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# Numerical Simulation: Smoke Movement at Stairwell of High-rise Buildings

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**Abstract**

The number of high-rise buildings in Kuala Lumpur is increasing at an alarming rate. For every high-rise building, the safe evacuation route, the stairwell, plays a crucial role. This aim of this paper is to investigate the smoke movement in stairwells as the safe evacuation route used in high-rise buildings for smoke safety management. The method used in this research paper is an experimental study using simulation. The simulation program used in this research is PyroSim, a software originally derived from another software, Fire Dynamics Simulator (FDS), which uses large-eddy simulation (LES) method. It is then tested on a 17-floor stairwell model with 12 different variants. The results from the simulation experiments show that the location of the fire source (fire floor) does influence smoke movement. It is observed that the smoke movement typically moves upwards during a fire event, but if the above floor or ceiling is already filled enough with smoke, due to the turbulent mixing happening, the smoke would also move downwards towards the lower floor. Furthermore, the opening affects/influences the strength of the stack effect in the smoke diffusion. The higher the opening height, the stronger the strength of the stack effect would be. In addition, the existence of an opening on the same level as the fire floor would create a path for the smoke to exit through. This has created an insight and overview on what to consider during a fire evacuation process to maintain visibility for the evacuees.

## 1.0 INTRODUCTION

Due to the rapid urbanisation of Kuala Lumpur, the capital city of Malaysia, the demand for high-rise buildings is increasing rapidly (Sekaran, 2024). According to Sekaran (2024), Kuala Lumpur is becoming a city with the most skyscrapers in Southeast Asia, with 241 buildings taller than 150 meters, and 6 buildings over 300 meters. This highlights the city's rapid vertical growth and the increasing demand for high-rise buildings in the region.

Regarding the above statement, land scarcity is becoming more evident as the high demand for high-rise buildings is increasing at a rapid rate as a result of the rise of population in the main city (Hanapi et al., 2022). Accordingly, due to the impressive growth, fire hazards in high-rise buildings are becoming more apparent (Hanapi et al., 2022). Conversely, fire hazards also lead to smoke hazards (Gomez et al., 2020). The issue of smoke hazards is often not openly discussed, yet they are one of the main factors in human death and fatalities (Gomez et al., 2020).

Conspicuously, in high-rise buildings, one of the major concerns is the stairwell (Ahn et al., 2020). This is because multiple floors are connected by vertical shafts, such as stairwells (Bilyaz et al., 2021). These connections create links for smoke movement between different areas (Bilyaz et al., 2021). Enclosed staircases are a critical component in buildings, and the behaviour of smoke is a significant factor influencing the safety of occupants. The spread of smoke within an enclosed staircase can impact visibility, air quality and the overall efficiency of evacuation procedures. Understanding smoke movement in this space is vital to ensure proper protection design and to mitigate potential risk to human safety.

In high-rise buildings, the existing infrastructure and accessibility are critical factors to be considered in designing spaces, including stairwells, to improve fire safety and manage smoke movement (Anhorn and Khazai, 2015 & Idham, and Andriansyah, 2021). Thus, it is significant to investigate the smoke movement in stairwells, as they are typically the safe evacuation route in high-rise buildings (Ahn et al., 2020). By analysing the numerical simulation of smoke movement in stairwells of high-rise buildings, the stated vertical channels become the main route for toxic smoke to spread to the non-fire floors during the outbreak of high-rise building fires (He et al., 2022). Hence, the comprehension of smoke movement during a fire outbreak in stairwell of high-rise buildings is vital in making sure the evacuation process can be done safely.

When discussing potential threat of fire and the spread of smoke in staircases, the location of the ignition may vary. Different ignition location influences how the smoke spreads as it effects the variation in pressure, temperature, gradient and airflow. Thus, understanding the effect of these differences is important in designing a staircase effectively, as it determines the downward or upward movement of evacuees.

Despite existing fire safety regulations and guidelines, the precise behaviour of smoke in enclosed staircases under different fire ignition and opening configurations is still not fully understood. While some studies have explored smoke movement, many of them do not consider the different effects of different ignition locations and opening positions. Thus, this paper aims to investigate the smoke movement in stairwells as the safe evacuation route used in high-rise buildings for smoke safety management. The insight gained could help assist the fire suppression strategies and the placement of ventilation systems, ultimately contributing to the development of safer building codes and practices.

## 2.0 LITERATURE REVIEW

### 2.1 Fire, Smoke Movement and Heat Release Rate

The amount of energy per unit time that a material releases into the environment when it undergoes combustion is the definition of heat release rate (Gomez et al., 2020). In a fire combustion, fire would go through three stages, which are growth, fully developed and decay (Gomez et al., 2020). Accordingly, in the fully developed phase, the heat release rate would remain constant (Gomez et al., 2020).

As the heat release rate increases, it results in a sharp increase in the velocity of the smoke flow (Gomez et al., 2020). This can be seen in Figure 1 where different air supply parameters are used (Huang et al., 2019). On top of that, the increase in heat release rate from the fire source also results in the buoyancy plume driving force decreasing (Gomez et al., 2020).

Other than that, a higher heat release rate also contributes to a more pronounced wall attachment effect on the side away from the fire (J. Zhang et al., 2019). Plus, most of the air flowing near the side wall would move at a higher speed, which is in the forward direction along the wall (J. Zhang et al., 2019).

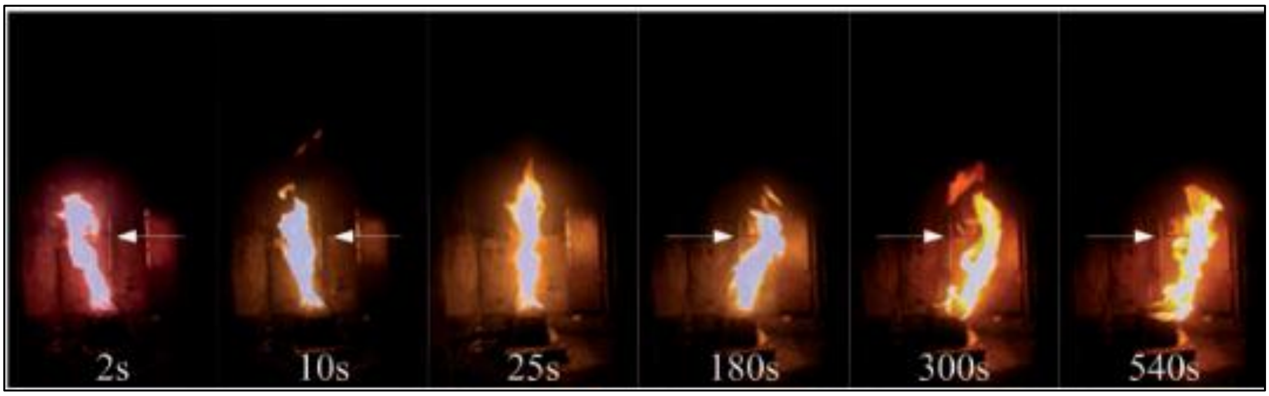



**Figure 1**. Fire growth in 540 seconds (Huang et al., 2019)

Nurud et al. (2019) proves that the heat release rate corresponds with the acceleration of the spread of hot smoke. Accordingly, due to the fire from the lower compartment, its energy input became the driving force for the flow in the close stairwell (Nurud et al., 2019). The study indicates that the higher the heat release rate is, the higher the smoke temperature is as well (Nurud et al., 2019).

However, due to the existence of the open ventilation, the temperature would reach its ambient temperature as the smoke was then well mixed with the air after minutes of the fire ignition (Nurud et al., 2019). Hence, it can be observed that initially, the heat release rate would highly affect the smoke temperature until it reaches its maximum stable heat value. (Nurud et al., 2019). Adding to that, heat release rate also directly determines the intensity of the stack effect. (Ji et al., 2020).

On top of that, the heat release rate determines the time taken for hot gases to reach the ceiling. (Ji et al., 2020). According to the study done by Lin et al. (2023), the difference in heat release rate will make a vital change in the speed of smoke spread.

Notably, the larger the heat release rate is, the smoke spreading rate would be greater on top of the thickness of the stable smoke layer is also significantly thicker (Lin et al., 2023). Plus, the greater the heat release rate is, the thermal buoyancy effect would also be stronger (Lin et al., 2023). Furthermore, it is proven in the same study that the indication of smoke temperature is also increasing correspondingly to the greater heat release rate (Lin et al., 2023).

### 2.2 Fire Location

Based on the studies done by J. Zhang et al. (2019), the fire location cannot be predicted in practice. In other words, piled up flammable debris is unpredictable, causing the location of the smoke to be random. This has a big influence on the flow of the smoke. It is worth noting that the direction of the airflow in the openings below the fire location was called the “inlet” (J. Zhang et al., 2019).

It is observed that at higher fire floor location, the amount of air entrainment is greater compared to lower fire location (J. Zhang et al., 2019). In other words, the number of inlet openings is influenced by the height of the fire location. At the same time, the number of inlet and outlet openings remains completely the same, causing the number of turbulent openings to decrease significantly (J. Zhang et al., 2019).

On top of that, the pressure varies significantly depending on where the fire is located. Because of hydrostatic loss, or the drop in pressure with height, there is less pressure on the higher floors (Bilyaz et al., 2021). Plus, due to the cold cases having higher air densities than the hot ones, the pressure in the cold cases is lower than the pressure in the hot cases at the same level (Bilyaz et al., 2021).

It is important to highlight that the temperature eventually drops as a result of the reduction in the rate of heat release (Bilyaz et al., 2021). In this case, the convective and radiative heat losses to the walls exceed the rate of heat release, even in the event that the fire continues (Bilyaz et al., 2021). The fire floor draws air from the ambient elevator shaft and stairwell as a result of the pressure drop that occurs below the ambient pressure at that level (Bilyaz et al., 2021). Because colder air is drawn into the floor during the suction process, the temperatures in the hot cases remain higher than in the cold cases at the end result (Bilyaz et al., 2021).

### 2.3 Stack Effect

Stairwells play a few significant roles in high-rise buildings, but their major function is as one of the safe evacuation paths if a fire were to happen (Bilyaz et al., 2021). Smoke movement is a big issue that one must focus on as it affects the safety of the occupants during a fire (Bilyaz et al., 2021). In the stairwell of the high-rise buildings, stack effect can occur due to the differences of the density between the interior and the exterior of the building as seen in Figure 2 (Bilyaz et al., 2021).

As hot air has a lighter density than cold air, the air with the higher temperature would travel to higher floors (Bilyaz et al., 2021). If a fire occurs in the lower floors, the initially cold air would convert into air with a higher temperature and flow upwards due to its lower density (Bilyaz et al., 2021). However, in a fire event, this air movement would lead to smoke movement as well (Bilyaz et al., 2021).

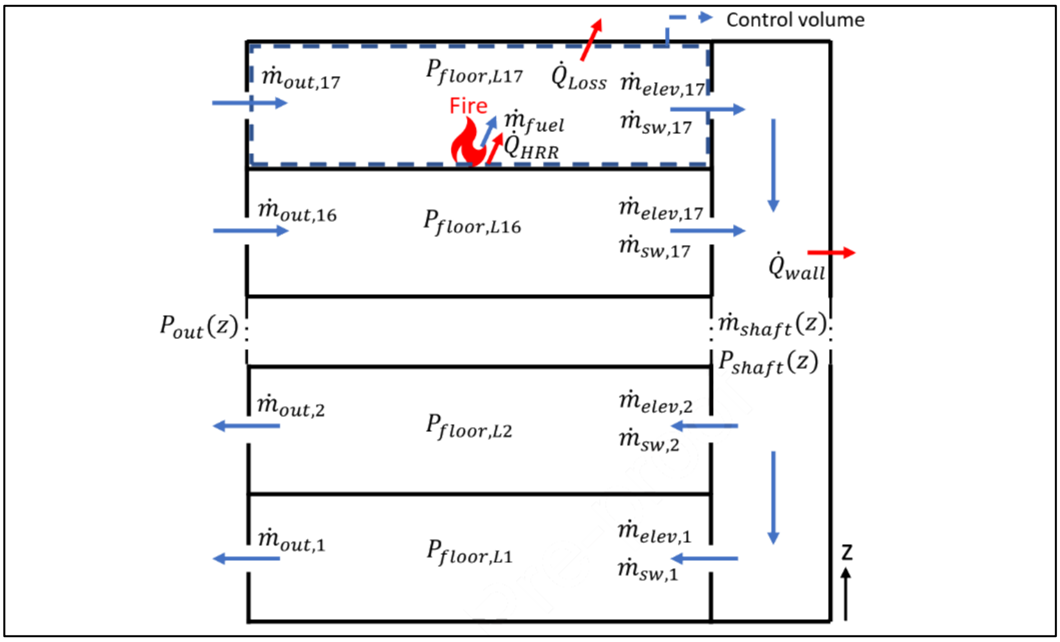



**Figure 2.** Reverse Stack Effect phenomenon. (Bilyaz et al., 2021)

When it comes to the stack effect, the temperature of the surroundings would also influence the way hot and cold air moves (Bilyaz et al., 2021). According to Bilyaz et al. (2021), it has been noted that in the warmer climates, the upper stories of the building are colder, resulting in the air penetrating and flowing through via the vertical shafts, and exits the building at lower levels. It is very remarkable to know that this phenomenon is known as the 'reverse stack effect' (Bilyaz et al., 2021).

Another point to be highlighted is how the stack effect can be strengthened or weakened (Huang et al., 2019). A stronger stack effect can be formed through both, the existence of an upper opening or a huge temperature difference (Huang et al., 2019). For instance, due to the stack effect, ambient air would flow through the corridor door of the fire floor, helping to keep the pressure balanced inside the building (Huang et al., 2019).

The stack effect can be much stronger when more smoke flows into the vertical shaft (Huang et al., 2019). Conversely, the stack effect can be weakened due to the higher inertia force required (Huang et al., 2019). This is because of the increase in ventilation velocity in the building itself (Huang et al., 2019). It would then cause the smoke to experience difficulty mitigating towards the shaft (Huang et al., 2019).

### 2.4 Openings

Based on the study done by Li et al. (2022), during a fire event, the staircase doors will be opened both above and below the fire floor, as it is determined that the strength of the stack effect is highly influenced by the height between the open stair, door at every floor and the fire floor. It was found that the smoke movement patterns are similar to each other when the stair doors are opened below the fire floor (Li et al., 2022).

The numerical models in the study were done with the stair doors on the first floor kept open or remain closed during the fire event on the eighth floor (Li et al., 2022). The result shows that during a fire event, the temperature distribution for the numerical model with the stair doors on the first floor opened has a larger cold area than the one with the stair doors closed (Li et al., 2022).

In a study conducted by Lee & Lau (2023), a numerical experiment was conducted to study the efficiency of multiple fire safety doors towards the smoke safety in vertical shafts. It has been observed that as the number of doors into the vertical shafts increases, the average flow rate decreases significantly(Lee & Lau, 2023).

Notably, the average flow rate in the shaft with 2 doors open compared to 4 doors open shows a significant difference (40% drop) (Lee & Lau, 2023). The reason for this is because the injection points of air are only located at every third level (Lee & Lau, 2023). Hence, in cases with 4 or more doors opened, the average flow rate would reach a stagnant level due to the additional storey serving as the inlet, supplying air to the ground floor (Lee & Lau, 2023).

As a result, the amount of air flowing into the corridor is less than the air flowing into the ground floor (Lee & Lau, 2023). The addition of another storey only leads to a minor reduction, as the air flowing through is already split between three storeys (Lee & Lau, 2023).

Another point worth highlighting is that as a result, it can be observed that when the windows are opened, the smoke velocity is faster in comparison to case 2(all windows closed) and case 3 (different inlet position) (Zhu et al., 2020). This further indicates that the smoke velocity is influenced by the opening of the vent in the stairwell rather than the opening positions (Zhu et al., 2020).

Furthermore, in cases with the same opening height, the number of pool fires increases due to the increase in the average velocity (He et al., 2020). With an increase in the opening height, the average velocity initially increases but then decreases (He et al., 2020). This can contribute to the strength of the stack effect (He et al., 2020).

Research done by Nurud et al. (2019) proves that the absence of a vent opening in the stairway causes a longer time for the smoke to enter and spread. As a result, the visibility and density of the smoke become more apparent on the lower floor after a certain duration of time (Nurud et al., 2019). Conversely, in the case where a vent opening is available, the diffusion of the smoke is faster and flows into the higher floor and finally through the vent opening (Nurud et al., 2019).

Furthermore, the vent opening area also influences the smoke temperature (Nurud et al., 2019). The smoke entrainment can be reduced through the increase of vent opening area, in addition to increasing the visibility (Nurud et al., 2019). Plus, it is shown that the vent opening at the top storey of the stairway is an effective way to provide more time for evacuation, firefighting and rescue work (Nurud et al., 2019).

While previous studies have examined the effects of heat release rate, fire location, stack effect, and ventilation openings on smoke movement in stairwells, most have investigated these factors in isolation and under simplified conditions. There is limited understanding of how smoke behaviour changes when fire ignition occurs at different vertical positions within a building, and even less so on how the position of open windows interacts with these ignition locations to influence smoke spread, velocity, and temperature distribution. This study addresses that gap by investigating smoke movement in a staircase with fire ignition at three different locations and varying window opening positions, providing realistic insights to improve smoke control strategies, evacuation planning, and firefighting safety in high-rise buildings.

## 3.0 METHODOLOGY

### 3.1 Data Collection Method

This study relies on a simulation-based experimental approach to analyse smoke movement in an enclosed stairwell during a fire event. The software used in this simulation is a large eddy simulation (LES), a computational fluid dynamics method, which means it is able to calculate the low-speed flows, on top of giving a focus on smoke and heat transfer from the fire (NIST, 2024). LES has been specifically chosen due to its ability to model complex fluid dynamics, in these cases, the smoke movement. It can accurately simulate the fire and smoke spreading behaviours in a confined environment. The step-by-step data collection procedure is shown in Figure 3 below.

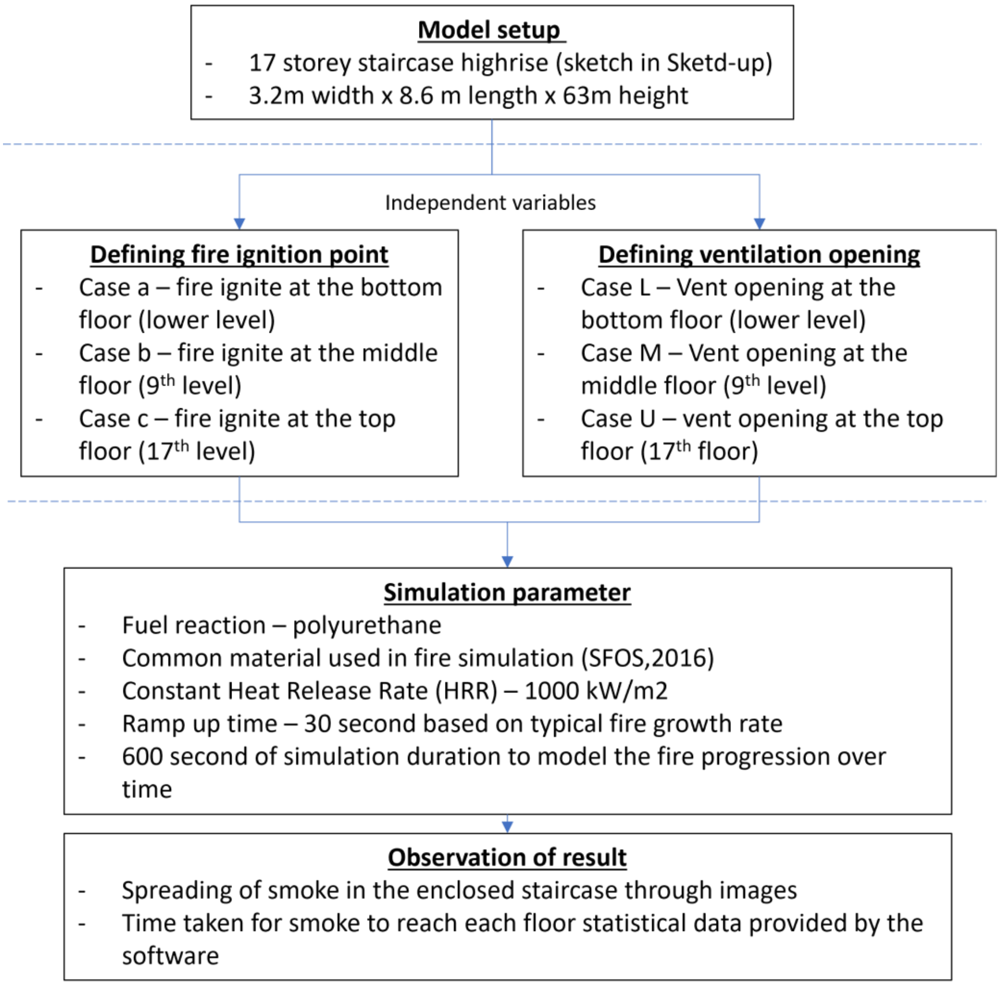



**Figure 3.** Modelling of the case study

### 3.2 Sample

This research was conducted on a numerical model of a stairwell situated in a high-rise building with 17 floors, as seen in Figure 4. In the Malaysian context, many high-rise residential buildings range between 15–25 storeys, particularly in medium-cost condominiums, government quarters, and urban housing projects. The *Uniform Building By-Laws 1984* classifies buildings exceeding 18.3 m (~6 storeys) as high-rise. Similar fire safety requirements, including staircase pressurisation, are applied across the 15–25 storey range. A 17-storey model was selected as it is representative of common Malaysian high-rise configurations, while maintaining computational feasibility. This height allows the simulation to capture the essential vertical smoke dynamics, including stack effect and pressurisation behaviour, that occur in taller buildings, while avoiding excessive simulation time and resource use. Numerical studies indicate that as shaft height increases, the stack-effect–induced pressure difference between the top and bottom of a stair shaft also increases, enhancing smoke containment within the fire floor up to a critical height beyond which additional height yields diminishing change in smoke spill-out patterns (Li et al., 2019). Previous studies have shown that smoke movement characteristics stabilise beyond a certain height, making 17 storeys a valid and efficient representation for this research.

The stairwell is naturally ventilated according to the positioning of the openings in certain experimental cases. The vent opening dimensions of 1 m × 2 m are consistent with common Malaysian high-rise staircase window sizes and meet the Uniform Building By-Laws 1984 ventilation requirement in By-law 40(1) and By-law 168, which stipulate that natural ventilation openings for staircases must have an area of not less than 1 m² for every 6 m² of floor area. The selected size also aligns with practical architectural designs for mid- to high-rise staircases, providing sufficient cross-ventilation for smoke purging during a fire. The sill height of 0.9 m above the finished floor level follows the guidance in MS 1553:2002 – Code of Practice on Staircases and Handrails, allowing unobstructed smoke exhaust in line with buoyancy-driven flow patterns. The openings were positioned at the ground floor, ninth floor, and seventeenth floor, depending on the case variant.

### 3.3 Procedure

The software used for this research was PyroSim, developed by Thunderhead Engineering (Thunderhead Engineering, 2024). It was designed to work hand in hand with Fire Dynamic Simulator (FDS), which was a type of fire simulation software developed by the Building and Fire Research Laboratory (BFRL) under the U.S. National Institute of Standards and Technology (NIST) (Thunderhead Engineering, 2024). PyroSim was one of the software that could be accessed via student licensing, so it is used in this simulation experimental study.

According to Thunderhead Engineering (2024) it is able to read 3D Computer-Aided Design (CAD) drawing files and provide tools that generate visuals from the text-only FDS-generated input file. The 3D CAD drawing software used in this experiment is SketchUp. In this simulation, the stairwell model was created in 3D making software, SketchUp.

The model measures 3.3 m in width, 8.6 m in length, and 51 m in height. In accordance with the Uniform Building By-Laws (UBBL) 1984, *By-Law 168* specifies that the total required exit width for staircases shall be determined based on the occupant load, with a minimum provision of 1,650 mm for sizable high-rise buildings to ensure efficient and safe evacuation. The model's staircase width meets this minimum requirement, thus complying with the stipulated egress capacity.

The floor-to-floor height of the model is 3.0 m, which is within the typical range for Malaysian residential high-rise buildings. This height satisfies *By-Law 194* of the UBBL 1984, which prescribes that rooms intended for human habitation shall have a minimum clear ceiling height of 2.5 m. The additional allowance accounts for slab thickness, structural systems, and mechanical/electrical services, ensuring both comfort and compliance with safety and habitability standards.

Figure 4 below shows how the frame of the staircase has been designed in the SketchUp and then uploaded into PyroSim to define the enclosed walls, the position of the opening and the point of fire ignition. On top of that, the fuel reaction used in each simulation was polyurethane, based on the SFPE (2016) Handbook, 5th Edition, Tables A.38 and A.39. The heat release rate per unit area value is kept constant in all simulations, which was 1000kW/$m^2$ (SFPE, 2016). The unit area of the burner used in this simulation was also kept constant at 1$m^2$ (SFPE, 2016). Hence, the constant heat release rate for every simulation was 1000kW (SFPE, 2016).

In the simulation, a $t^2$ fire growth model was applied with a ramp-up interval of 30 seconds between scenarios. This interval was chosen to represent realistic variations in fire growth rate and occupant response time in an enclosed staircase with limited ventilation. The $t^2$ growth model, as referenced in the *SFPE Handbook of Fire Protection Engineering* and NFPA guidelines, is widely used to approximate actual fire development patterns, where growth rates are categorised as slow, medium, fast, or ultra-fast. A 30-second increment provides a temporal resolution that is fine enough to capture transitional changes in smoke movement, temperature rise, and visibility reduction during the early to intermediate fire growth phases, while also aligning with typical tenability threshold times of approximately two to three minutes before conditions become untenable. This interval offers a practical balance between computational efficiency and the need for detailed observation of critical parameters affecting available safe egress time (ASET) in Pathfinder simulations.

Furthermore, the computer used for this analysis was: AMD Ryzen 5 PRO 4650U with Radeon Graphics @ 2.10GHz, 16.0 GB RAM, 64-bit operating system, x64-based processor. The mesh generated in the simulation was divided based on the flooring. For each floor, the number of cells per mesh count was 37,500. The total number of cells per mesh generated for the model was 637,500. The grid size of the mesh was 0.2 * 0.2 * 0.2. The division method for the mesh boundary was uniform.

Each of the simulations was ran for 600s (10 minutes), and the smoke visualisation (soot density) was observed with the temperature contour by using the 3D slice and planar slice drawing function. The simulation was categorised into a few cases: A, $A_L$, $A_M$, $A_U$, B, $B_L$, $B_M$, $B_U$, C, $C_L$, $C_M$ and $C_U$, where each case had different variables as shown below in Table 1. A, B and C work as the independent variables where case A represent a fire source location ignites at the lower level, case B represent the middle level (level 9), and case C represents the upper level (level 17). The next alphabet of L, M and U beside each case represents the location of the opening position. L represent the lower-level opening position, M represent the middle level, while U represent the upper level of opening.

Stairwell model from SketchUp | Stairwell model with walls in PyroSim | The position of the fire source and the opening of the stairwell model in PyroSim

**Figure 4.** Modelling of the case study.

However, it is vital to note that the limitation of this study was that computer simulations or numerical experiments required high computer specifications, which at the time of this research, were not available. Due to this, the modelling was required to be kept simple to ensure the time taken for the smoke visualisation was kept moderate and possible to be done within schedule.

**Table 1.** Varied Parameters in all Simulations

| Case | Fire Source Location | Opening Position |
|---|---|---|
| A | Lower Level | - |
| $A_L$ | Lower Level | Lower Level |
| $A_M$ | Lower Level | Middle Level |
| $A_U$ | Lower Level | Upper Level |
| B | Middle Level | - |
| $B_L$ | Middle Level | Lower Level |
| $B_M$ | Middle Level | Middle Level |
| $azB_U$ | Middle Level | Upper Level |
| C | Upper Level | - |
| $C_L$ | Upper Level | Lower Level |
| $C_M$ | Upper Level | Middle Level |
| $C_U$ | Upper Level | Upper Level |

## 4.0 RESULTS AND DISCUSSIONS

To better understand how the location of a fire in a stairwell impacts smoke behaviour and movement in a high-rise building, both with and without ventilation openings, 12 simulations were carried out. These simulations tested various variables and parameters to explore how different conditions affect smoke dynamics. A key focus of the study is the role of window position and how it influences the movement of smoke when the fire originates from three distinct ignition points within the stairwell.

### 4.1 Smoke Movement in Lower-Level Fire Position with Different Opening Level Position

**Table 2.** Case A with fixed position of fire source and different opening positions.

| Case | Fire Source Location | Opening Position |
| --- | --- | --- |
| A | Lower Level | - |
| $A_L$ | Lower Level | Lower Level |
| $A_M$ | Lower Level | Middle Level |
| $A_U$ | Lower Level | Upper Level |

Table 2 shows the simulation parameters for cases A, $A_L$, $A_M$, and $A_U$, where the fire source location remains constant at the lower levels and are analysed on the smoke movements based on different opening positions. According to the experiment, the presence of an opening does indeed influence the smoke movement in the stairwell. As shown in Table 3, for case A, the time required for the smoke to fill the ground floor and begin to diffuse towards the second floor is around 30 seconds. In comparison to Table 2 for case $A_L$, at the 30s- mark, the smoke still does not diffuse to the second floor and is just beginning to fill the first floor.

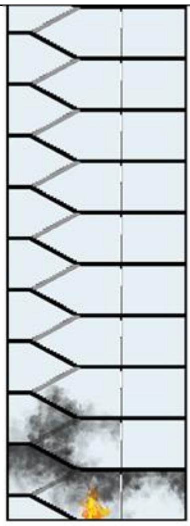
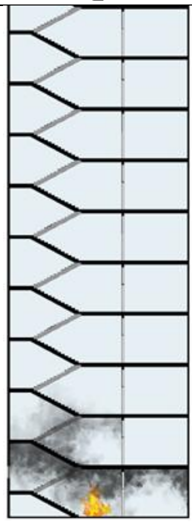
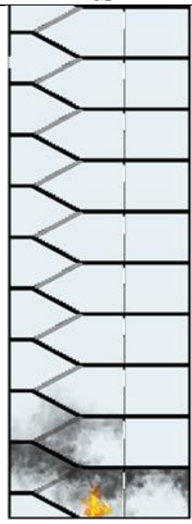
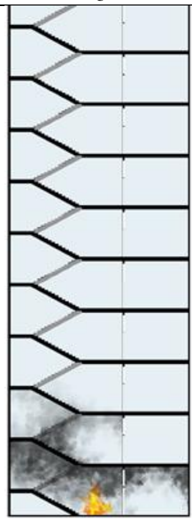
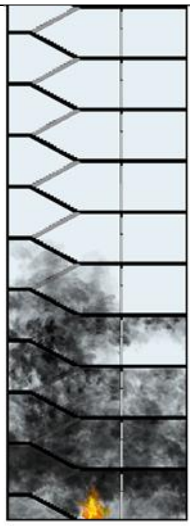
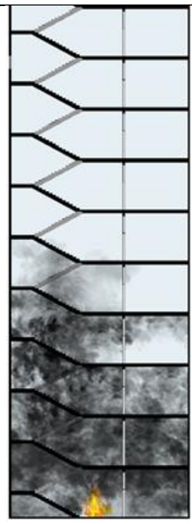
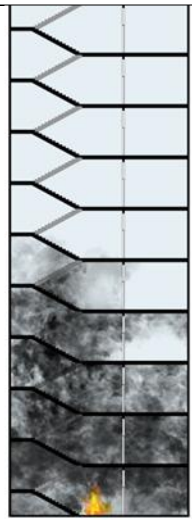
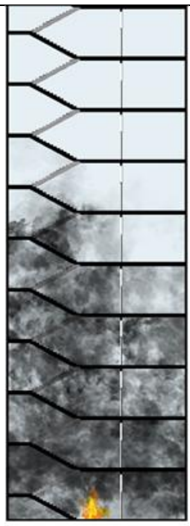
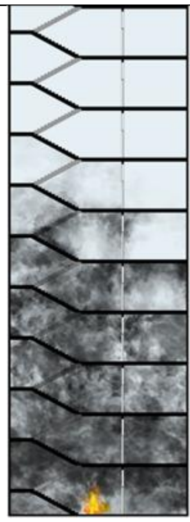
Meanwhile, at the 120s mark for case A, the smoke starts to diffuse, filling up the third floor as opposed to case $A_L$, where the smoke starts filling up the second floor. Plus, it can be observed that the smoke density in case $A_L$ is less than in case A. As a result, this shows that the fire evacuation process during case $A_L$ has better visibility than case A.

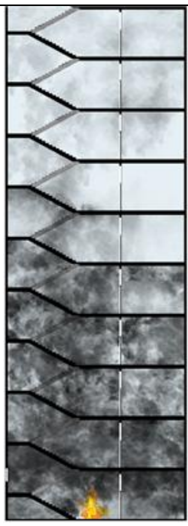
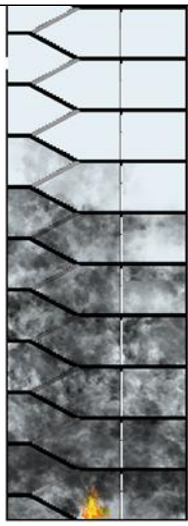
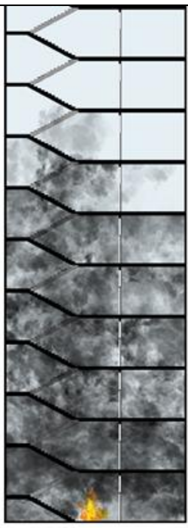
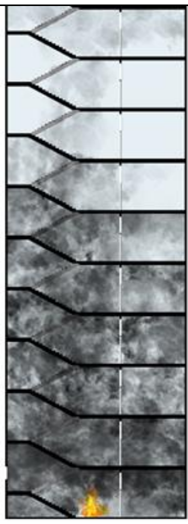
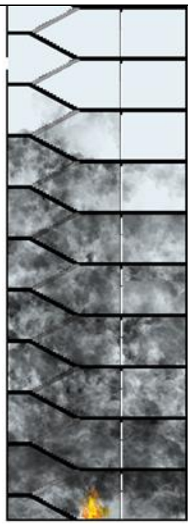
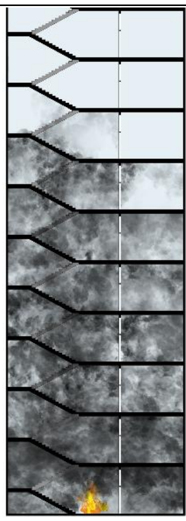
At the 540s mark, for case $A_L$ with the presence of an opening installed at the lower floor, the smoke was able to propagate up until the ninth floor and above, compared to case A, where the smoke only propagated up until the seventh floor. The smoke in case $A_L$ flowed through the opening to exit the building.

Furthermore, according to Li et al. (2022), the movement of the smoke is influenced by the stack effect. As such, smoke would move upwards from the fire floor as seen in both case A and $A_L$. On top of that, a previous study shows that the spreading of smoke in higher floors was significantly decreasing as the opening height increased (X. Zhang et al., 2020). Plus, the smoke concentration on the lower floors increased to a certain degree (X. Zhang et al., 2020). This is proven to be true in this simulation experiment as well. As shown in Table 3, the spreading of smoke in case $A_M$ is faster than in case $A_L$ (Figure 3.2). At the 30s mark, in case $A_L$ the smoke was just beginning to fill in the first floor, while in case $A_M$, the smoke was already starting to diffuse towards the second floor.

The smoke concentration and density in case $A_L$ at the 540s mark was also significantly lower compared to case $A_M$ and $A_U$. However, the changes in the smoke density were not that significant in case $A_M$ as compared to case $A_U$. This resonates with the research done by X. Zhang et al. (2020), which shows that the smoke concentration would slightly increase with the increase of opening height, but only to a certain extent. Although the result discusses as such, it can be seen that the level of smoke spreading (lower soot level) throughout the staircase is more significant when the window position is at the same level with the fire.

**Table 3.** Experimental Study for case A, $A_L$, $A_M$, and $A_U$ with fixed position of fire source and different opening positions.

| Case/time | Case A | Case $A_L$ | Case $A_M$ | Case $A_U$ |
|---|---|---|---|---|
| **30 seconds** |  |  |  |  |
| **120 seconds** |  |  |  |  |
| **240 seconds** |  |  |  |  |

| | | | | |
|---|---|---|---|---|
| **300 seconds** |  |  |  |  |
| **540 seconds** |  |  |  |  |

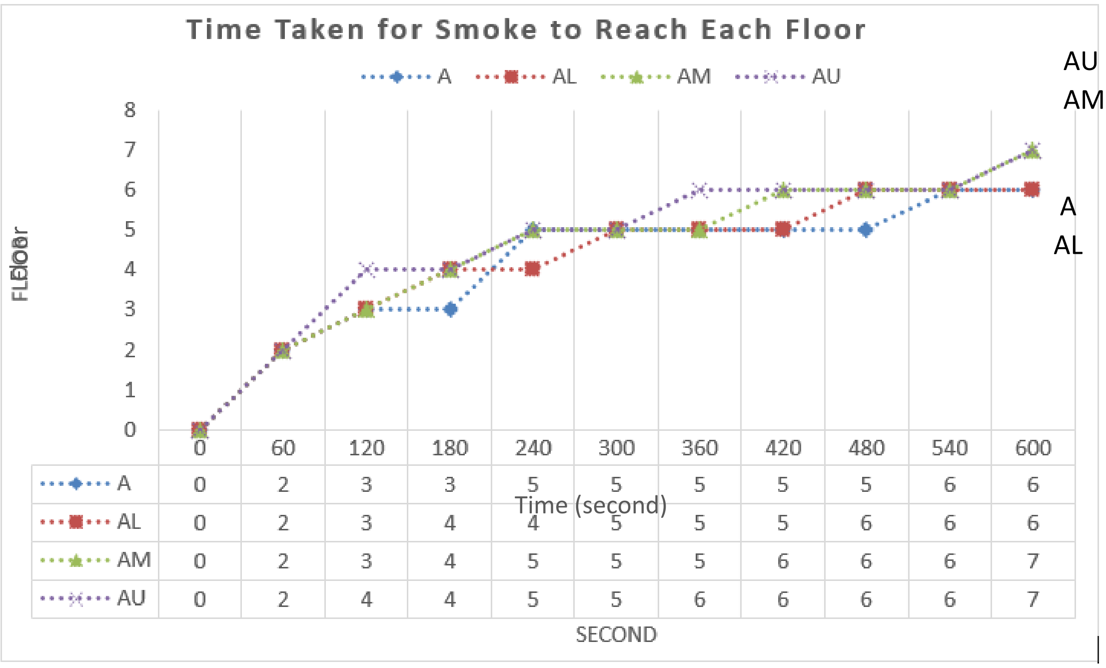



**Figure 5.** Time Taken for Smoke to Reach Each Floor in Case A, $A_L$, $A_M$, and $A_U$

From Figure 5, it can be seen that the smoke dispersion for case $A_U$ is the most pronounced compared to cases A, $A_L$, and $A_M$. For the first 120 seconds, the smoke movement in case $A_U$ is the first to reach the 4th floor compared to the other cases that have only reached the 3rd floor.

Additionally, at the 360s time mark, the smoke has moved upwards towards the 5th floor in case A, $A_L$ and $A_M$, but has already moved towards the 6th floor in case $A_U$. After 600 seconds, the smoke dispersion in cases $A_M$ and $A_U$ reached up to the 7th floor, while only reaching the 6th floor for cases A and $A_L$.

In contrast, the smoke movement seen in Table 5 (Case B) shows a slight difference as opposed to Table 3 (Case A). The fire floor is located on the ninth floor, and as seen in the 120s time mark in Table 5, the smoke begins to diffuse upwards instead of going downwards. Li et al. (2022) suggests that the movement of smoke going upwards implies the influence of the stack effect, while the downward movements are due to the pressure differences occurring in the stairwell.

From here, we could see a pattern of the smoke dispersion rate being faster as the opening height increases. A study from He et al. (2020) has proven that the average velocity of the smoke movement has a parabolic relation with the opening height, as it initially increases, but later decreases as the opening height increases. Further evidence also shows that the stack effect would have higher effectiveness as the opening height increases (He et al., 2020).

### 4.2 Smoke Movement in Mid-Level Fire Position with Different Level of Opening

**Table 4.** Case B, $B_L$, $B_M$, and $B_U$ with fixed position of fire source and different opening position

| Case | Fire Source Location | Opening Position |
|---|---|---|
| B | Middle Level | - |
| $B_L$ | Middle Level | Lower Level |
| $B_M$ | Middle Level | Middle Level |
| $B_U$ | Middle Level | Upper Level |

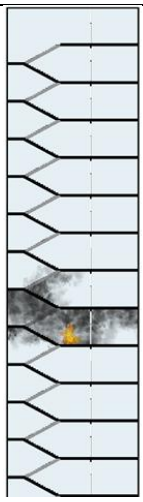
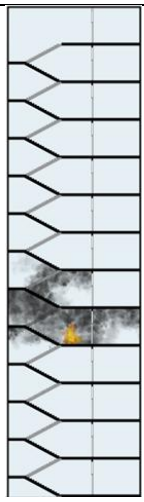
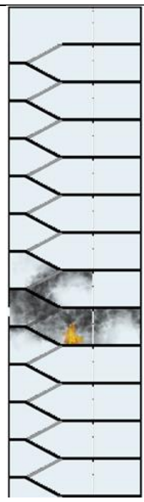
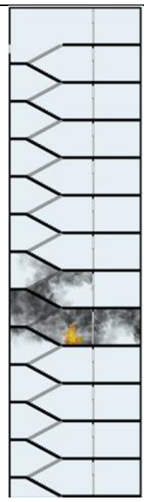
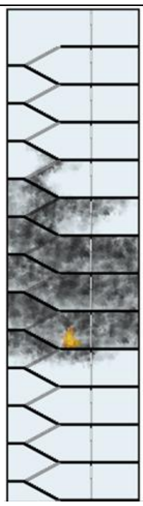
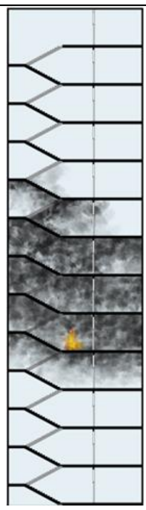
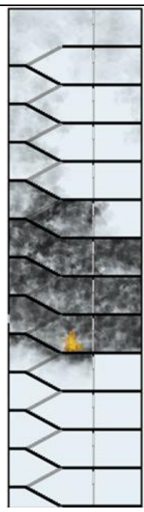
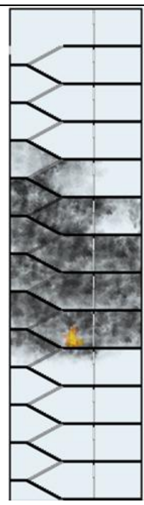
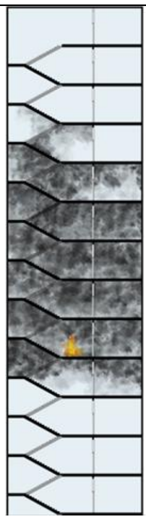
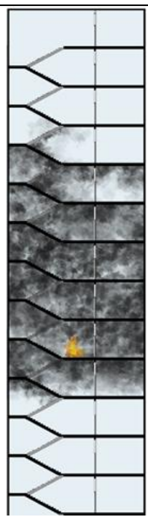
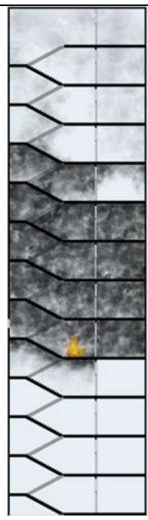
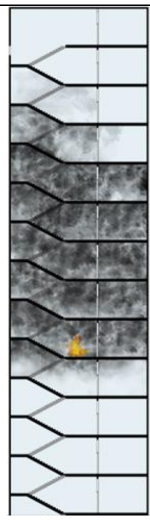
Table 4 shows the simulation parameters for cases B, $B_L$, $B_M$, and $B_U$, where the fire source location remains constant at the middle levels and are analysed on the smoke movement based on different opening positions. In case $B_L$ (Table 5), the smoke movement rate is slower as opposed to case B. According to Table 5, at the 240s mark, the smoke has started to diffuse towards the 14th floor, while, in case $B_L$, the smoke was just beginning to fill the 13th floor. It can also be observed. that the smoke density is less compared to in cases B and $B_L$. Additionally, in case $B_M$, the smoke diffused towards the upper level up till the 17th floor, while in case $B_L$, the smoke diffused only until the 15th floor in 540 seconds. This occurs due to the existence of the ventilation that is installed above the floor level which causes the stack effect strength to increase significantly (He et al., 2020).

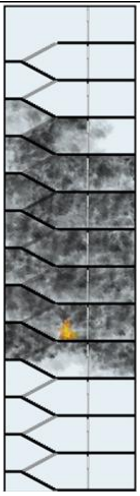
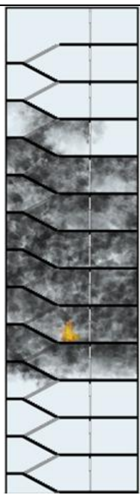
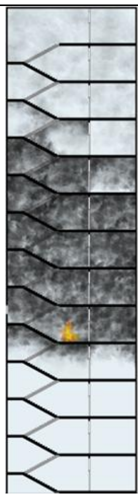
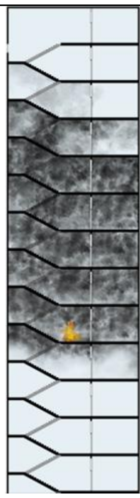
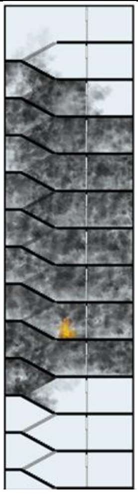
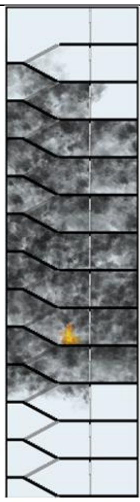
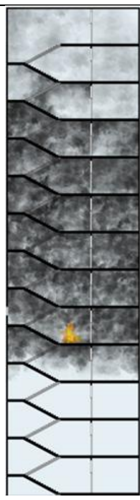
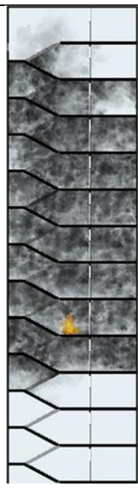
It is proven through this experimental study that the air density would be smaller due to the flame from the fire source stretching to reach an area provided with fresher air, also known as the lower air pressure area which in turn, increases the smoke diffusion as seen in a previous study done by He et al. (2022). This can be seen in case B, $B_L$, $B_M$, and $B_U$, where the fire spreads towards the lower region which contains lower-pressure air.

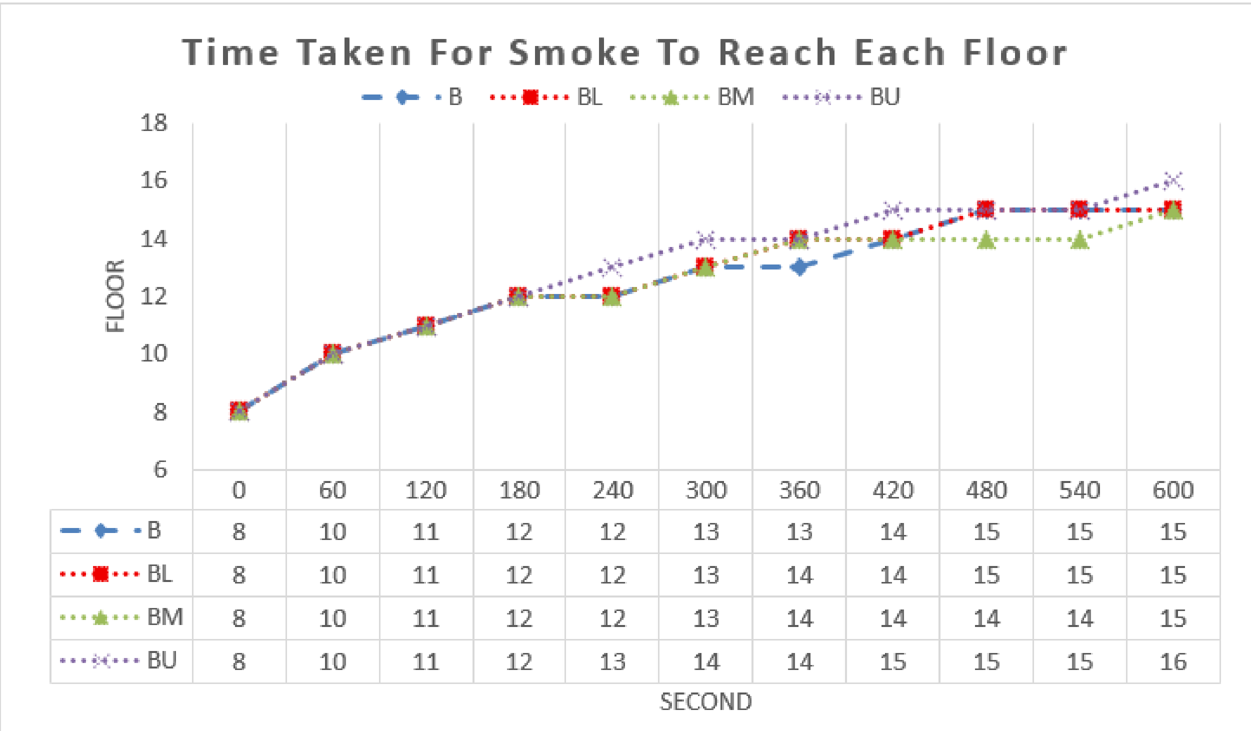
From Table 5, it can be seen that the smoke diffusion rate is faster in case $B_U$ than in case $B_M$. It can be observed clearly at 540 seconds, in case $B_U$, the smoke has started to fill the 15th floor, while in case $B_M$, the smoke was just starting to disperse towards the 15th floor.

This shows that, towards a certain extent, the height of the opening as opposed to the fire flooring gives an influence towards the smoke movement (He et al., 2020). On top of that, it is evident that the strength of the stack effect depends on the height of the opening (He et al., 2020). As the opening height increases, the strength of the stack effect in the stairwell would also increase but would reach a point where it would then decrease instead (He et al., 2020).

**Table 5.** Experimental Study for case B, $B_L$, $B_M$, and $B_U$ with fixed position of fire source and different opening position.

| Case/time | Case B | Case $B_L$ | Case $B_M$ | Case $B_U$ |
|---|---|---|---|---|
| **30 seconds** |  |  |  |  |
| **120 seconds** |  |  |  |  |
| **240 seconds** |  |  |  |  |

| | | | | |
|---|---|---|---|---|
| **300 seconds** |  |  |  |  |
| **540 seconds** |  |  |  |  |




| | 0 | 60 | 120 | 180 | 240 | 300 | 360 | 420 | 480 | 540 | 600 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| B | 8 | 10 | 11 | 12 | 12 | 13 | 13 | 14 | 15 | 15 | 15 |
| BL | 8 | 10 | 11 | 12 | 12 | 13 | 14 | 14 | 15 | 15 | 15 |
| BM | 8 | 10 | 11 | 12 | 12 | 13 | 14 | 14 | 14 | 14 | 15 |
| BU | 8 | 10 | 11 | 12 | 13 | 14 | 14 | 15 | 15 | 15 | 16 |

**Figure 6.** Time Taken for Smoke to Reach Each Floor in Case B, $B_L$, $B_M$ and $B_U$

As shown in Figure 6, case $B_U$ has the fastest smoke velocity compared to cases B, $B_L$ and $B_M$. For the first 180 seconds, all cases have a similar and apparent pattern. However, at the 240s mark, case $B_U$ shows a different rate as its smoke movement is the first to reach the 13th floor, as opposed to cases B, $B_L$ and $B_M$, which have only reached the 12th floor.

Moreover, for case $B_M$, the smoke movement reached the 14th floor in 360 seconds and tried to fill the 14th floor between the 360s-540s time mark. This can be explained due to the fire location and the opening located on the same floor, which is the 8th floor.

According to a study done by He et al. (2022), further evidence has been found that flame would stretch to reach fresher air and increase the smoke diffusion. However, in case $B_M$, the smoke would exit through the opening found on the same level, leading to a lower smoke density and a less apparent smoke dispersion compared to the other cases.

On top of that, at 600 seconds, the smoke diffusion in case $B_U$ is the most apparent as it is able to reach the 16th floor as opposed to cases B, $B_L$ and $B_M$, which have only reached the 15th floor. This further proves the evidence found in Bilyaz et al. (2021). It is a matter of fact that with the presence of an upper opening, a stronger stack effect would be formed in order to create a balanced pressure inside the vertical channelling, such as a stairwell (Bilyaz et al., 2021).

### 4.3 Smoke Movement in Upper-Level Fire Position with Different Levels of Opening

**Table 6.** Case C, $C_L$, $C_M$ and $C_U$ with fixed position of fire source and different opening position

| Case | Fire Source Location | Opening Position |
|---|---|---|
| C | Upper Level | - |
| $C_L$ | Upper Level | Lower Level |
| $C_M$ | Upper Level | Middle Level |
| $C_U$ | Upper Level | Upper Level |

Table 6 shows the simulation parameters for cases C, $C_L$, $C_M$ and $C_U$, where the fire source location remains constant at the upper levels and are analysed on the smoke movement based on different opening positions. In Table 7, the fire source was located on the 17th floor and started to spread towards the lower floor. This is due to the smoke dispersion going upwards to fill the ceiling plane. Once the upper level is completely filled with smoke as seen in the 120s mark, the smoke dispersion begins to diffuse downwards.

The study by Li et al. (2022) proves that smoke dispersion is highly influenced by the pressure inside the stairwell. Notably, the pressure difference between the higher region and the lower region is a positive value (Li et al., 2022). Therefore, the smoke moves downwards until the pressure reaches the point of equilibrium (Li et al., 2022).

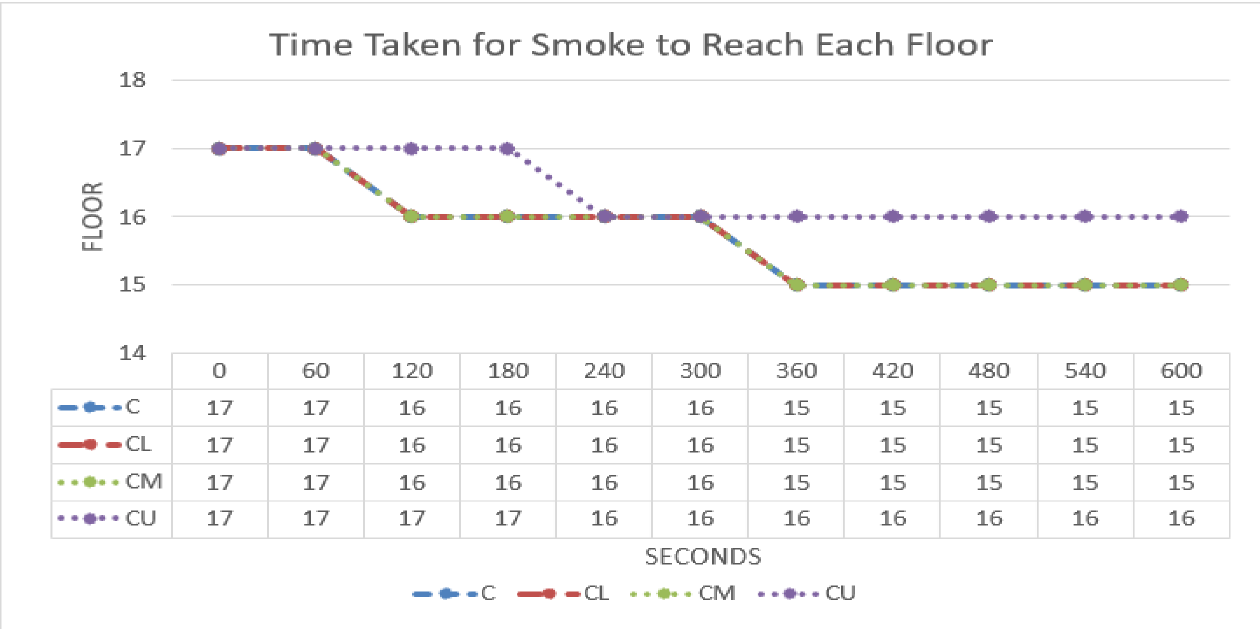
From the experiment, based on Table 7, the smoke dispersion is faster when the opening is positioned in the lower and middle levels. As seen in cases $C_L$, $C_M$, and $C_U$, the smoke dispersion is faster than in case C. This is because, as stated in Zhu et al., (2020), the opening would increase air supply. It is able to accelerate the movement of hot smoke, leading to a faster smoke diffusion compared to if there is no opening (Zhu et al., 2020).

Moreover, cases $C_L$ and $C_M$ do not have an apparent difference as compared to C and $C_U$. This is because in the upper region, turbulent mixing dominates the movement of the smoke dispersion (He et al., 2020). Furthermore, He et al. (2020) also suggests that the rising velocity gradually decreases with increasing height because of the turbulent mixing happening in the upper region.

Conversely, in case $C_U$, at the 30s mark, the smoke gradually fills up the 17th floor and exits through the opening. This is parallel to the evidence provided by He et al. (2022) which proves that smoke would disperse greatly under the influence of lower air pressure.

The upper opening provided in case $C_U$ creates a path for the smoke to exit into a space with lower pressure, which leads to lower smoke density as compared to case $C_M$. This can be seen at the 240s mark in case $C_U$, where the smoke was just beginning to diffuse towards the 16th floor, while in case $C_M$, the smoke had already been filling up the 16th floor.

In cases C, $C_L$, $C_M$ and $C_U$, an obvious decreasing trend can be seen as shown in Figure 7. This is because the fire floor is located at the top of the stairwell, which is the 17th floor. Due to this, no further upper level can be reached by the smoke. As a result, from the ceiling level, the smoke movement would lead downwards, as the upper region of the smoke movement is only influenced by turbulent mixing and no stack effect is involved (He et al., 2020).



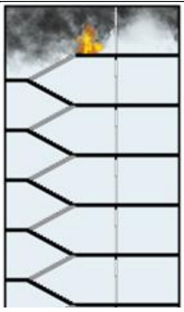
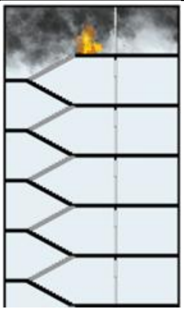
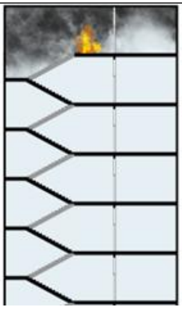
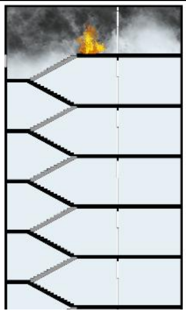
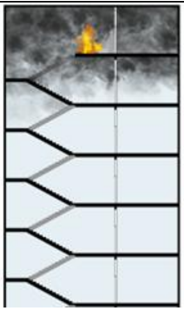
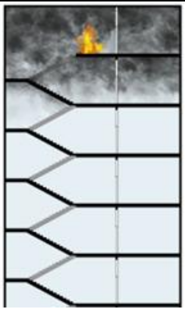
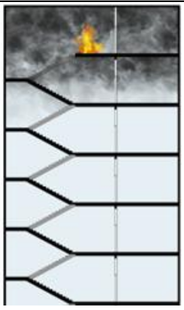
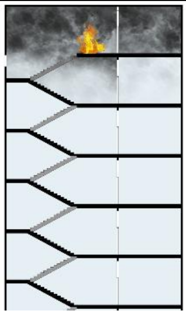
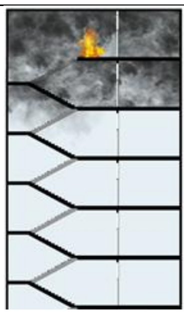
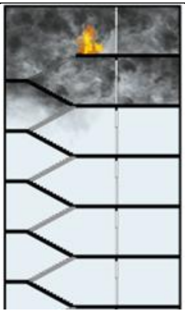
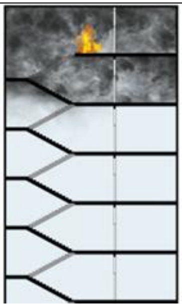
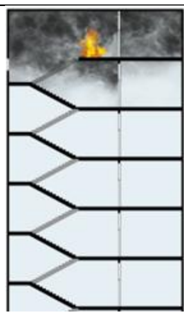
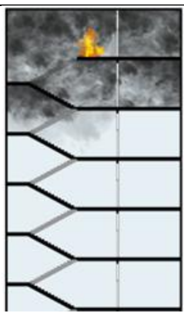
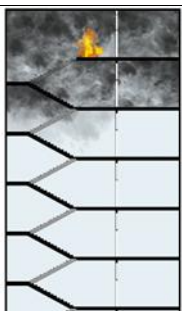
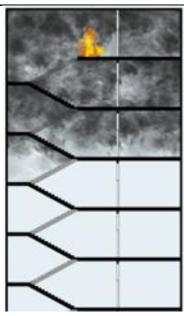
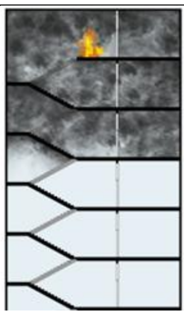
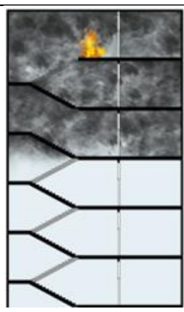
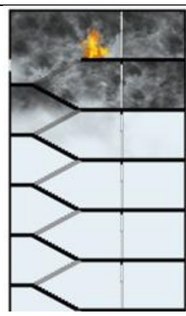

| | 0 | 60 | 120 | 180 | 240 | 300 | 360 | 420 | 480 | 540 | 600 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| C | 17 | 17 | 16 | 16 | 16 | 16 | 15 | 15 | 15 | 15 | 15 |
| CL | 17 | 17 | 16 | 16 | 16 | 16 | 15 | 15 | 15 | 15 | 15 |
| CM | 17 | 17 | 16 | 16 | 16 | 16 | 15 | 15 | 15 | 15 | 15 |
| CU | 17 | 17 | 17 | 17 | 16 | 16 | 16 | 16 | 16 | 16 | 16 |

**Figure 7.** Time Taken for Smoke to Reach Each Floor in Case C, $C_L$, $C_M$ and $C_M$.

This also explained how there are no apparent difference in the results of C, $C_L$ and $C_M$ at the 600s mark. It can be highlighted that at the 120s mark, the smoke dispersion in case C, $C_L$ and $C_M$ have reached the 16th floor, while for case $C_U$, the smoke was still on the same level, which was the 17th floor.

This is because the opening was on the same level as the fire floor in case $C_{U,}$ causing the smoke to go through the opening as an exit path. Therefore, it is safer for evacuees to go downstairs during smoke dispersion, as the differences between air density and thermal smoke density would cause the smoke to flow above the fire floor (J. Zhang et al., 2019).

**Table 7.** Experimental Study for cases C, $C_L$, $C_M$ and $C_M$ with fixed position of fire source and different opening position.

| **Case/time** | **Case C** | **Case $C_L$** | **Case $C_M$** | **Case $C_U$** |
|---|---|---|---|---|
| **30 seconds** |  |  |  |  |
| **120 seconds** |  |  |  |  |
| **240 seconds** |  |  |  |  |
| **300 seconds** |  |  |  |  |
| **540 seconds** |  |  |  |  |

## 5.0 CONCLUSIONS

According to the overview results gained from this research, it can be concluded that the behaviour and movement of smoke in the event of a fire in the stairwell of a high-rise building can be effectively predicted using numerical simulation software such as PyroSim, which integrates the Fire Dynamics Simulator (FDS). The aim of this study was to investigate the smoke movement in stairwells, which serves as the primary safe evacuation route in high-rise buildings for smoke safety management. Overall, PyroSim proves to be a practical and accessible tool for future researchers, as its user-friendly interface requires only a short learning period to operate effectively.

The results indicate that the strength of the stack effect increases as the opening height is increased, directly influencing smoke behaviour within the stairwell. Specifically, an opening located on the same floor as the fire floor serves as a direct exhaust path for smoke, resulting in reduced smoke density at that level, while also enabling higher smoke diffusion to adjacent spaces. This understanding is critical for evacuation planning, as it highlights the importance of strategic vent placement to balance smoke clearance on the fire floor while minimising smoke migration to escape routes above. In practical terms, such findings could guide the design and operation of stairwell ventilation systems, ensuring that safe, tenable conditions are maintained for occupants during evacuation.

From a stairwell design perspective, the study provides evidence that controlling window opening positions and understanding their interaction with fire location can help reduce smoke accumulation in key evacuation zones. This has direct implications for both active smoke control measures (such as automated vent systems) and passive design strategies (such as compartmentalisation and fire-rated door placement). These design considerations can significantly improve occupant survivability by maximising visibility, lowering toxic gas exposure, and maintaining safe temperatures along evacuation paths.

To further improve the accuracy of simulation-based research, it is highly recommended that future studies increase the level of detail in the 3D building models, including architectural features such as railings, balusters and balustrades, as these may subtly influence smoke flow patterns. Moreover, while simulation tools like PyroSim can reliably predict physical smoke movement, they do not currently account for evacuee behaviour or human factors. Panic, reduced mobility, and decision-making under stress can all alter the speed and efficiency of evacuation, and thus, integrating crowd dynamics modelling with smoke simulation could provide a more comprehensive understanding of real-world evacuation performance. Ultimately, the integration of these findings into building codes, evacuation strategies, and stairwell design standards could enhance life safety in high-rise buildings by ensuring that stairwells remain as safe and functional escape routes throughout a fire event.

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