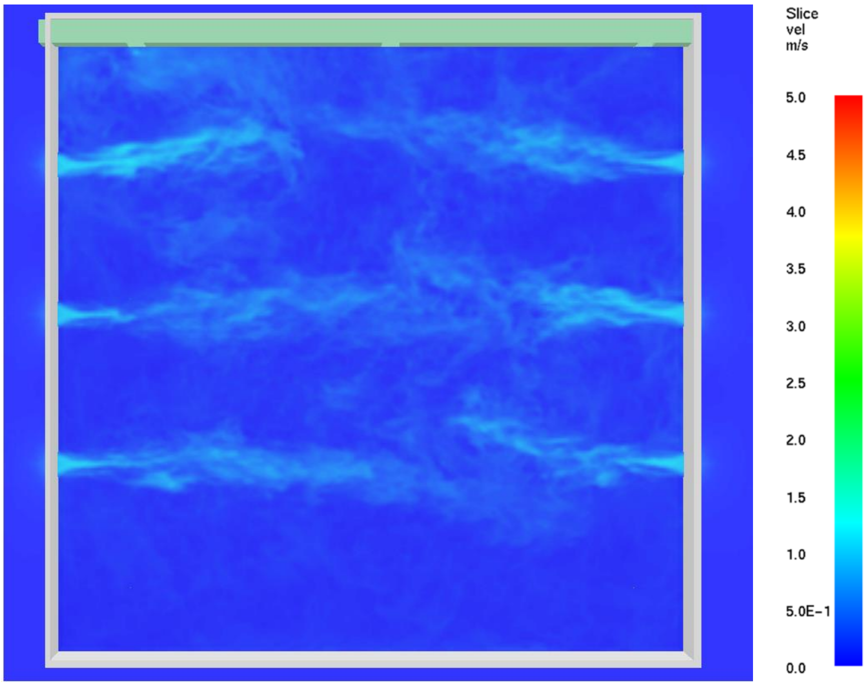


***Figure 14**: CFD Model for Case Study 1 (No Fire, SED only), z=1.6m*

The volume flow rate and mass flow rate recorded through the air inlet is normal with the flow rates distributed evenly through each air inlet opening and the sum of the flow rate matches the SED extraction rate of 18.2m^3/s.

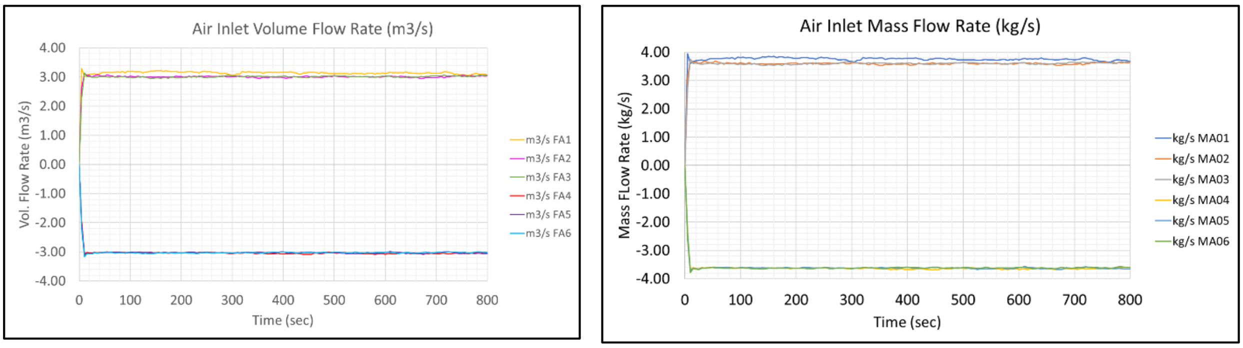


Figure 15: *Volume and Mass flow rates measured across the 6 air inlet openings*

The volume flow rate and mass flow rate measured through the SED points reveals a progressive drop in volume flow rates across each SED point opening along the duct with the SED point closest to the extraction fan having the highest share of the extraction flow rate but a significant drop in the flow rate is observed across the latter 2 SED points along the duct.

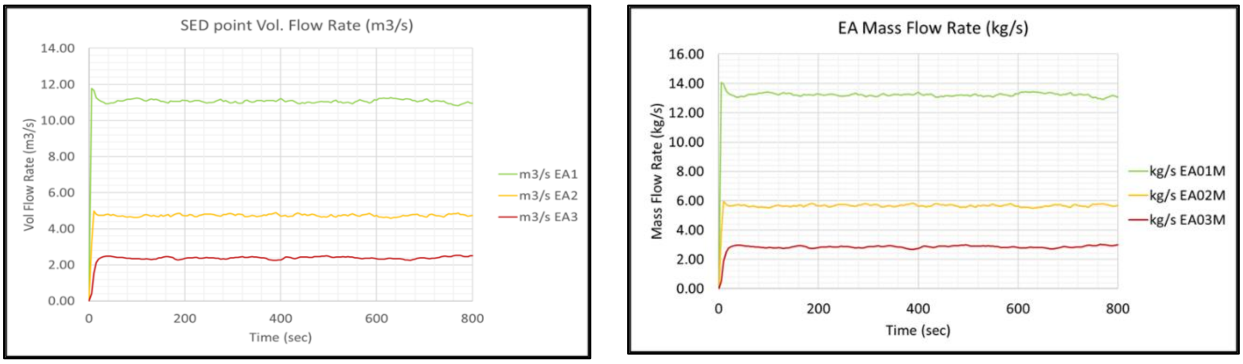


Figure 16: *Volume and Mass flow rates measured across the 3 SED points*

The pressure drops and velocity across 10 interval points inside the SED are shown below. The results indicate the largest pressure drop occurring between zones 1 and 2 of the measurement interval which corresponds with the higher velocity as well due to the highest extraction flow rate through SED point 1. The pressure drops gradually increase before the next SED point opening. There is also a significant drop in velocity across each SED point due to the corresponding increase in pressure after the SED point opening. The pressure drops and change in velocities across SED point 2 and 3 are smaller but proportional to the respective flow rates passing through each SED point.

SED point of interest	SED Point 1				SED Point 2				SED Point 3	
Measurement Interval	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Pressure (Pa)	-131.63	-17.46	-16.86	-17.12	-22.50	-3.79	-3.68	-3.65	-4.23	-1.66
Velocity (m/s)	14.47	3.98	3.95	4.48	5.84	1.46	1.30	1.19	1.36	0.24

Table 4: *Pressure Drops and Velocities inside the SED at steady state (intervals 1 – 10)*

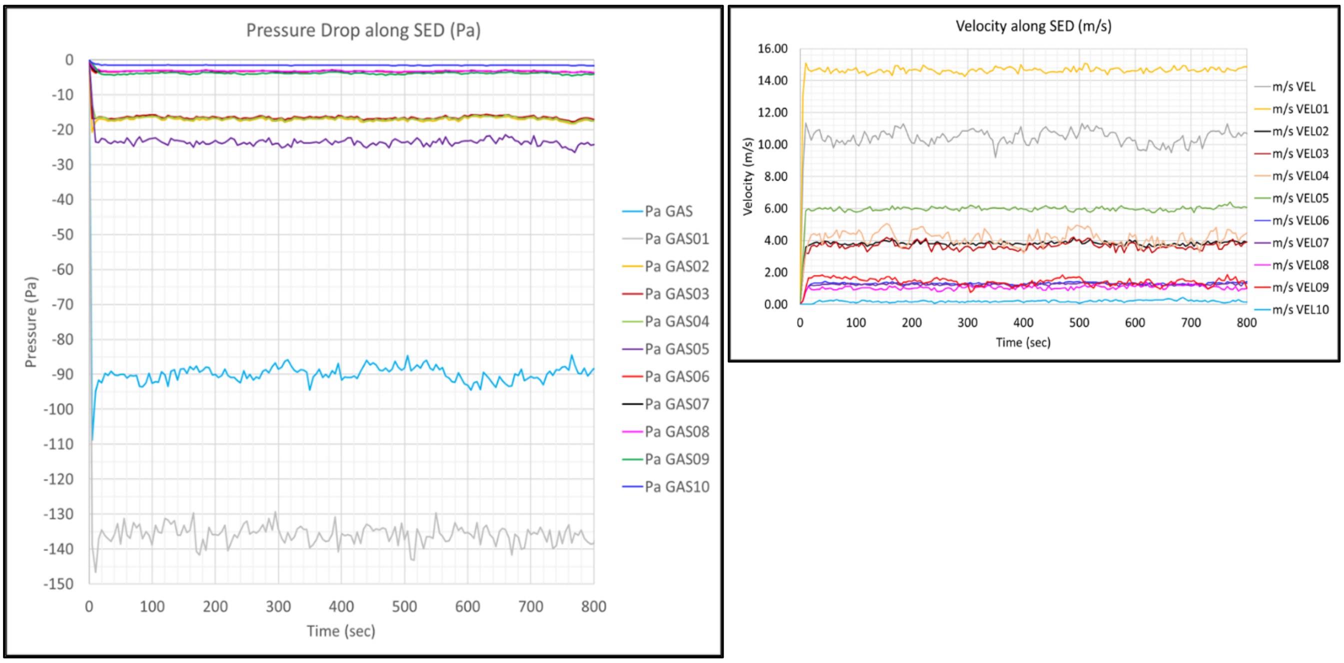


Figure 17*: Pressure Drop and Velocities across 10 measuring intervals along the SED*

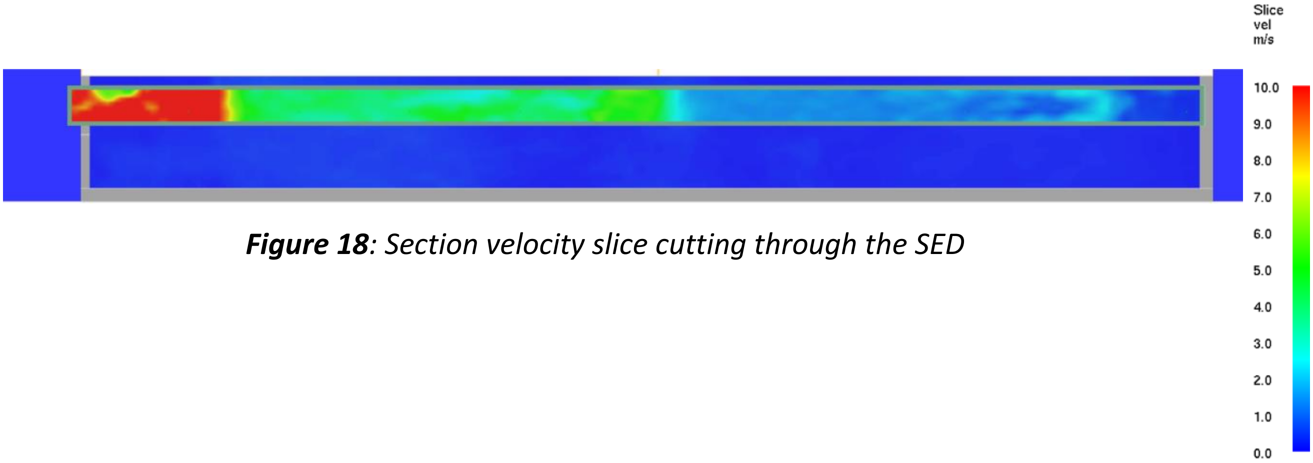


Figure 18*: Section velocity slice cutting through the SED*

The Darcy-Weisbach equation is an empirical correlation which calculates the pressure loss inside a duct due to friction along the length of the duct for a fluid flow and is given by the equation below:

$$\frac{\Delta p}{L} = f_{\mathrm{D}} \cdot \frac{\rho}{2} \cdot \frac{\langle v \rangle^2}{D_H},$$

The equation provides for a relation where the pressure loss is proportional to the length of the duct squared with the velocity of the fluid flow along that given length.

Assuming a smooth pipe friction factor and a square duct equivalent diameter, a verification check is performed by using the data from the simulation in Table 4 above and calculating using the Darcy-Weisbach equation, the relationship between pressure loss and the velocity squared along the duct distance is plotted as follows:

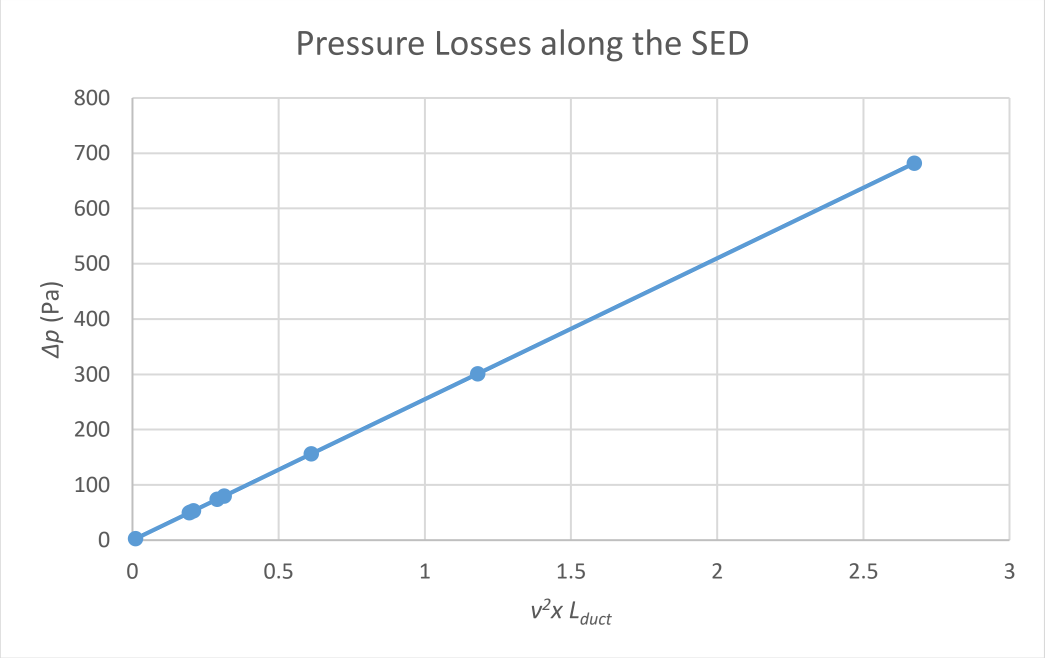


***Figure 19**: Graph of Δp against $v^2 x\ L_{duct}$*

The graph plot above verifies that the pressure losses are proportional to the velocity squared over a given duct length for this case study.

5.2 Case Study 2: Scenario without SED Extraction (Natural Vent)

The second case study analyses the compartment fire but without the effect of mechanical smoke extraction. This case shall provide information on the smoke flow behavior through naturally induced ventilation and observing the impact on the smoke layer height and temperature in the compartment.

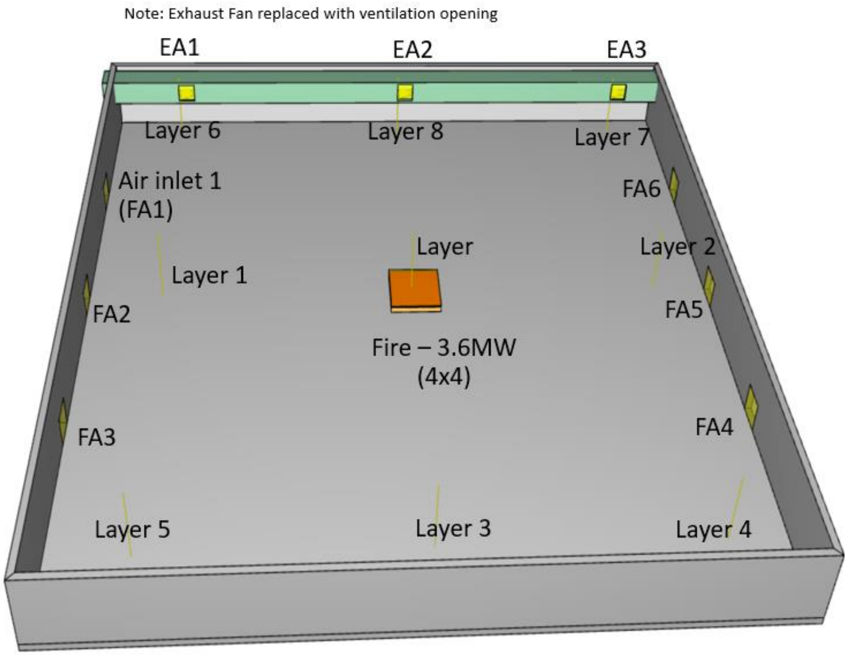


***Figure 20**: CFD Model for Case Study 2 (No SED Extraction, Fire only)*

Taking into the consideration the relatively large HRR of the fire with respect to the height and overall volume of the compartment, it is no surprise that the smoke layer descends significantly lower than the performance criteria of z=2.5m in the naturally ventilated scenario. The limited exhaust openings area to the external environment, confined to the cross-sectional area of the SED is insufficient to maintain the desired smoke layer and as a result, the smoke layer also spills out through the air inlet openings of the compartment.

Temperature slice across the height of z= 2.6m shows elevated temperatures in the compartment in excess of 60°C although the threshold of the upper layer temperature of 200°C is not exceeded. It should be noted that due to the mesh size of 20cm in FDS, the nearest available slice height is taken at z=2.6m instead of z=2.5m.

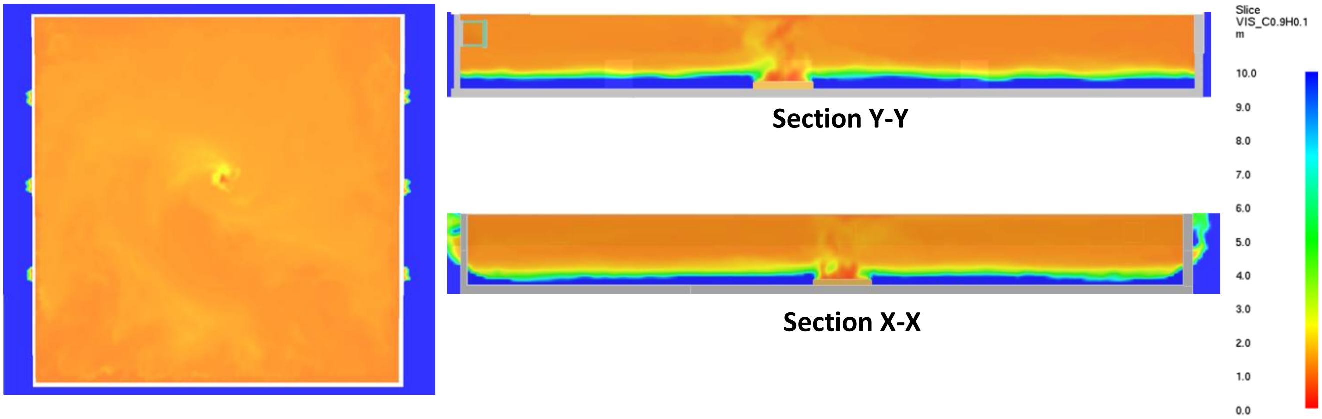


Figure 21: *Smoke Visibility Slices at z=2.6m (left), Section X-X and Y-Y visibility slices cutting through the center of the fire (right)*
(visibility scale: red indicates thick smoke region, blue indicates smoke free region)

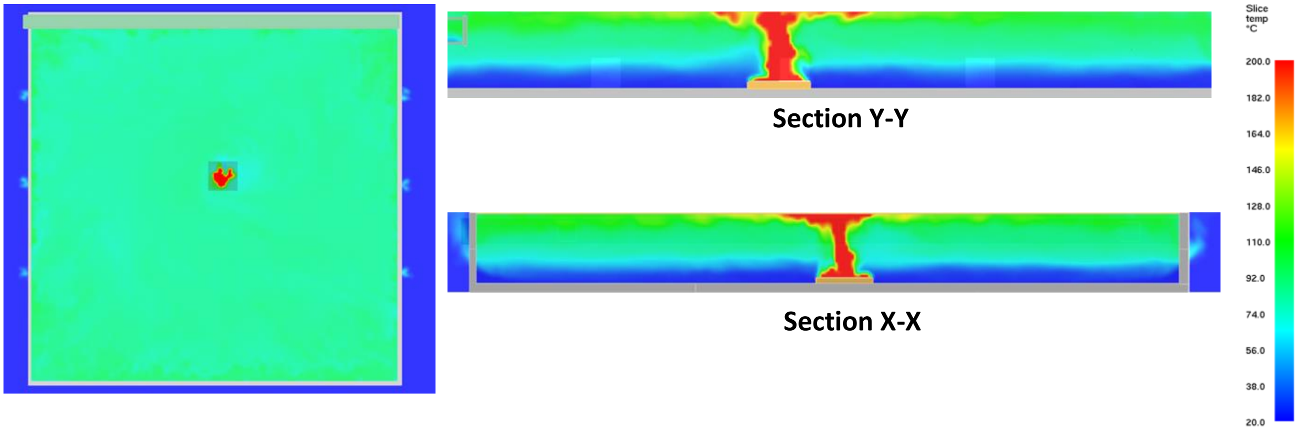


Figure 22: *Temperature Slices at z=2.6m (left), Section X-X and Y-Y temperature slices cutting through the center of the fire (right)*
(temperature scale: red indicates hot smoke region, blue indicates cold air region)

Figure 23: *3D Smoke visualization showing the smoke flow from the SED outlet (top left, green box) and the smoke layer deepening to almost floor level in the compartment and smoke flows out from the air inlet openings.*

Referring to the air inlet flow rates, the air inlet flow rate is very turbulent with spikes of inflow and outflow initially, indicating insufficient smoke exhaust outlet as the air inlet opening itself begins to act as both smoke exhaust and air inlet simultaneously. As the smoke layer descends and spills out of the air inlet openings, the flow rate gradually stabilizes in a single direction of flow which in this case indicates there is a continuous outflow of smoke out of the air inlet openings.

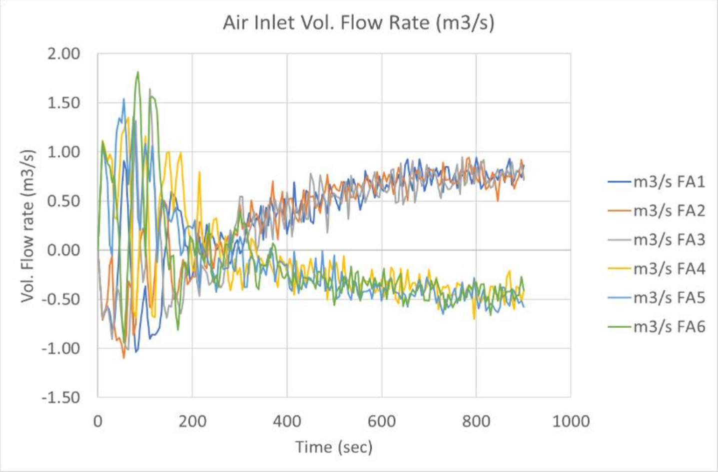


Figure 24*: Air inlet volumetric flow rate (No SED Extraction, Fire only)*

The SED point flow rate in this case study is the natural flow rate of the smoke through the SED openings and reveals a larger increase in exhaust flow rate through the first SED point nearest to the SED outlet opening. The 2 SED openings further along the duct, shows a stagnating rise in exhaust flow rate as the smoke layer fills up the SED space and the smoke flow through the 2 openings eventually reach a bottleneck capped by the rate of flow out via the SED outlet opening.

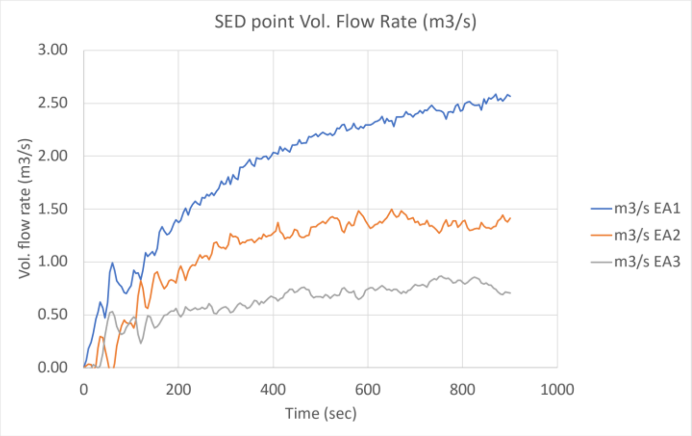


Figure 25*: SED points volumetric flow rate (No SED Extraction, Fire only)*

5.3 Case Study 3: Base Case Scenario

The base case scenario applies the default perimeters of the simulation to the CFD model and shall include the SED extraction and the fire. The previous two case studies present the results for respective cases without the fire and without the SED extraction and this case combines both permutations to see the changes in smoke flow behavior or air flow patterns in the compartment and SED.

From the visibility and temperature slices in the Figure below, it is observed that the inclusion of the mechanical extraction to the SED shows noticeable improvements in the visibility slice of the smoke layer due to the extraction rate of 18.2m^3/s being significantly higher than the naturally induced outlet flow rate in Case Study 2 which tops out at about 5m^3/s. The smoke layer temperature also shows a reduction in the maximum recorded temperature.

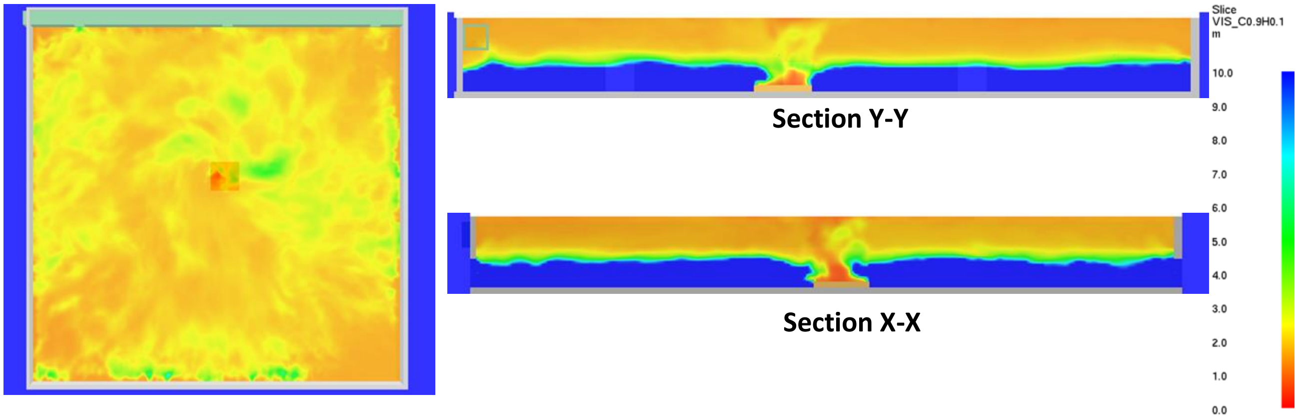


Figure 26: *Smoke Visibility Slices at z=2.6m (left), Section X-X and Y-Y visibility slices cutting through the center of the fire (right)*
(visibility scale: red indicates thick smoke region, blue indicates smoke free region)

Figure 27: *3D Smoke visualization showing a higher smoke layer in the compartment and no smoke outflow from the air inlet openings.*

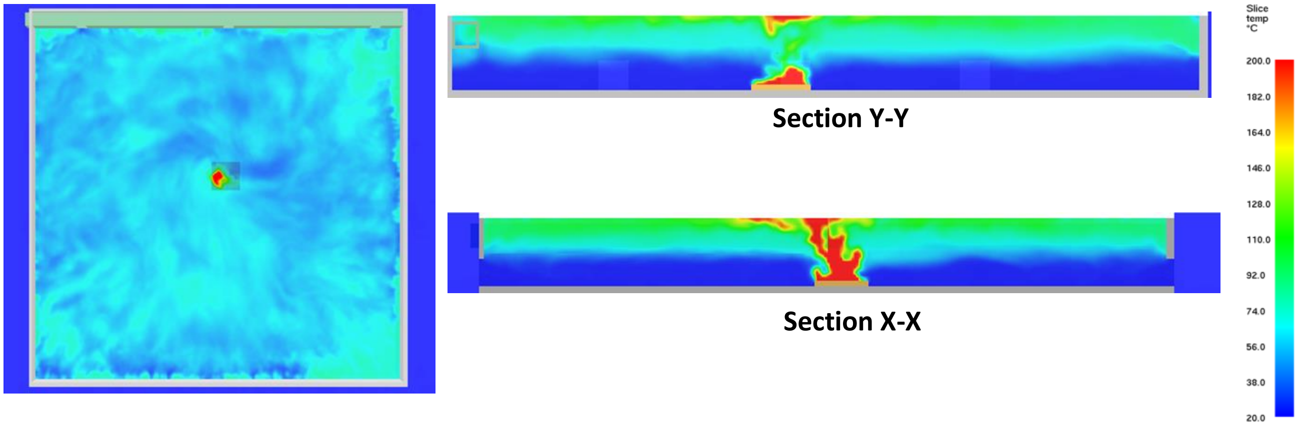


Figure 28: *Temperature Slices at z=2.6m (left), Section X-X and Y-Y temperature slices cutting through the center of the fire (right)*
(temperature scale: red indicates hot smoke region, blue indicates cold air region)

The smoke layer settles at a height of approximately 2.2m which is about 12% lower than the tenability criteria of height of 2.5m as calculated in the initial empirical correlations. The calculated extraction flow rate which was deemed sufficient to achieve a smoke free height of 2.5m was inadequate as shown in the CFD visibility slice results. This shows that there are inherent limitations in the empirical correlations which made the calculated result inaccurate in comparison to the CFD simulation outcome.

There was an assumption of a uniform smoke layer & smoke temperature for the empirical calculations which is not how the hot smoke layer behaves in reality. There are almost certainly temperature differences across the hot smoke layer due to the interface boundary with the cold air underneath and the complexity of smoke flow and the formation of a distinct hot upper zone and cold lower zone. The smoke layer is also not uniform as the impact of turbulence mixing between the smoke and cold air layers will disturb the uniformity of the smoke layer continuously. In the empirical correlations, there were also no assumptions of heat losses to the boundaries of the compartment whereas this characteristic is captured in the CFD model with the proper assigning of materials to the compartment boundary conditions which allows for heat losses.

Instead of the air inlet opening functioning as both smoke exhaust and air inlet as seen in Case Study 2, the air inlet now functions normally with full incoming air flow rate as the smoke layer has not deepened to the extent of needing to spill out from the top of the air inlet. As seen from the graphs below, the initial phase of the smoke layer height descends rapidly as it fills the compartment smoke reservoir space.

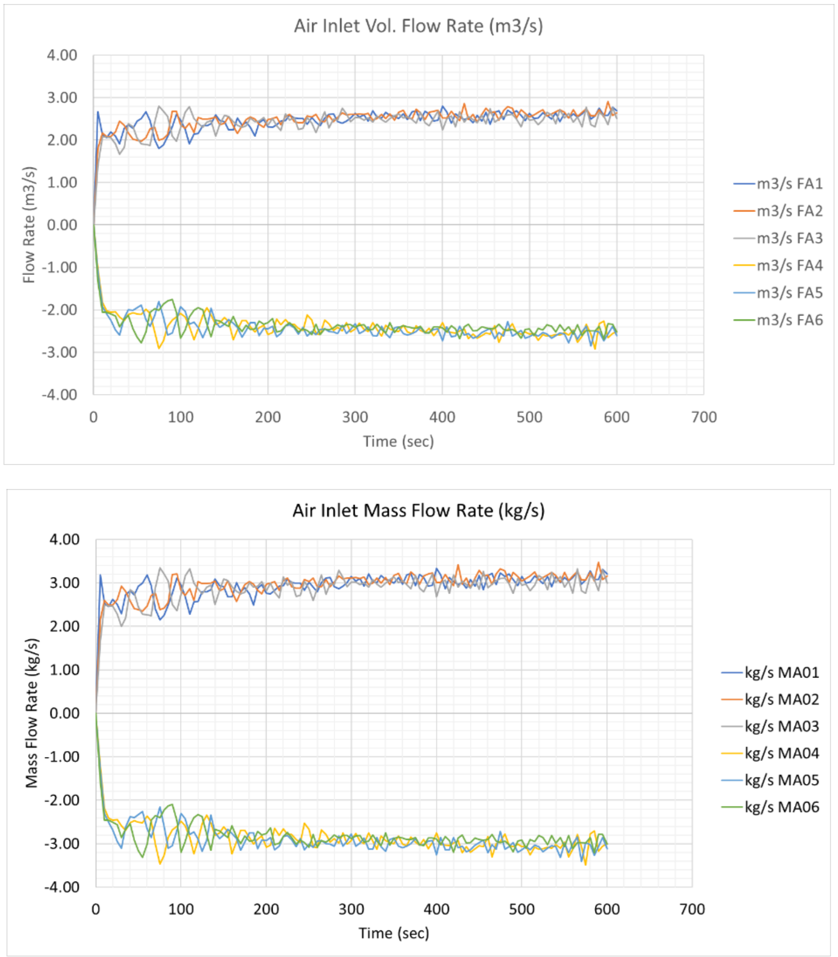
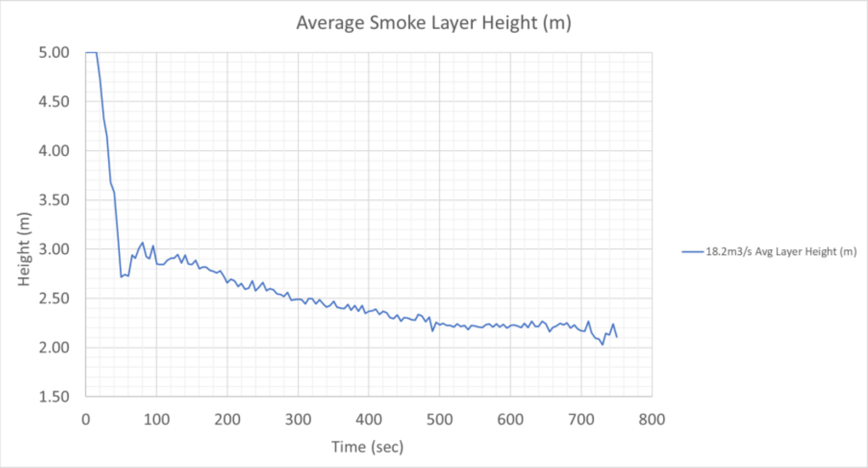


Figure 29*: Graphs of air inlet volume flow rate (above) and air inlet mass flow rate (below)*

As the formation of the hot smoke layer is complete, the smoke layer height then gradually descends until it reaches a steady state smoke layer from the simulation time of 500s onwards. The average temperature of the smoke layer climbs gradually but plateaued as it approached the steady state smoke layer and never exceeded 100 °C. It should be noted that there were some numerical instabilities in the results from the time interval of 700s onwards.



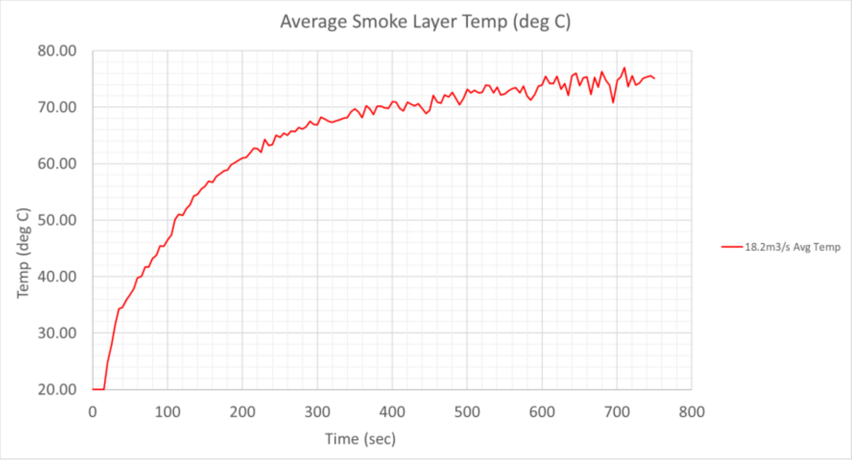


Figure 30*: Graphs of average smoke layer height (above) and average smoke layer temperature (below)*

The SED points extraction rates in the base case scenario are relatively similar to what it was before in Case Study 1 (no fire) with SED point 1, nearest to the exhaust fan having the highest extraction rate and the effectiveness drops as it goes further along the duct towards SED point 2 and point 3. The total volumetric flow rate across the 3 SED points tallies with the exhaust fan flow rate indicating no loss in flow rate between the SED points relative to the exhaust fan. The mass flow rate however, exhibits a slight decrease from the start of the simulation for the first 200 seconds most prominently in SED point 1. The constant volume flow rate but decreasing mass flow rate shows a reduction in density of the fluid flow through the SED point which is indicative of smoke flowing through instead of air, and this is most notable in the most efficient extraction point, SED point 1, along the duct.

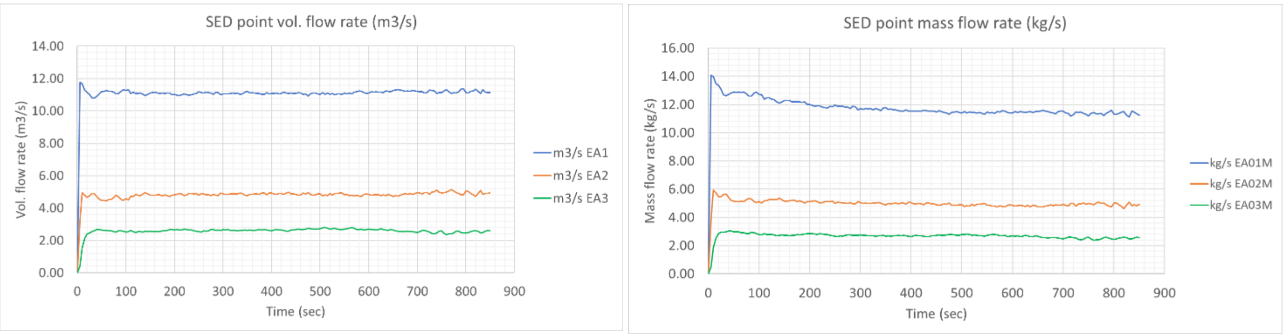


***Figure 31**: Graphs of SED points volume flow rate (above) and SED points mass flow rate (below)*

The pressure drop and velocity variation along the duct also shows similar patterns as observed in Case Study 1 (no fire). The biggest pressure drop occurs at SED point 1 followed by SED point 2 and point 3.

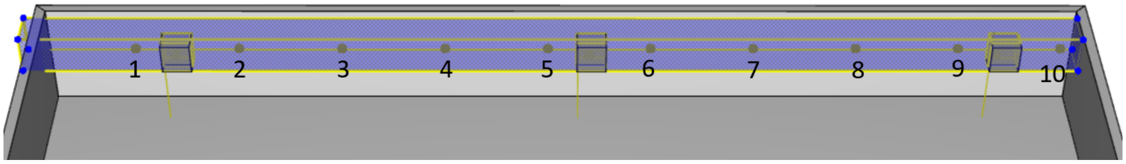


***Figure 32**: Measurement intervals along SED duct (1-10)*

SED point of interest	**SED Point 1**				**SED Point 2**				**SED Point 3**	
Measurement Interval	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Pressure (Pa)	-113.63	-13.30	-12.89	-13.39	-19.30	-0.79	-0.78	-0.80	-1.84	0.88
Velocity (m/s)	14.36	4.18	4.19	4.80	6.19	1.21	1.28	1.19	2.24	0.19

***Table 5:** Pressure Drops and Velocities inside the SED at steady state (intervals 1 – 10)*

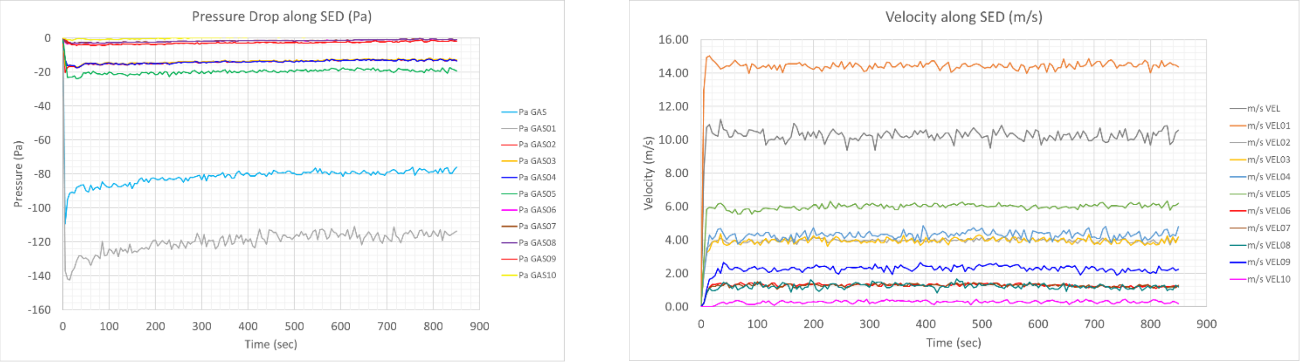


***Figure 33**: Graphs of pressure drop and velocity along SED*

5.4 Scenarios with Varying SED Extraction Rate

The first parameter for the sensitivity case studies is the modification in the SED extraction rate. It is now established that the base case calculated extraction rate based on empirical correlations are not sufficient to achieve the smoke free height tenability criteria of 2.5m although only having a shortfall by about 0.3m to achieving it. Additional iterations are made with an increase in extraction rate by 25% and 50% to gauge the improvements if any, to the performance of the SED system in reducing the smoke layer depth.

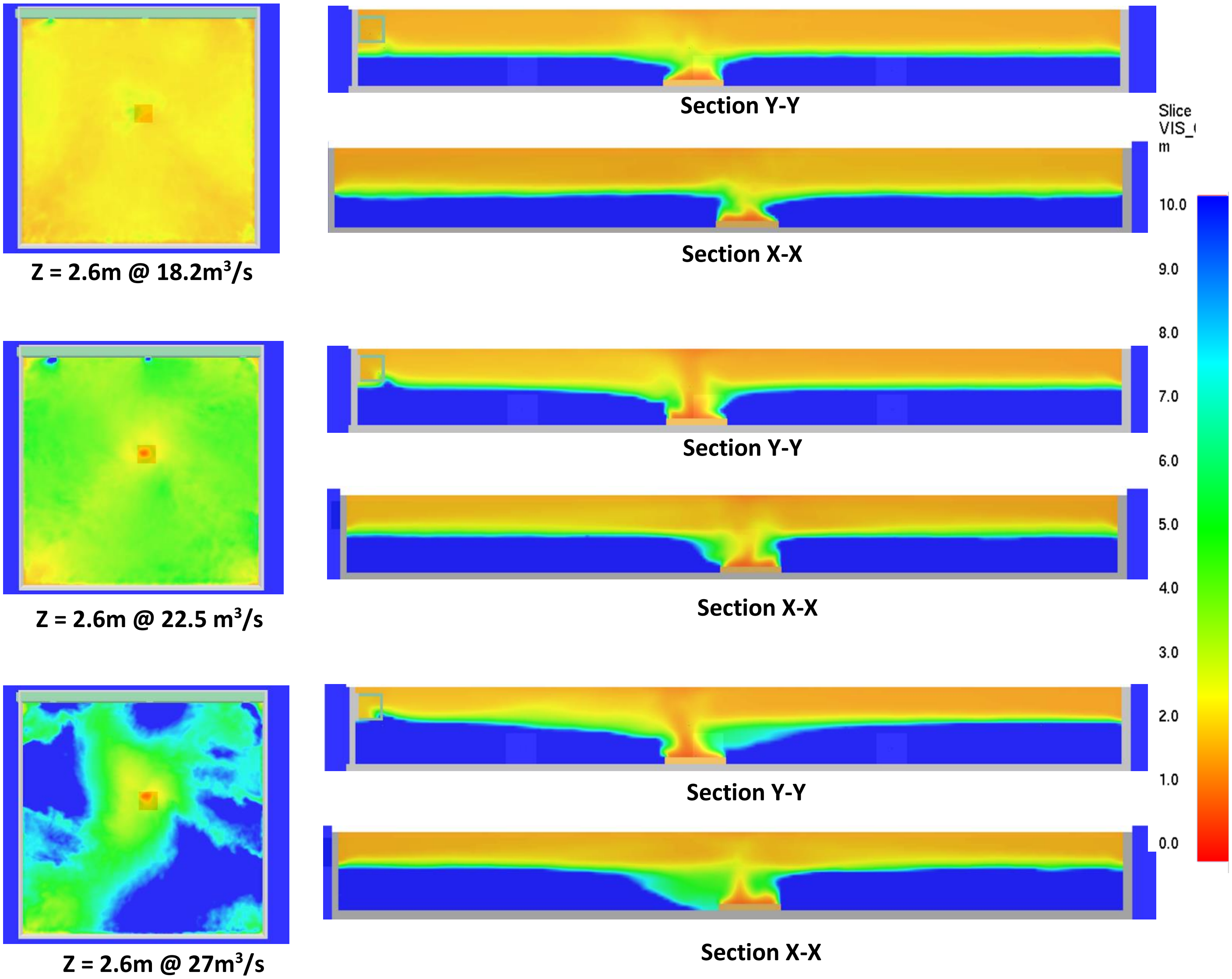
Simulation Scenario	**SED Extraction rate (m^3/s)**
Base Case	18.2
Sensitivity Case 1 (25% upsize)	22.5
Sensitivity Case 2 (50% upsize)	27.0

Table 6: *Sensitivity Study on the SED Extraction Rates with an upsize by 25% and 50%*

As the primary focus of this scenario is to analyse the performance improvements in terms of smoke tenability limits, it is reasonable to only prioritize the output data concerning visibility, temperature and the changes in SED flow rates to determine if plugholing occurs at higher extraction capacities.

The visibility slice results reveal that an increase of 25% in the SED extraction rate to 22.5m^3/s was enough to cause some plugholing effects for SED point 1 although its appears that SED point 2 remains unaffected. The visibility results for a 50% increase to 27m^3/s shows notable improvements in smoke free patches around the compartment but the section Y-Y slice across the SED point 2 reveals some plugholing effect occurring which means SED point 1 is likely to have more severe plugholing.

It is to be noted however, that the visibility slice as shown in the Figure below, is limited to a height of z = 2.6m, hence it may not be truly representative of the smoke layer behaviour at the tenability criteria height of 2.5m which will be better presented in the average smoke layer height graph next.



Z = 2.6m @ 18.2m^3/s

Section Y-Y

Section X-X

Z = 2.6m @ 22.5 m^3/s

Section Y-Y

Section X-X

Z = 2.6m @ 27m^3/s

Section Y-Y

Section X-X

Figure 34: *CFD results at top - extraction at 18.2m^3/s, CFD results at middle – extraction at 22.5m^3/s, CFD results at bottom – extraction at 27m^3/s.*

Referring to the graphs below, for an extraction rate increase of 25%, the average smoke layer height does in fact settle within proximity to the tenability criteria smoke free height of 2.5m from the simulation time period of 500s onwards. This means the calculated smoke extraction rate based on the plume correlations with its numerous limitations and assumptions, were about 25% off from the required rate of extraction based on CFD simulations. The 50% increase in extraction capacity was more than sufficient to maintain the tenability criteria of the smoke layer in this fire scenario. The average smoke layer temp shows a noticeable improvement when the extraction rate was increased by 25% but it shows minor improvements as the extraction is raised further by 50%. The temperature slices of the CFD results shall not be presented as it can be deduced from the average temperature readings that the smoke layer is unlikely to exceed the tenability limit of 200 °C at this fire size for this compartment size.

The increase in extraction rate shall be explored further in the following sensitivity case studies when the fire location is varied.

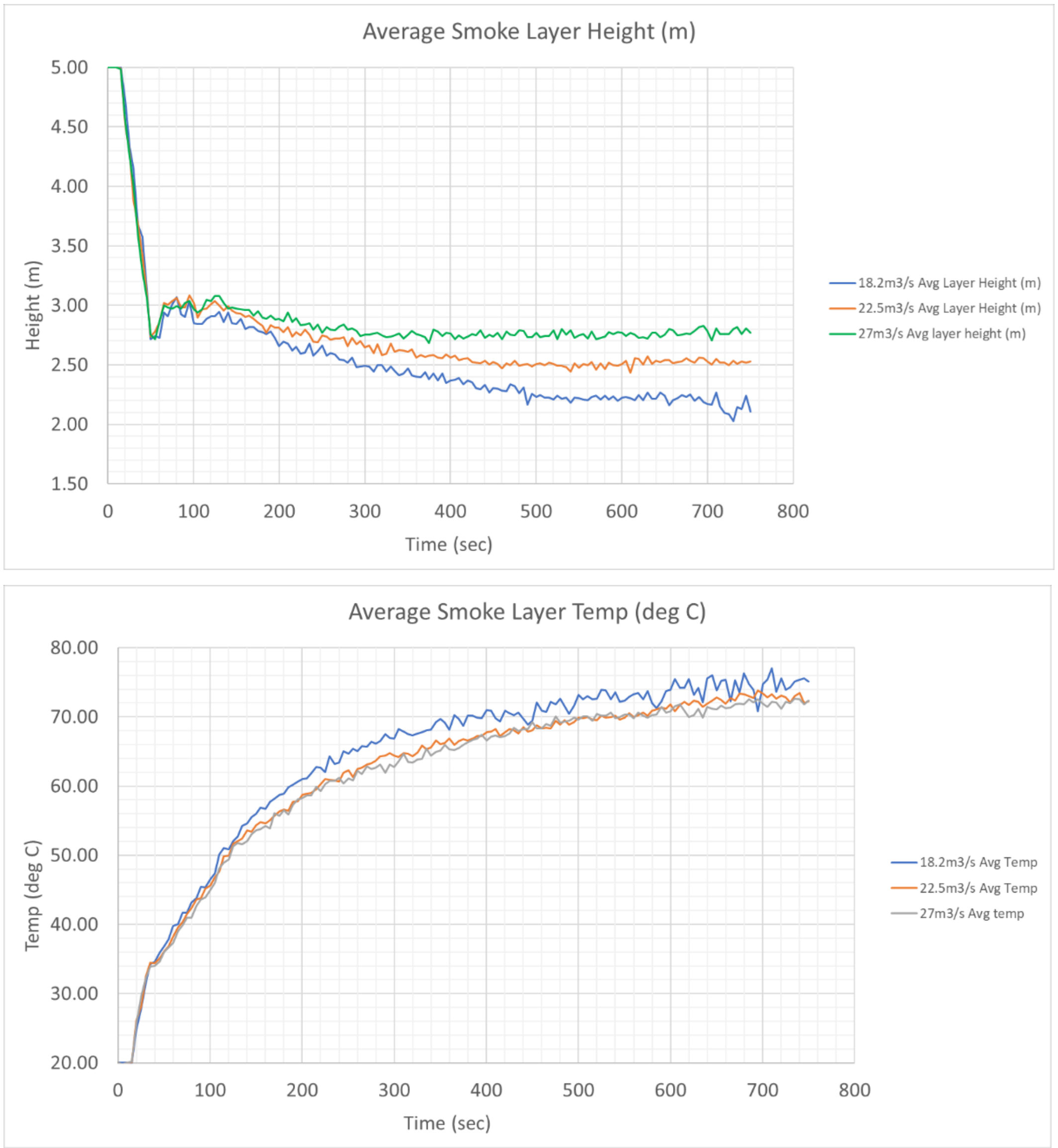


Figure 35: *Graph of average smoke layer height (top), graph of average smoke layer temperature (bottom)*

The mass flow rate and volume flow rate of the three SED points in all cases exhibit similar behaviour to what was analysed previously, with SED point 1 delivering the highest extraction capacity followed by SED point 2 and 3. The drop in mass flow rate is also showing a similar trend with SED point 1 showing the biggest drop in mass flow rate indicating the most effective at extracting smoke although it shall be noted that as the simulation achieves steady-state conditions for 22.5 m^3/s and 27m^3/s , plugholing effect was visible from the visibility slices at SED Point 1 and 2.

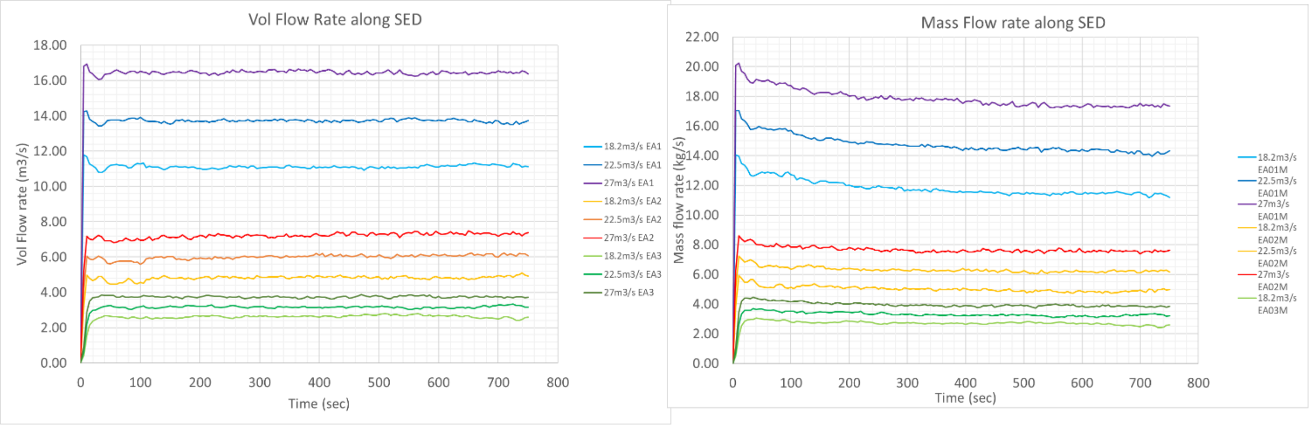


***Figure 36**: Graph of SED volume flow rate (left), graph of SED mass flow rate (right)*

5.5 Scenarios with Varying Fire Location

The subsequent parameter to be assessed for the sensitivity case studies is the change of fire location. With all other parameters fixed (*SED extraction rate = 18.2m^3/s, no. of SED points =3 , single SED configuration*), the simulation is repeated with two different fire locations in addition to the base case fire scenario at the center of the compartment.

The second fire location is at the location most remote from the SED which is at the opposite corner of the compartment. This represents a worst-case scenario where the fire is furthest away from the SED extraction point and its impact on the performance of SED system is evaluated.

The third fire location is at the location nearest to one of the air inlet openings. This fire location is of interest due to the possibility of the air inflow coming through the inlet opening tilting the smoke plume and causing additional turbulence to the smoke layer as it develops, which could in theory, result in more air entrainment into the smoke layer and deepen the smoke layer height significantly.

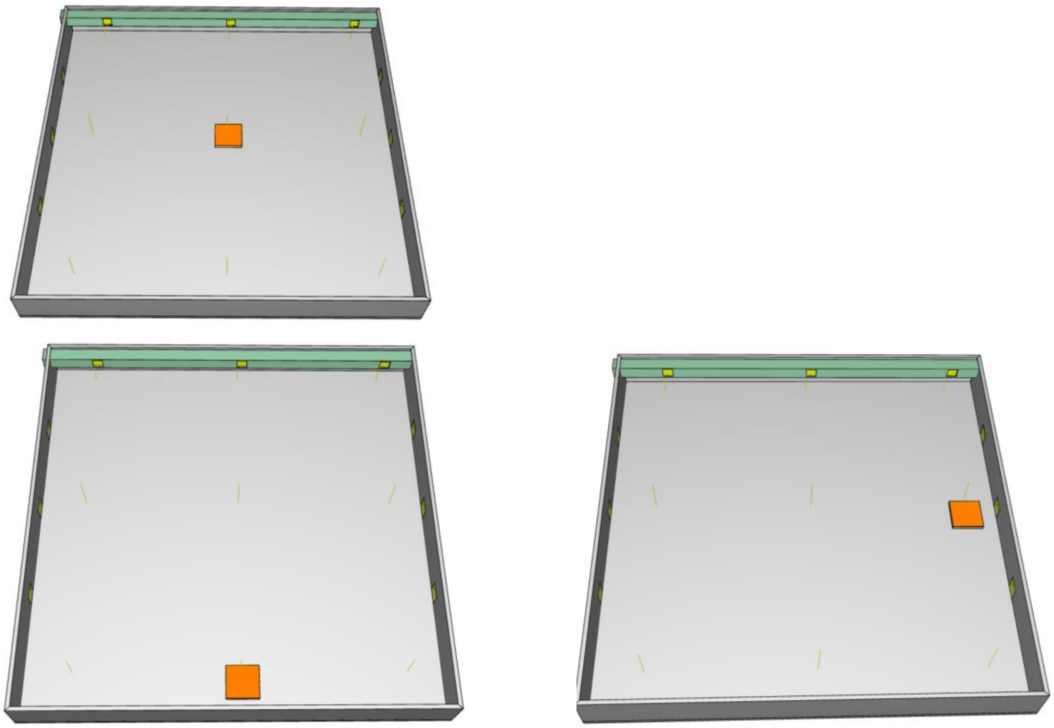


Figure 37*: From anti-clockwise, fire at center of compartment (top), fire remote from SED (left), fire near air inlet (right)*

The comparison of visibility slices shows different smoke thickness in the compartment across all three fire locations. The visibility slices for the remote fire and the air inlet fire appears to be slightly worse than that for the centre fire.

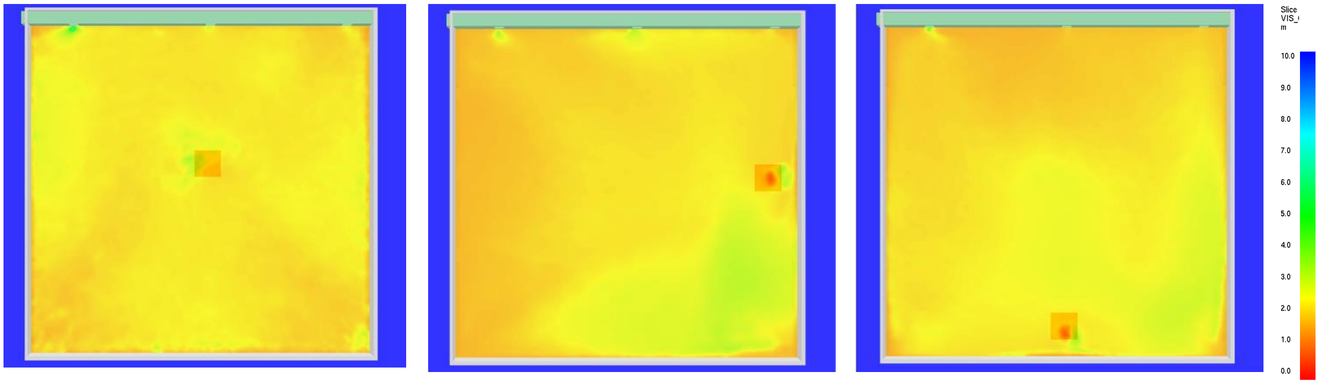


Figure 38*: Visibility slices at z=2.6m for fire at center of compartment (left), fire near air inlet (middle), fire remote from SED (right)*

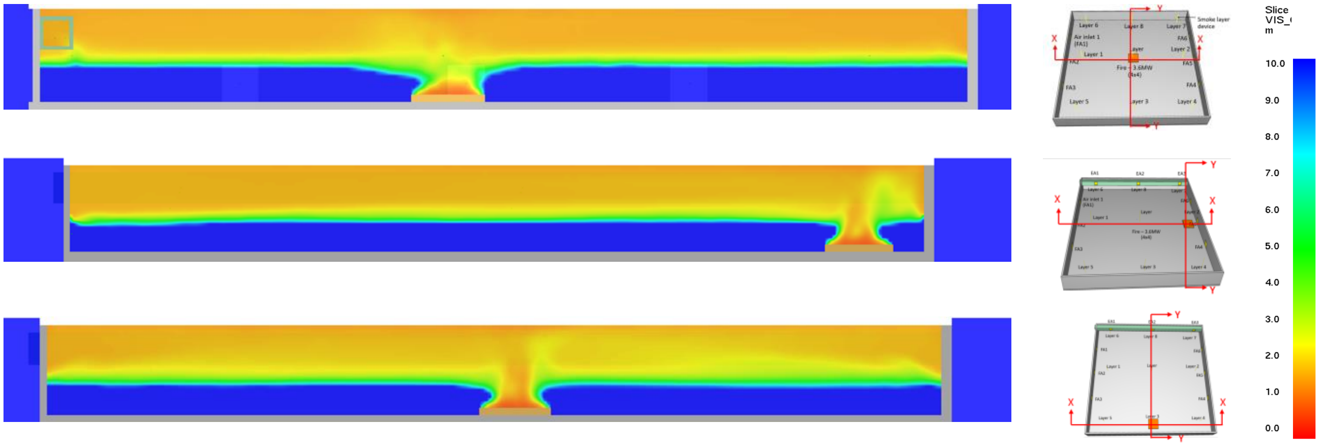


***Figure 39**: Visibility slices at Section X-X across the fire for fire at center of compartment (top), fire near air inlet (middle), fire remote from SED (bottom)*

One observation of note is that for the air inlet fire location, section X-X slice above indicates that the smoke does not spill out to the external despite being close to the air inlet opening. This may be due to a stronger air entrainment effect near the fire and therefore, generates a stronger pulling force of air from outside into the compartment thus preventing smoke flowing out through the inlet opening.

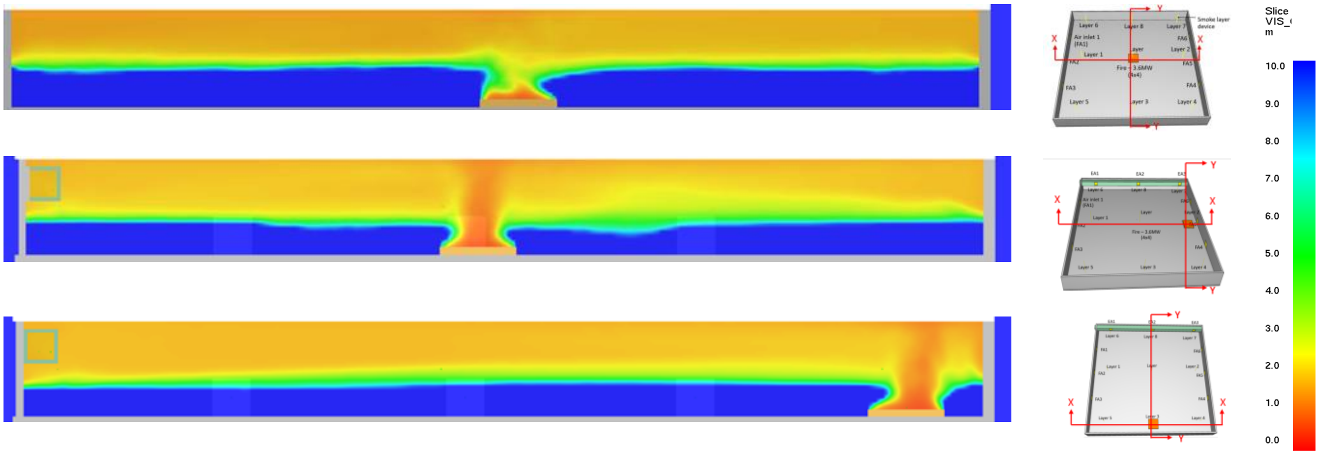


***Figure 40**: Visibility slices at Section Y-Y across the fire for fire at center of compartment (top), fire near air inlet (middle), fire remote from SED (bottom)*

Based on the average smoke layer height graph below, the fire near the air inlet is the worst fire location as it has the lowest average smoke layer height among all three fire locations. The fire remote from the SED trails closely to the centre fire although during the developing phase of the smoke layer, the average smoke layer height is also lower than that of the centre fire.

It can be deduced that contrary to some arguments that a fire scenario at the centre of the compartment is the worst-case fire scenario due to maximum air entrainment from all sides of the fire, that statement is not necessarily true as seen from these results. The hypothesis of the fire remote from the SED extraction location and fire near the air inlet exhibiting deeper smoke layer heights is proven true with the air inlet fire location being the worst case due to air entrainment at higher speeds directly from the air inlet opening next to the fire. This situation may cause greater turbulence and consequently, more mixing of replacement air with the smoke layer.

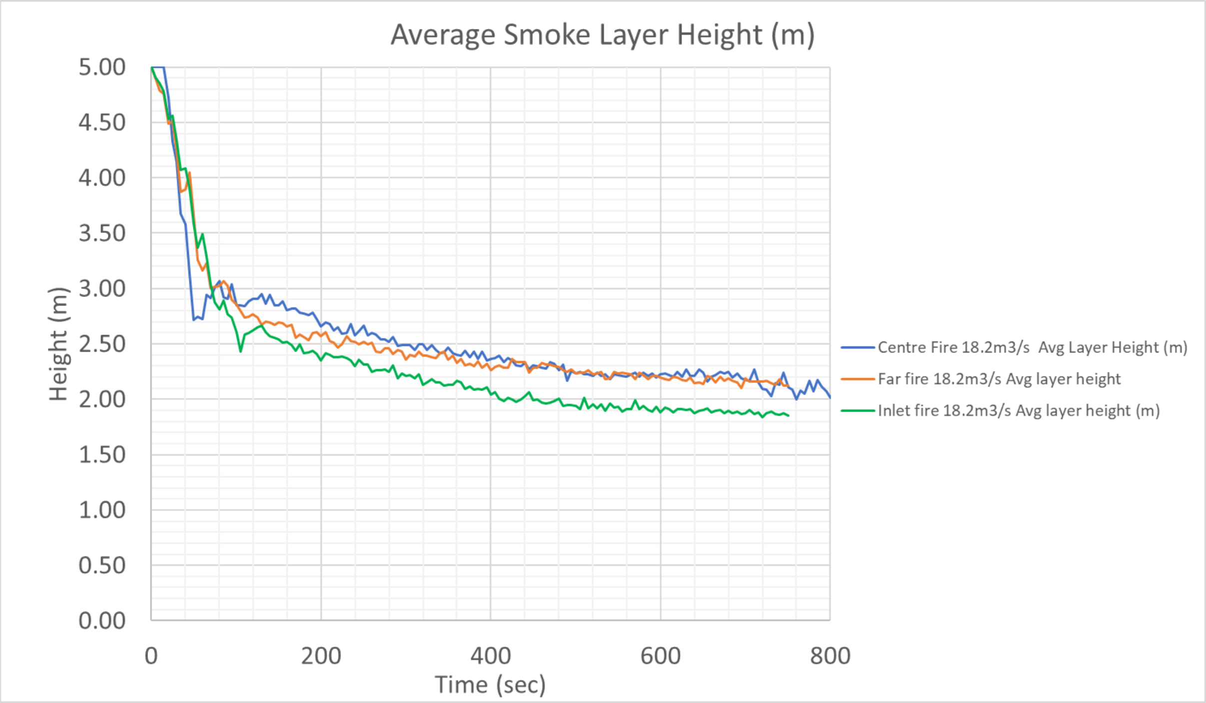
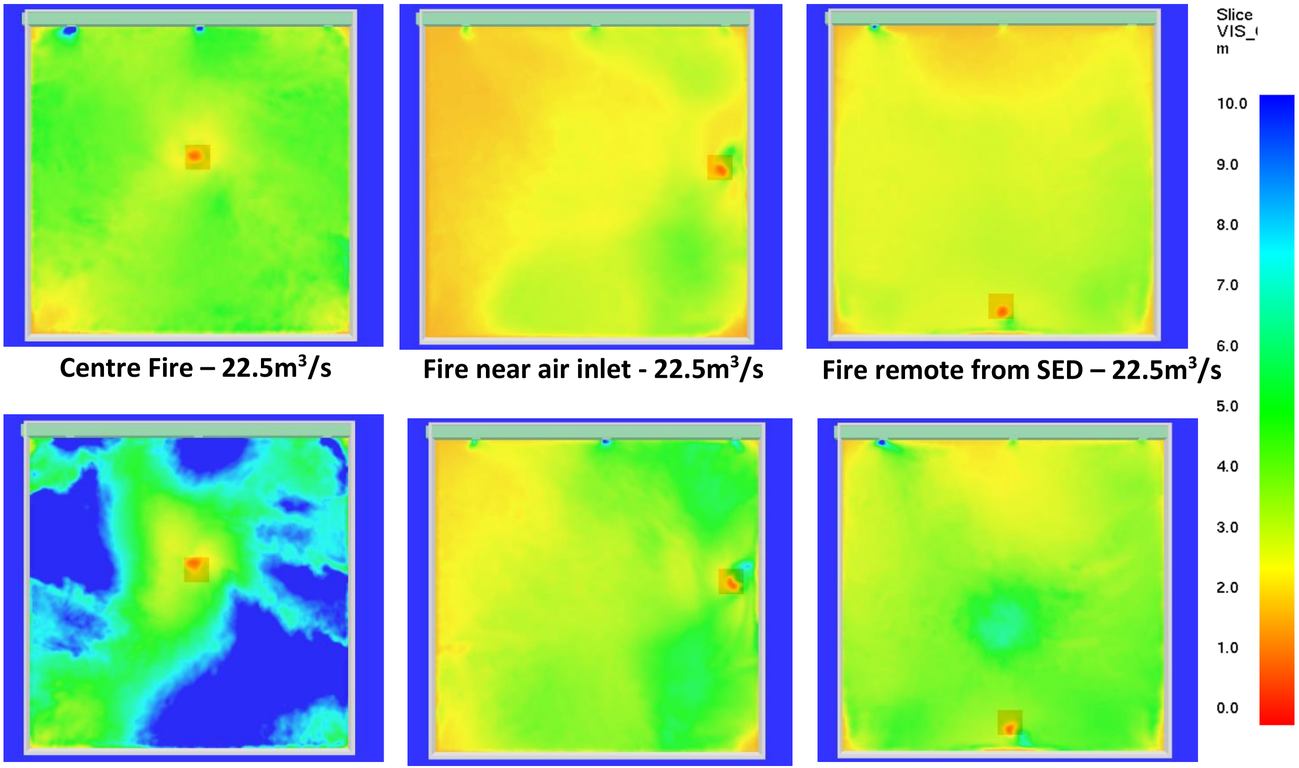


Figure 41: *Graph of average smoke layer height for centre fire, remote from SED fire, and fire near air inlet*

As briefly mentioned at the end of the previous sensitivity study on variations of the extraction rate, it could be interesting to investigate if the upsized extraction rate is able to improve the visibility and smoke layer height results for the other 2 fire locations such that it could achieve the tenability criteria height of 2.5m. Therefore, the increased extraction rates of 22.5m^3/s and 27m^3/s are applied to the remote from SED fire scenario and the fire near air inlet scenario to observe the extent of improvements the increased flow rate provides for these 2 worse fire locations.

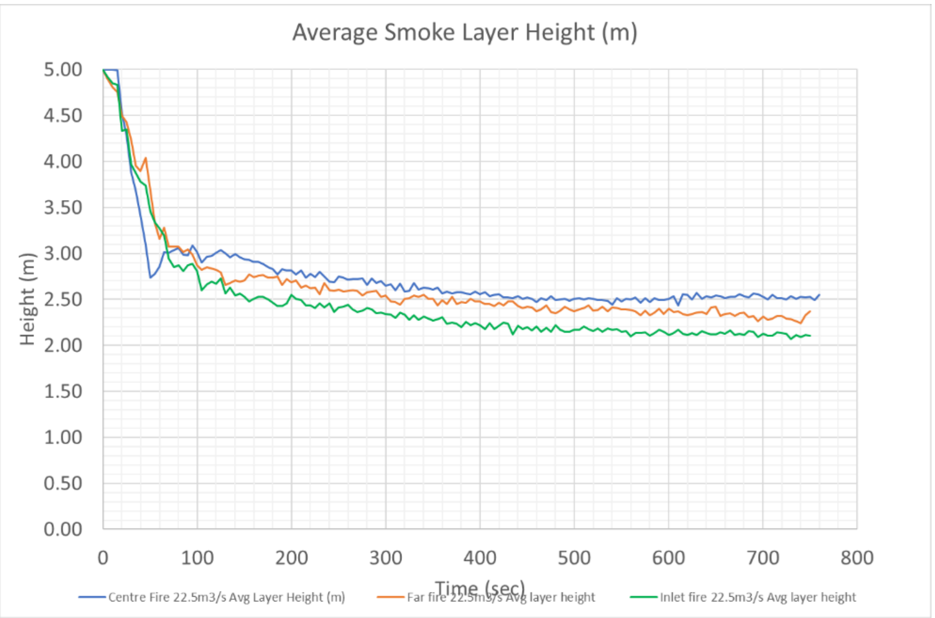


Centre Fire – 22.5m^3/s **Fire near air inlet - 22.5m^3/s** **Fire remote from SED – 22.5m^3/s**

Centre Fire – 27m^3/s **Fire near air inlet - 27m^3/s** **Fire remote from SED - 27m^3/s**

Figure 42*: Top (left to right) - three fire locations at 22.5m^3/s at z=2.6m;*
Bottom (left to right) – three fire locations at 27m^3/s at z=2.6m

The visibility slice results above reveal that the significant improvements observed from the upsized extraction rate for the centre fire scenario are not repeated for the two new fire locations. The visibility results for fire near air inlet and fire remote from SED are significantly worse than it is for the centre fire location. It appears that the tenability results at 2.5m smoke free height was not achieved by the upsize in SED extraction rate for the fire near air inlet and fire remote from SED.



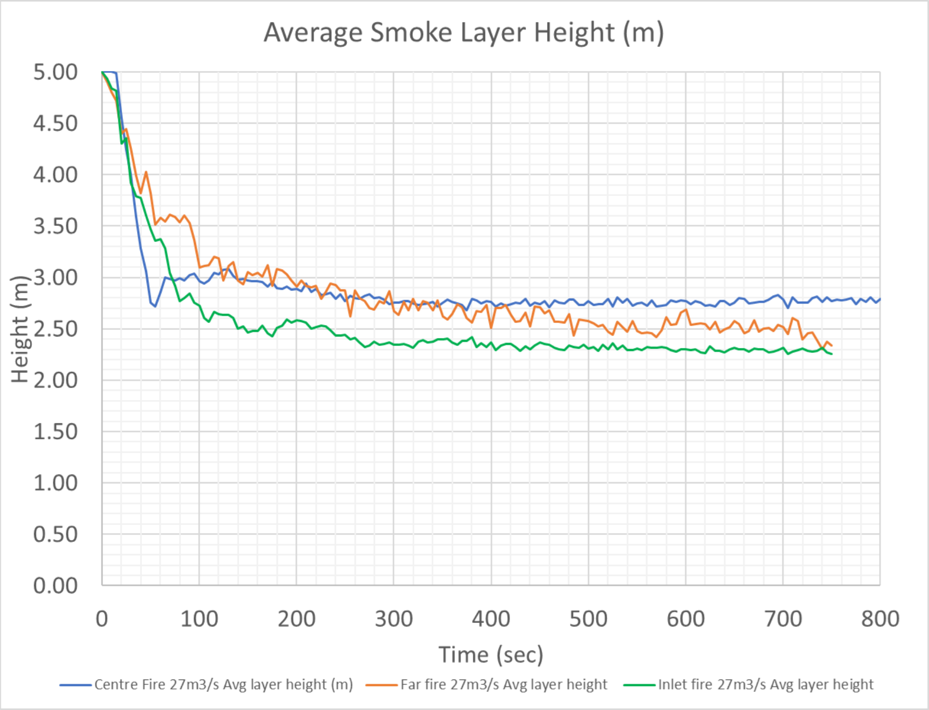


Figure 43: *Top – Graph of average smoke layer height at 22.5m*^{3}*/s*
Bottom – Graph of average smoke layer height at 27m^3*/s*

The average smoke layer height graphs above verify the observation from the slices previously that the upsized extraction rates are not sufficient for the fire near the air inlet scenario and the fire remote from SED scenario to pass the tenability criteria of 2.5m smoke free height.

The remote from SED fire scenario failed the 2.5m smoke free height criteria marginally, while the fire near air inlet produces significantly worse smoke layer depth than the other 2 fire locations.

With the findings above, it can be deduced that the proposed solution of a single SED in the compartment with the SED extraction rates tested are not feasible for a SHC design solution for the compartment. Alternative fire protection measures may be required such as smoke barriers or fire separation by compartmentation to delay the smoke filling time or to mitigate smoke spread completely. With a compartment of that size (2,500m^2) and a height of 5m, it may not be feasible to raise the SED extraction rate to the required extraction rate to achieve the tenability criteria as it may require excessively large fans and duct sizes which may not fit in the compartment space and the extraction rate may be so high, that the air inlet velocity will be significantly higher thus generating strong turbulence within the compartment.

5.6 Scenarios with Varying No. of SED Extraction Points

The base case simulation tested was tested with a total of 3 SED extraction points along the duct. The sensitivity study assessed shall investigate the smoke flow patterns, velocity in the duct, mass and volumetric flow rates when the SED is provided with only a single extraction point.

The visibility slices below demonstrates the performance of the SED is worse when there is only a single SED point compared to base case where there were 3 SED points. Similar to the base case, it can be seen on the slice of 22.5m^3/s there is a minor effect of plugholing and it is expected to be more prevalent in the 27m^3/s slice results although the plugholing effect is masked by the smoke free patch appearing at the upper right corner of the compartment near the SED point.

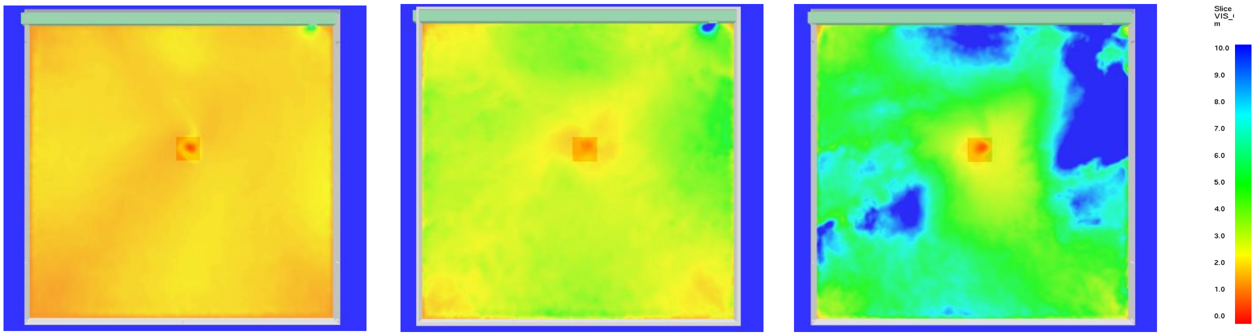


***Figure 44**: Visibility slices at z=2.6m for 18.2m^3/s (left), 22.5m^3/s (centre), 27m^3/s (right)*

The primary reason for the reduced performance of the SED system as compared to the base case is because of the amplified effect of plugholing on the single SED point as compared to the plugholing effect on the 3 SED points in the base case scenario, as seen from the Section visibility slice below cutting through the SED point.

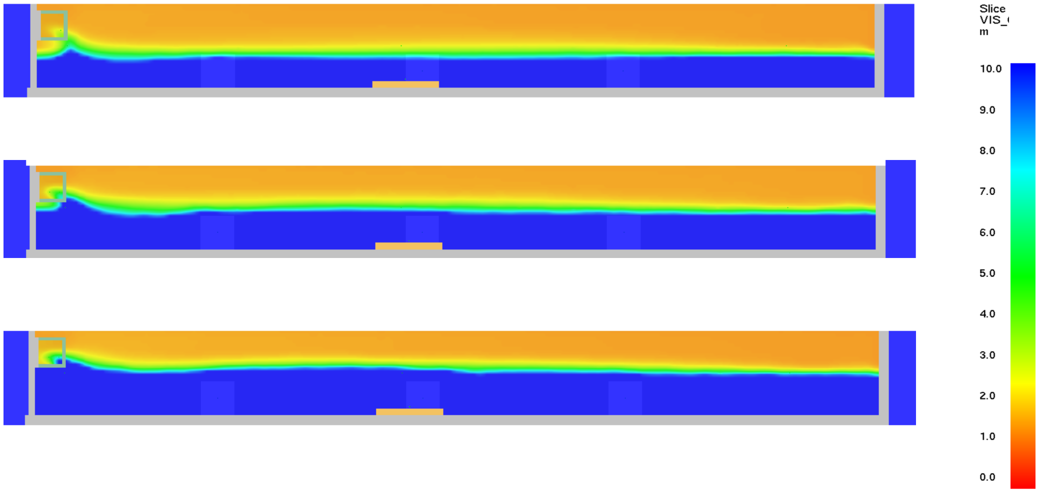


Figure 45: *Section X-X Visibility slices across the SED point for 18.2m^3/s (top), 22.5m^3/s (centre), 27m^3/s (bottom)*

The average smoke layer height graph below also indicates a slightly degraded performance of the SED system with a single point compared to the base case as the scenario with 22.5m^3/s shows a lower average smoke layer than that in the base case with 3 SED points.

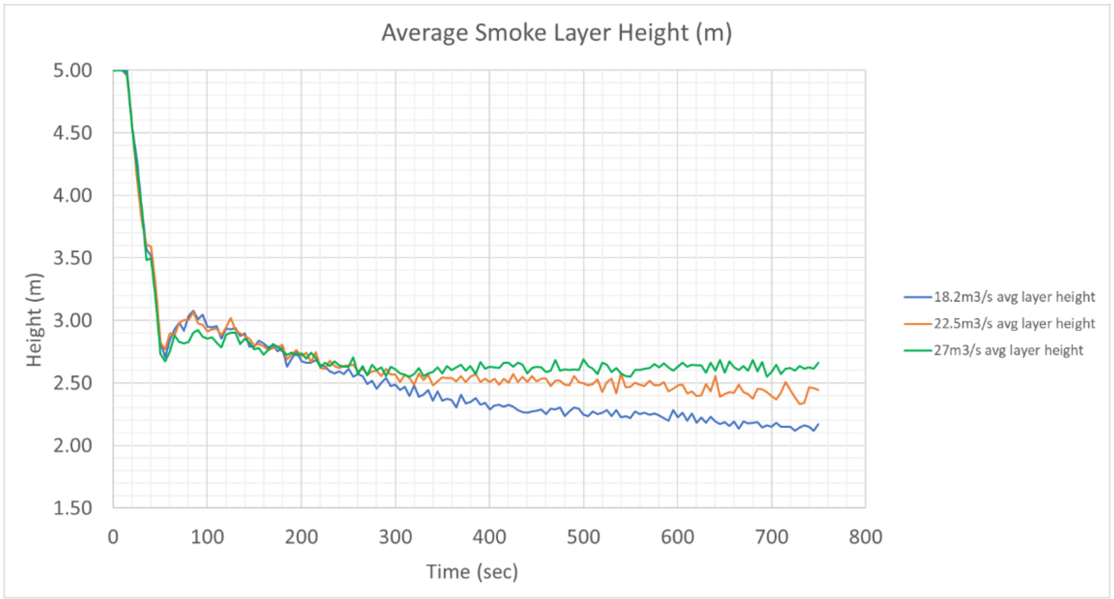


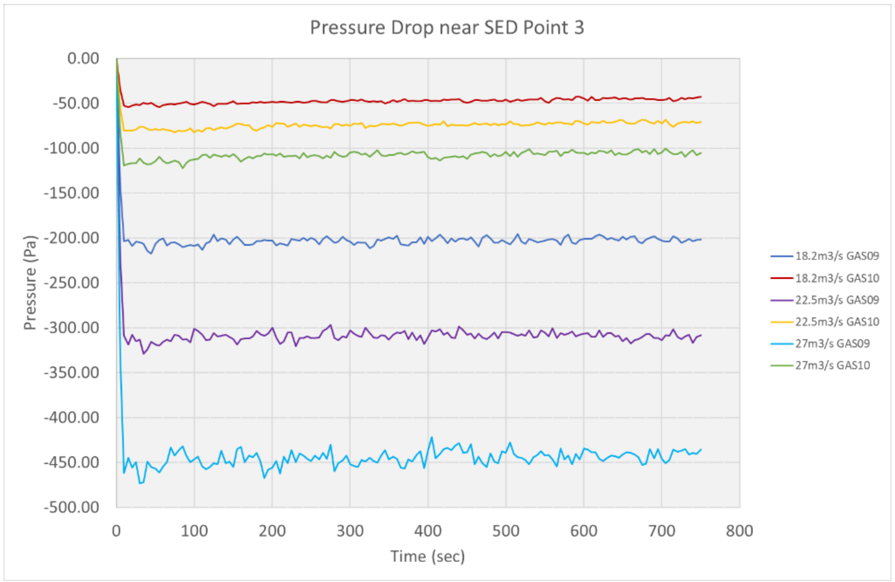
Figure 46: *Average smoke layer height for 18.2m^3/s, 22.5m^3/s and 27m^3/s with 1 SED point*

The pressure drop and change in velocity across the SED point is as expected and scales proportionally as the extraction flow rate increases. The velocity chart pinpoints to another underlying reason as to why the single point SED system performs worse than 3-point SED. The velocity of the SED point is too high such that it extracts more ambient air than smoke which causes a more significant plugholing effect as mentioned above thus, reducing the efficiency of the SED system. As there is only a single SED point opening on the duct, the mass and volume flow rate of the SED point are identical to that of the extraction fan rate.

A further comparison of the pressure differences from the SED extraction to the last SED extraction point shows a significant pressure difference between the scenarios involving 1 SED point against 3 SED points along the duct. This implies that the static pressure loss encountered by the exhaust fan is higher when the duct encounters more components which may cause friction to the fluid flow such as fittings or vents. Consequently, the exhaust fan for the scenario involving 3 SED points will require a significantly higher static pressure to overcome the pressure difference and extract air from the final SED point. As a result, the efficiency of a SED system with more SED extraction points are lower as compared to SED system with less extraction points, of which to overcome the reduced efficiency, a fan with higher static pressure is needed which is more costly.

Flow Rate	**18.2m^3/s**			**22.5m^3/s**			**27m^3/s**		
Location of Pressure measuring device	**Pressure at Exh Fan (Pa)**	**Pressure at SED before Point 3 (Pa)**	**Pressure at SED after Point 3 (Pa)**	**Pressure at Exh Fan (Pa)**	**Pressure at SED before Point 3 (Pa)**	**Pressure at SED after Point 3 (Pa)**	**Pressure at Exh Fan (Pa)**	**Pressure at SED before Point 3 (Pa)**	**Pressure at SED after Point 3 (Pa)**
Scenario with 1 SED point	-140.72	-201.67	-43.00	-220.01	-308.24	-71.07	-321.63	-435.48	-105.39
% Difference to pressure at exhaust fan	100%	43%	-69%	100%	40%	-67%	100%	35%	-67%
Scenario with 3 SED points	-80.85	-1.64	1.04	-123.56	-4.95	-0.60	-180.08	-7.64	-1.73
% Difference to pressure at exhaust fan	100%	98%	-101%	100%	96%	-99%	100%	96%	-99%

Table 7: *Case study with 1 SED point Pressure difference from Extraction Fan (x=0m) to just before SED Point 3 (x=45m) and just after SED point 3 (x=50m)*



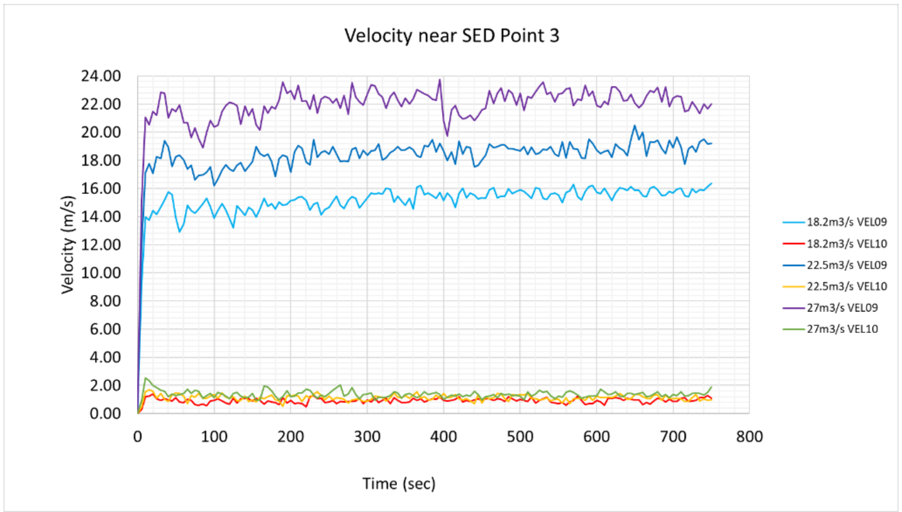


Figure 47*: Graphs of pressure drop and velocity in the SED near the single SED point.*

5.7 Scenarios with Multiple SED Configuration

Ideally, a SED system works best when it is distributed evenly across the compartment or space it serves. Confining the SED to just a single duct may not be the most effective way to extract smoke in the compartment especially if it's a large compartment like a production floor area or a warehouse.

This sensitivity case study shall compare the performance of the SED system between a single SED configuration and the varied SED perimeter involving two ducts with the additional SED located at the opposite end of the compartment. The centre fire and fire near air inlet scenarios shall be tested to determine the differences of the performance of the SED system between one SED and two SED configurations. The SED extraction rates are split equally for the two SED system thus each SED gets half of the total extraction rate while the number of SED points is set at 3.

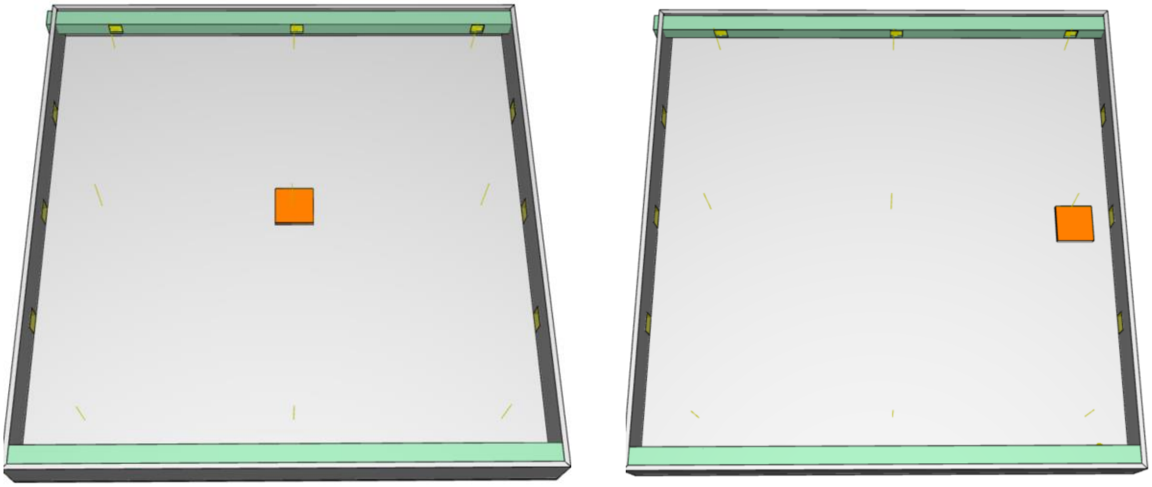


***Figure 48**: Fire scenarios with 2 SED systems and 3 points each SED; centre fire (left), fire near air inlet (right)*

The visibility slices below show a considerable improvement in the smoke layer visibility compared to the base case of 1 SED for the centre fire scenario and plugholing effect was visible when the extraction rate was upsized to 27m^3/s. As the SED extraction rate is split evenly across two ends of the compartment, the smoke layer is extracted from both ends of the SED. Due to reduction in extraction rate in each SED by half, the flow rates through the SED points, pressure drops and velocities in the duct are also reduced by half thus minimizing the effect of plugholing on the SED point which leads to an improved efficiency in smoke extraction. The fire near air inlet scenario however still proved too demanding to be resolved by the splitting of one SED into two, with the visibility slice still firmly less than 10m at slice height of z= 2.6m for all extraction rate cases.

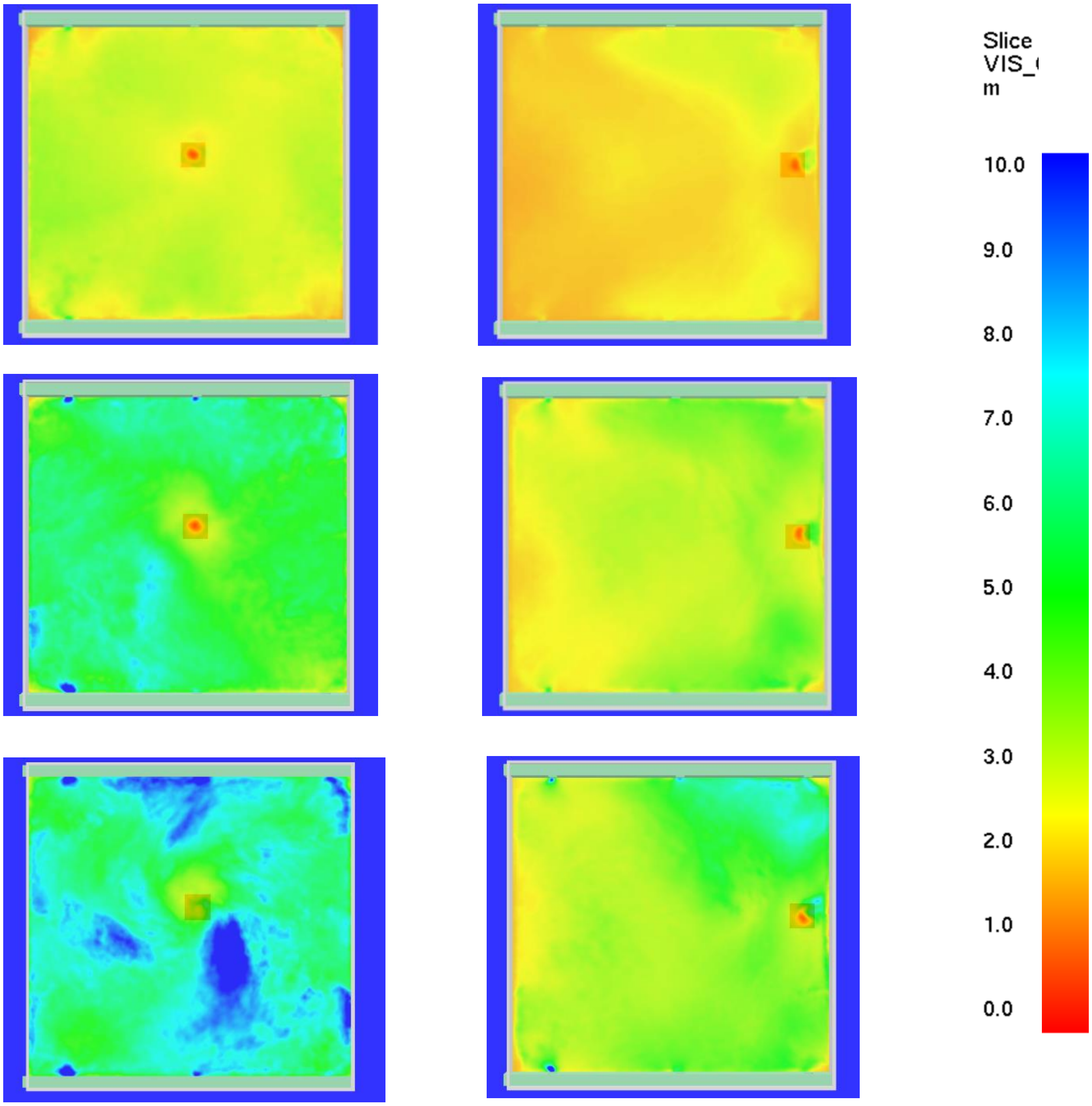


Figure 49: *Visibility slices at z=2.6m for centre fire (left) and fire near air inlet (right) at 18.2m^3/s (top), 22.5m^3/s (middle) and 27m^3/s (bottom).*

Based on the section slice across the SED points on both ends of the SED, the centre fire scenario does show some plugholing effect occurring at the extraction rate of 27m^3/s (13.5m^3/s for each SED. The addition of more SED points along the duct or the increase in size of the SED point are some ways of mitigating the plugholing effect which reduces the efficiency of the SED system.

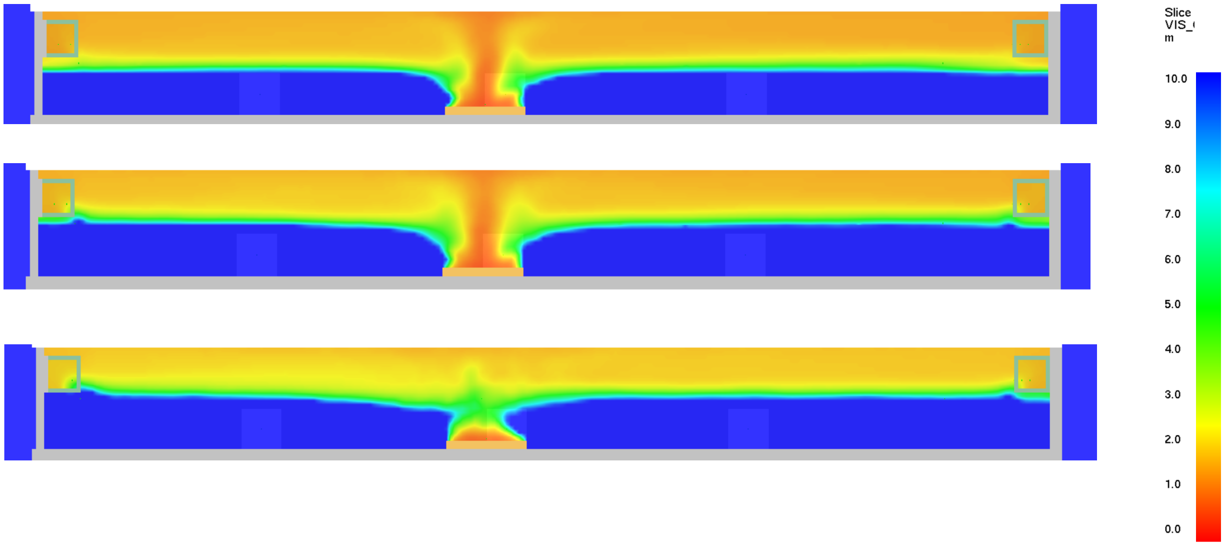
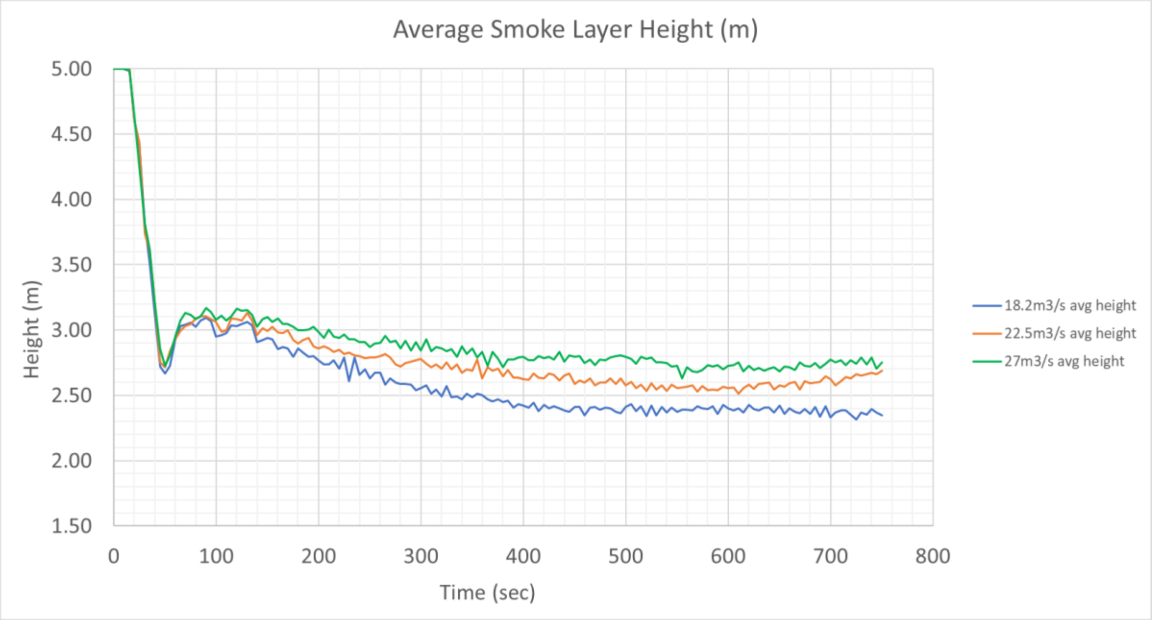


***Figure 50**: Visibility slices at Section Y-Y across axis of fire for centre fire scenario at 18.2m^3/s (top), 22.5m^3/s (middle) and 27m^3/s (bottom)*

The average smoke layer height graphs confirm the findings from the visibility slices that the multiple SED configuration for the centre fire scenario does help to improve the performance of the SED system and maintain a higher smoke free height across all extraction rate cases. The splitting of the SED extraction rate into half for each SED meant the flow rates, pressure drops and velocities along the duct are also reduced linearly by half from the base case hence, there is no different observation or data to report.

The average smoke layer height graphs for the air inlet fire scenario confirms that even with multiple SED in the compartment the tenability criteria of 2.5m still remains a big challenge to achieve for that fire location due to the impact of stronger air entrainment flow into the compartment as discussed previously.



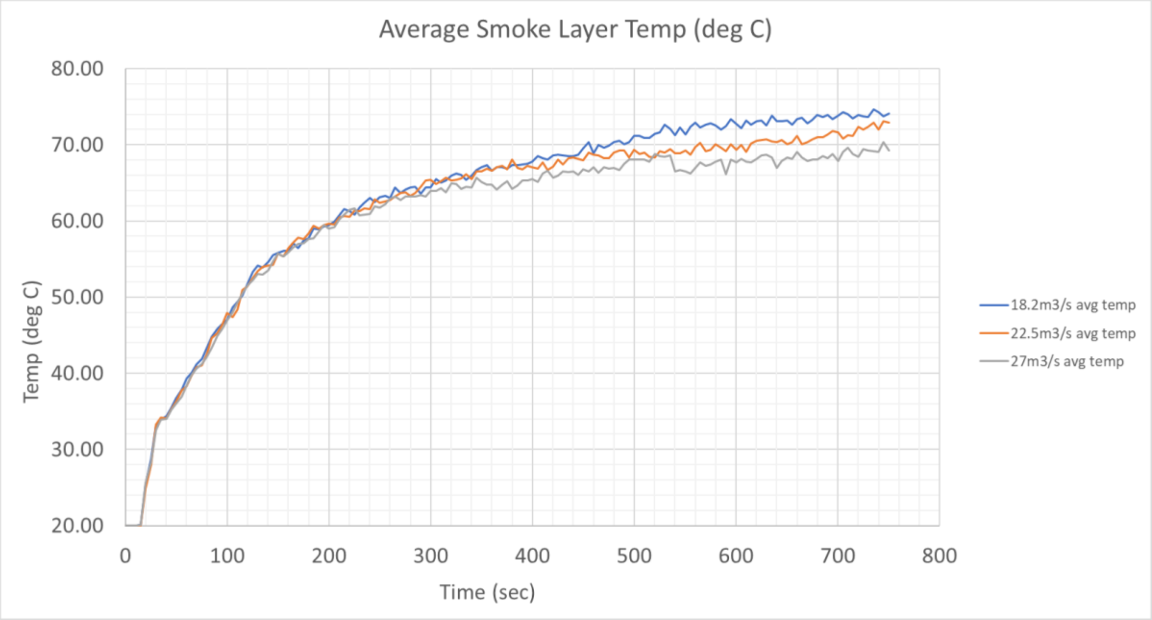


Figure 51*: Graph of average smoke layer height and temperature for centre fire*

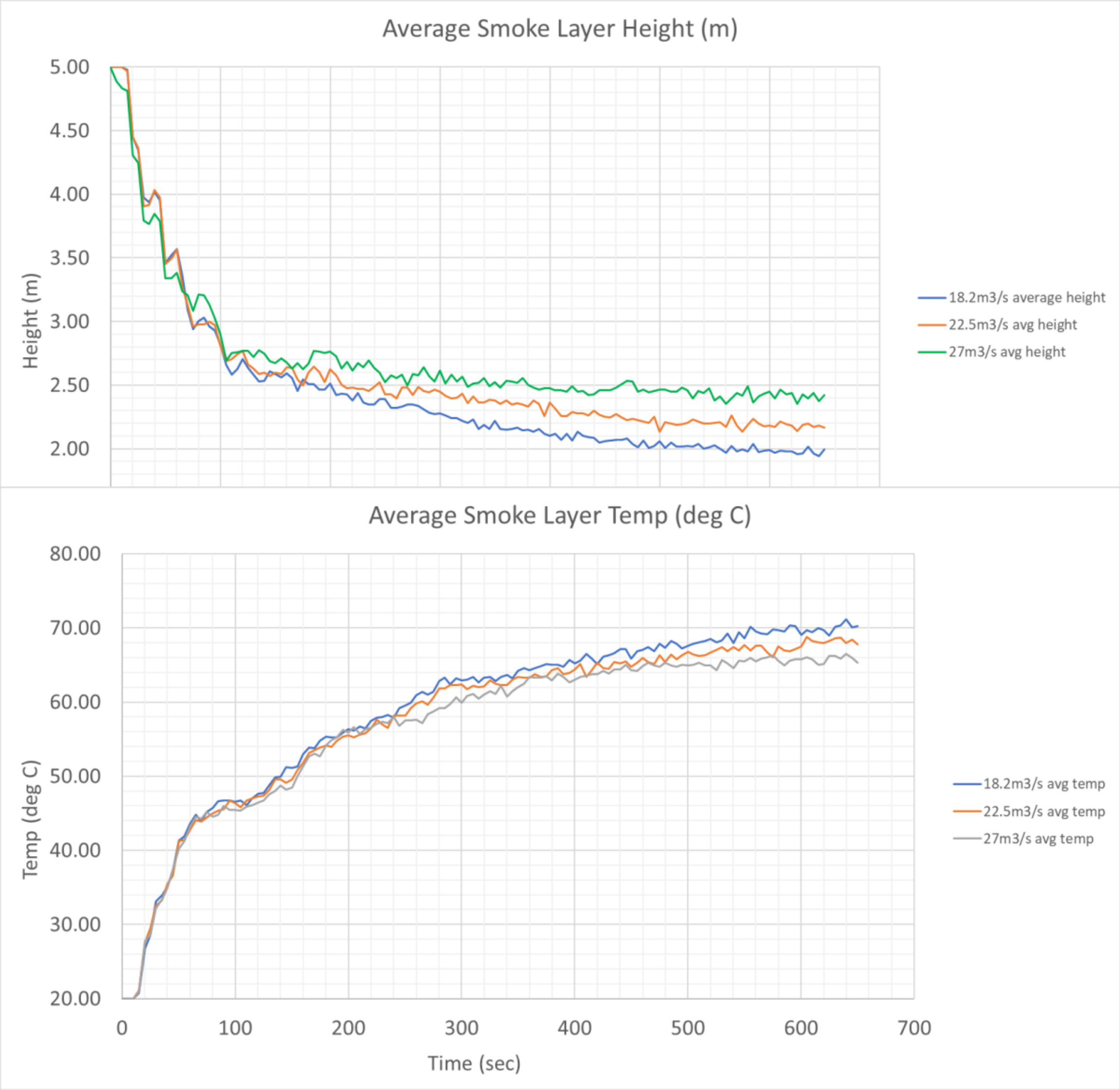


Figure 52*: Graph of average smoke layer height and temperature for fire near air inlet*

6 Conclusion

The primary purpose of this thesis is to serve as an informative guide for the design of a mechanical SED system in an office compartment which aims to satisfy the tenability limits performance criteria for occupant life safety during evacuation. Extensive simulation cases have been carried out to analyse the interactions of various perimeters such as the SED configuration, SED extraction rate, the number of SED extraction points and different fire locations on the performance of the SED system in the office compartment.

The following are some key conclusions that were identified from the study conducted:

- The calculated values obtained from empirical correlations are not accurate. The empirical correlations act more as a simplified method which provides an initial magnitude estimate for the design of the SED system to achieve the desired smoke free height. There are many assumptions embedded in the empirical correlations which simplifies the calculations at the expense of validity of the calculated results.

- The pressure losses inside the duct are proportional to the velocity squared of the desired length of duct for which the fluid flows through, in agreement with the Darcy-Weisbach formula for pressure losses for a fluid flowing through a duct or pipe.

- The fire scenario of Case Study 2 where the the SED acts as a natural vent opening shows that the naturally induced flow rates through the SED are much weaker than that of mechanical exhaust fans.

- As the SED extraction rate increases, the performance of the SED system improves as the average smoke layer height rises. However, care must be taken in the design of high extraction rates in a SED system as it may lead to plugholing effect which may reduce the efficiency and performance of the SED system at removing smoke from the compartment.

- The higher the number of SED points, generally, the better the SED system performance as the extraction flow rate is split across more points which leads to lower velocities of flow and less likely to generate turbulence or cause plugholing which in turn starts extracting cold air instead of smoke and reduces the efficiency of the SED system.

- The worst fire location as identified in a single compartment in this thesis, is a fire near a replacement air inlet. Due to the stronger air entrainment force being near the fire, the air inlet pulls in replacement air stronger and causes turbulence to the smoke plume thus increases the mixing of ambient air and hot smoke layer producing more smoke than any other fire location studied.

There are several limitations and constraints encountered in this thesis, which are listed below. Potential future research work to expand the scope of this study is suggested for consideration:

- The current simulation in the thesis neglected some input parameters such as, detection time, fire growth rate and SED system activation ramp-up time which would have otherwise been critical for the determination of the available safe egress time (ASET) of occupants evacuating from the compartment.

- Scaled experiments could be conducted to validate the smoke layer heights calculated from the empirical correlations and the values obtained from the CFD simulation.

- The current simulation only assumes a straight SED. Realistically, it is near impossible to be able to design a straight duct without any bends, elbows, curves or expansion and contractions especially in a constrained compartment space. There are pressure losses as a fluid flow through the many bends and elbows along a duct which may potentially impact the performance of the SED system.

- Additional parameter variations could be studied such as fan static pressure specifications, duct aspect ratio, size of the SED extraction points and different design fire sizes.

7 Acknowledgement

I would like to express my sincere gratitude to everyone who have helped and supported me along my journey in the IMFSE programme and towards the completion of my thesis. First and foremost, I express my sincerest gratitude to my main thesis promoter, Dr. Georgios Maragkos for his advice and knowledge sharing which was very valuable in my journey through the progress of the thesis from the initial simulation setup stages, through the analysis of the results until the completion of the thesis.

Special thanks to Prof. Ir. Dr. Bart Merci, my thesis co-promoter whose extensive depth of knowledge in the field of fire safety engineering and CFD made me better appreciate the purpose of empirical correlations, understanding their limitations and how the CFD application of the empirical correlations can reveal startling differences for the final simulation results in comparison to the theoretical calculations based on empirical correlations.

This is also a great opportunity to thank my family and friends who greatly motivated me to pursue the IMFSE programme in the first place. Without their encouragement, there was no certainty I would have participated in the programme and I would have missed out on all the discoveries and technical knowledge not known prior to enrolling in the IMFSE programme.

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9 Appendix

FDS Input Code for Case Study 1 (No Fire – SED only)

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    DENSITY=2280.0/
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    FYI='Drysdale, Intro to Fire Dynamics - ATF NIST Multi-Floor Validation',
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    CONDUCTIVITY=45.8,
    DENSITY=7850.0,
    EMISSIVITY=0.95/

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    VOLUME_FLOW=18.2/
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    BACKING='VOID',
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    MATL_MASS_FRACTION(1,1)=1.0,
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&BNDF QUANTITY='BACK WALL TEMPERATURE'/
&BNDF QUANTITY='CONVECTIVE HEAT FLUX'/
&BNDF QUANTITY='GAS TEMPERATURE'/
&BNDF QUANTITY='RADIATIVE HEAT FLUX'/
&BNDF QUANTITY='WALL TEMPERATURE'/
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&SLCF QUANTITY='VELOCITY', VECTOR=.TRUE., PBZ=1.5/
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&SLCF QUANTITY='TEMPERATURE', PBZ=2.5/
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&SLCF QUANTITY='VELOCITY', VECTOR=.TRUE., PBX=6.8/
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&SLCF QUANTITY='VELOCITY', VECTOR=.TRUE., PBY=-23.3/
&SLCF QUANTITY='VISIBILITY', PBY=-23.3/
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&SLCF QUANTITY='TEMPERATURE', PBY=-1.3/
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&SLCF QUANTITY='VISIBILITY', PBZ=2.0/
&SLCF QUANTITY='TEMPERATURE', PBZ=2.0/

&TAIL /
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FDS Input Code for Case Study 2 (No SED, Fire only)

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&TIME T_END=900.0/
&DUMP NFRAMES=180/
&RADI RADIATION=.FALSE./

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    H=1.7,
    O=0.3,
    N=0.08,
    AUTO_IGNITION_TEMPERATURE=0.0,
    CO_YIELD=0.042,
    SOOT_YIELD=0.03,
    HEAT_OF_COMBUSTION=2.5E4,
    RADIATIVE_FRACTION=0.3/

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22.25,0.0,5.0/
&DEVC ID='LAYER->UTEMP', QUANTITY='UPPER TEMPERATURE', XB=26.25,26.25,-22.25,-
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    CONDUCTIVITY=1.8,
    DENSITY=2280.0/
&MATL ID='STEEL',
    FYI='Drysdale, Intro to Fire Dynamics - ATF NIST Multi-Floor Validation',
    SPECIFIC_HEAT=0.46,
    CONDUCTIVITY=45.8,
    DENSITY=7850.0,
    EMISSIVITY=0.95/
&SURF ID='Wall',
    RGB=204,102,0,
    BACKING='VOID',
    MATL_ID(1,1)='CONCRETE',
    MATL_MASS_FRACTION(1,1)=1.0,
    THICKNESS(1)=0.4/
&SURF ID='Fire',
    COLOR='RED',
    HRRPUA=225.0,
    TMP_FRONT=300.0/
&SURF ID='SED',
    RGB=146,202,166,
    BACKING='VOID',
    MATL_ID(1,1)='STEEL',
    MATL_MASS_FRACTION(1,1)=1.0,
    THICKNESS(1)=0.1/

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SURF_ID='Wall'/
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&TAIL /
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FDS Input Code for Case Study 3 (Base Case Scenario)

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    N=0.08,
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    SOOT_YIELD=0.03,
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&DEVC ID='LAYER->UTEMP', QUANTITY='UPPER TEMPERATURE', XB=26.25,26.25,-22.25,-
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&BNDF QUANTITY='BACK WALL TEMPERATURE'/
&BNDF QUANTITY='CONVECTIVE HEAT FLUX'/
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&BNDF QUANTITY='RADIATIVE HEAT FLUX'/
&BNDF QUANTITY='WALL TEMPERATURE'/
&SLCF QUANTITY='VISIBILITY', PBZ=1.5/
&SLCF QUANTITY='VELOCITY', VECTOR=.TRUE., PBZ=1.5/
&SLCF QUANTITY='TEMPERATURE', PBZ=1.5/
&SLCF QUANTITY='VELOCITY', VECTOR=.TRUE., PBZ=2.5/
&SLCF QUANTITY='TEMPERATURE', PBZ=2.5/
&SLCF QUANTITY='VISIBILITY', PBZ=2.5/
&SLCF QUANTITY='VISIBILITY', PBZ=3.4/
&SLCF QUANTITY='TEMPERATURE', PBZ=3.4/
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&TAIL /
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FDS Input Code for Scenario with Mutiple SED (Sensitivity Study sample)

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&TIME T_END=900.0/
&DUMP NFRAMES=180/
&RADI RADIATION=.FALSE./

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&MESH ID='4', IJK=100,102,15, XB=36.0,56.0,-52.9,-32.5,-0.6,2.4/
&MESH ID='5', IJK=200,68,30, XB=-4.0,16.0,-5.3,1.5,2.4,5.4/
&MESH ID='7', IJK=148,84,15, XB=-4.0,25.6,-46.1,-29.3,2.4,5.4/
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    H=1.7,
    O=0.3,
    N=0.08,
    AUTO_IGNITION_TEMPERATURE=0.0,
    CO_YIELD=0.042,
    SOOT_YIELD=0.03,
    HEAT_OF_COMBUSTION=2.5E4,
    RADIATIVE_FRACTION=0.3/
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&DEVC ID='LAYER->UTEMP', QUANTITY='UPPER TEMPERATURE', XB=26.25,26.25,-22.25,-
22.25,0.0,5.0/
&DEVC ID='FA1', QUANTITY='VOLUME FLOW', XB=0.5,0.5,-12.5,-10.5,0.0,2.0/
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     CONDUCTIVITY=1.8,
     DENSITY=2280.0/
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&SURF ID='Fire',
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