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The Smoke Temperature Analysis and Smoke Gas Component Distribution Using the Staircase Pressurisation System

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Abstract: This study investigates the impact of staircase pressurisation systems on smoke temperature and the distribution of smoke gas components in a 3-storey building using Computational Fluid Dynamics (CFD) simulations. Staircase pressurisation systems are designed to create a differential pressure that prevents smoke infiltration, ensuring staircases remain safe evacuation routes. This research uses CFD to predict the effectiveness of pressurised staircase systems on smoke gas product carbon dioxide (CO_2) infiltration into the staircase space at a differential pressure of 50 Pa, as per MS 1472, in comparison to a non-pressurised staircase system. The inlet of the smoke mass flow rate and temperature are 6.544 kg/s and 535K, respectively. The simulations reveal that without a pressurisation system, smoke can occupy the 3-storey building in less than 5 minutes. Conversely, the pressurisation system prevents smoke from propagating and infiltrating the stairwell. Moreover, the staircase pressurisation system reduces the maximum air temperature in the staircase space from 535K to approximately 307K. This study analyses both smoke temperature and gas component distribution to evaluate the effectiveness of staircase pressurisation systems.

Keywords: Computational fluid dynamics (CFD); Differential pressure; Fire safety; Smoke control system; Staircase pressurisation system.

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1. INTRODUCTION

Fire and smoke represent critical hazards in various enclosed environments, including urban underground utility tunnels [1], road tunnels [2], high-rise buildings [3], subway stations [4], building corridors [5], and car parks [6]. In building design, paramount importance is placed on safeguarding occupant lives during fire emergencies. Consequently, all buildings and premises, particularly public structures like hospitals, must incorporate safe and reliable escape routes [7]. Smoke, due to its rapid spread, often poses the most significant impediment to occupant egress, with smoke inhalation being a leading cause of fatalities in fire incidents [8]. This challenge is particularly pronounced in large-scale structures such as hospitals, commercial malls, and high-rise commercial buildings. For example, a tragic incident in 2016 at Sultanah Aminah Hospital (HSA) in Johor Bahru, Malaysia, resulted in six patient fatalities due to smoke inhalation [9]. The Fire and Rescue Department of Malaysia (FRDM) or Bomba, has identified key fire safety concerns in commercial buildings, including deficiencies in mechanised firefighting systems, inadequate accident management practices, and insufficient worker competency in safety protocols [9]. Mechanised firefighting techniques, most notably staircase pressurisation systems, are vital in significantly delaying smoke spread, thereby extending the safe evacuation window for occupants. According to FRDM or Bomba, the lack of a mechanised firefighting system, poor accident management practices, and the incompetence of workers regarding safety issues are the main concerns of fire safety in commercial buildings [9]. Mechanised firefighting techniques, including a staircase pressurisation system, can significantly delay the spread of smoke and provide residents more time to escape safely.

Despite advancements in building regulations and the widespread adoption of pressurisation systems, challenges persist. Variations in building design, fire dynamics, and operational conditions can affect the efficacy of these systems [10]. Understanding how different factors influence smoke propagation and the performance of pressurisation systems is critical for enhancing building safety protocols. Thus, Bellido [11] introduced the methodology to assess the staircase pressure performance. They used a single pressure sensor to control the mechanism of the fan. According to the results, the air pressure severely dropped due to sudden door opening, and an insensitive air pressure damper causes a long duration of air pressure recovery.

Malaysian Standards MS1472 and British Standard Institution BS5588: Part 4 (1978) recommend that the air differential pressure in the staircase be set around 50 Pa [12, 31]. Therefore, the staircase pressurisation system requires an air pressure control mechanism to ensure that the staircase air pressure is within the set range. Automatic pressure smoke damper (APSD) is widely used in controlling air pressure in escape routes, including staircases. In 2013, Lee [13] conducted a comprehensive assessment of APSD. The authors stressed that the APSD performance is dependent on blade angle and air pressure differences. Next, the experimental study staircase pressurisation has been expanded by [14]. The authors applied staircase pressurisation system for 40-storey high-rise buildings to understand the implications of the non-pressurised fire protection lobby next door to the pressurised staircase. The findings concluded that the fire protection lobby improved the effectiveness of the staircase pressurisation system for high-rise buildings. The other factor that affects the effectiveness of the staircase pressurisation system is the size of the door. According to You [15], a higher force is required to open the staircase for a larger emergency door than a smaller emergency door when the staircase is pressurised activated. The force is directly proportional to the area at the given air pressure difference. Therefore, a larger door needs more time to open than a smaller door, which is not good for old occupants and children. In the other study by You [16], the mock-up building has been developed to understand the effect of air pressure difference and leakage area. The air pressure difference range of the study was between 45 Pa and 55 Pa. In the article, the authors stated that characteristics influence air flow leakage, including ventilation flow rate, air pressure difference between two compartments, air velocity, and the opening-closing force door.

Furthermore, while regulations mandate the installation of staircase pressurisation systems in certain high-rise buildings, the effectiveness of these systems in real-world fire scenarios requires thorough validation. This necessitates rigorous scientific analysis, such as Computational Fluid Dynamics (CFD) simulations, to simulate and predict smoke behaviour under various conditions. Besides fire safety applications, CFD is also widely used in aeronautics [17], heat exchangers [18], semiconductor [19], combustion [20], and electric vehicle [21]. A few studies on smoke and fire propagation have been conducted using the Fire Dynamics Simulator (FDS). Lu [22] examined the efficacy of the powered ventilation system utilising FDS to mitigate smoke propagation during a fire. The data analysis shows that powered ventilation gives firefighters great visibility and keeps the smoke from spreading. Wesseling's [23] smoke ventilation analysis is another example. The FDS analysis for different boundary conditions showed that powered ventilation is better than natural ventilation when it comes to visibility range for evacuation, especially five minutes after a fire accident.

A CFD analysis was conducted by Lee [24] to evaluate the efficacy of the staircase pressurisation system in high-rise buildings. In a staircase room, the differential pressure between 50 Pa and 100 Pa has been investigated. The finding shows that the staircase pressurisation was very effective in consistently maintaining the required pressure differentials across varying conditions. In 2018, Park [25] claimed that the speed of the elevator affects the differential pressure in the vestibule and living room for high-rise buildings. As a result, the authors conducted a numerical study to prove their hypothesis. The study used the ANSYS CFX CFD code. According to the CFD results, the air differential pressure rises with lift speed. Finally, the authors propose an empirical correlation for predicting air differential pressure at given lift speeds and locations. According to Sung's observations [26], in addition to building size and air pressuring method, air leakage through the damper and fire size influences the performance of the staircase pressurisation system. According to the findings, whole-floor pressurisation necessitates twice the air flow rate as parted-floor pressurisation.

In this regard, numerous studies have explored the efficacy of various smoke control methods within building structures. CFD simulation has emerged as a powerful tool for this purpose, accurately simulating smoke spread and predicting temperature and gas concentrations in real-time [10]. Prior research has leveraged CFD to simulate smoke control in diverse environments, from underground car parks [11] to high-rise buildings, investigating systems like natural and mechanical smoke extraction [12], the effects of elevator movement [13], and damper leakage [14].

However, Table 1 indicates a critical gap in the literature with respect to CFD studies that specifically assess staircase pressurisation systems in the context of Malaysian building codes. This study addresses that gap by providing a novel, focused application of CFD to assess a pressurisation system's performance directly against the requirements of MS 1472, which mandates a 50 Pa differential pressure. The primary objective is to accurately predict the system's effectiveness in preventing carbon dioxide (CO_2) infiltration and maintaining a safe temperature within a simulated 3-storey building. The findings are expected to provide valuable, data-driven insights for Malaysian fire safety professionals, assisting them in the design and implementation of effective smoke control strategies that are fully compliant with national standards.

2. METHODOLOGY

The methodology of the present study includes geometric modelling, meshing, computational setup, grid-independent test, and comparison of CFD data with the Guide to Fire Protection in Malaysia textbook [7].

2.1 Geometric Modelling

Ansys Design Modeller was used to develop a basic 3-storey building geometric model. The building area is 62 m^2 per floor with dimensions of 10 m in length, 6.2 m in width, and 3.5 m in height. The staircase has a floor area of 25.73 m^2 per floor and features a single emergency door with one leaf, measuring 2 m in height and 0.8 m in width. At the roof, has a 1.2 m by 1.2 m opening for the injection fans and a 0.4 m by 0.4 m damper opening near the emergency door. Figure 1 shows a schematic model of the 3-storey building with a staircase, and Table 2 displays the overall modelling dimensions.

A precise geometric modelling is required to accurately capture the flow of smoke and heat as if it were in a real-world building, particularly at corners, through doors and up staircases. Thus, this model includes some important architectural features like staircases, doors, and ventilation openings to ensure that the mesh generation and boundary conditions are applied correctly.

Table 1. A comparison of the current research to existing literature, highlighting key research gaps and contributions.

Comparison Point	**Existing Literature & Research Gap**	**The Present Study**
Primary Focus	Broad studies on various smoke control methods, lacking a focused analysis on a single system.	A dedicated CFD evaluation of a staircase pressurisation system.
Regulatory Context	Research often follows generic principles, not specific national building codes.	Conducted to meet Malaysian Standard MS 1472.
Key Performance Metric	Focus on general metrics like temperature, not the effect of a precise differential pressure.	Analyses the impact of a 50 Pa differential pressure on smoke and gas distribution.
Practical Relevance	General contributions, lacking localised, data-driven evidence for a specific country's regulations.	Provides actionable insights for fire safety professionals in Malaysia.
Validation Method	Validation against general data, not a specific national standard's performance metrics.	Validated against the air leakage requirements of MS 1472.
Smoke Gas Analysis	General smoke spread analysis.	Provides detailed, quantitative data on CO_2 mass fraction distribution.
Temperature Analysis	General temperature profiles.	Quantifies temperature reduction in a critical evacuation path from 538K to 310K.
Building Geometry	Wide range of building types, often with idealised geometries.	A representative three-story building model is used to create a realistic benchmark.
Simulation Duration	Studies on short-term dynamics, not sustained system performance.	A 600-second simulation proves the system's long-term effectiveness.
Study Scope	Focus on a single aspect or parameter, offering an incomplete picture of safety.	A holistic analysis covering both smoke gas distribution and temperature profiles.

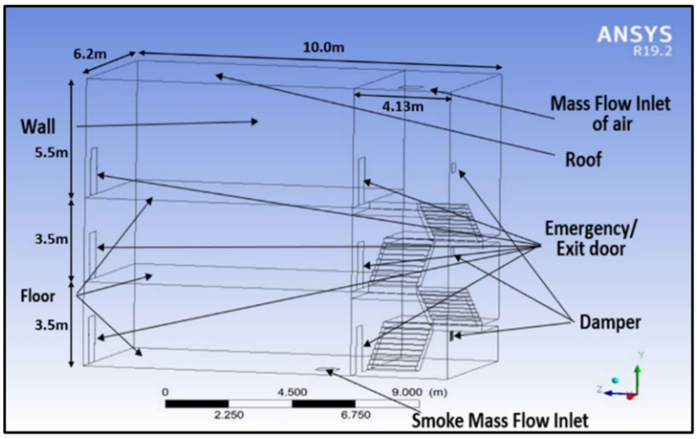


Figure 1. Schematic model of a 3-storey building.

Table 2. 3-Storey modelling dimensions.

Building/ Office		Staircase	
Area, *A*	62 m^2 (10 m x 6.2 m) - each floor	Area, *A*	25.73 m^2 (4.15 m x 6.2 m) - each floor
Length, *L*	10 m	Length, *L*	4.13 m
Width, *W*	6.20 m	Width, *W*	6.20 m
Height, *H*	3.5 m	Height, *H*	3.5 m
1-leaf emergency exit door	1.6 m^2 (2 m x 0.8 m) - each floor	1-leaf emergency exit door	1.6 m^2 (2 m x 0.8 m) – each floor
		Opening injection fans	1.44 m^2 (1.2 m x 1.2 m)
		Damper	0.16 m^2 (0.4 m x 0.4 m) - each floor

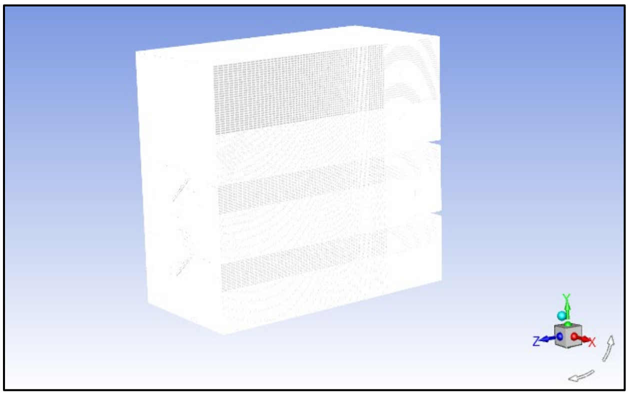


Figure 2. Overall three-dimensional model with a hexagonal mesh.

2.2 CFD Mesh Generation

In the current study, ANSYS Meshing was used to create an air domain mesh within the building. To ensure accurate and reliable results, the CFD simulation employed a rigorous meshing procedure. To account for the building geometry's complex architectural features, an unstructured or hybrid mesh was generated. A Grid Independence Test (GIT) was conducted to ensure grid independence and minimise spatial discretization errors. Three mesh configurations were evaluated as given in Table 3: a coarse mesh (2,452,020 nodes), a fine mesh (3,418,860 nodes), and a very fine mesh (3,556,980 nodes). The fine mesh, as illustrated in Figure 2, was ultimately selected for all simulations as it provided excellent convergence with the very fine mesh while significantly reducing computational time from 20 hours to only 3 hours per simulation case. This approach ensured that the mesh quality was sufficient to produce reliable results without an excessive computational burden.

Table 3. Number of nodes for each meshing model.

Model	Description	Number of Nodes
1	Coarse Mesh	2,452,020
2	Fine Mesh	3,418,860
3	Very Fine Mesh	3,556,980

2.3 Computational Setup

ANSYS Fluent was used to model the time-unsteady distribution of smoke and temperature during a transient simulation between 0 s and 600 s with and without a staircase pressurisation system. The k-omega turbulence model was employed for its robustness in accurately resolving flow phenomena in near-wall regions, which was essential for capturing the detailed dynamics of smoke movement. The solver settings were configured with a time step of 0.1 seconds, and convergence was monitored with a residual target of 10^{-6} for continuity, momentum, and species equations, and 10^{-7} for the energy equation, ensuring high accuracy of the converged solution.

The fluid density was modelled as an ideal gas, and gravity was enabled to properly account for the stack effect, a critical factor in vertical smoke propagation. A species transport model was activated to track the concentration of key combustion products, specifically CO_2 and carbon monoxide (CO). The physical properties of the concrete walls, including wall conductivity and specific heat, were assumed to be adiabatic to simplify the model and focus the analysis on the early-stage smoke and temperature dynamics. This simplification is common in fire simulations where the transient effects of conduction through the building fabric are considered secondary to convective and radiative heat transfer within the gas phase during the initial critical phase of fire development [27].

In the boundary conditions setup, the mass flow inlet and pressure outlet were used to allow flow into and out of the building. As shown in Figure 1, mass flow inlets were installed on the ground-level CO_2 inlet and the roof-level air pressure inlet. The pressure outlets were located on both open and cracked doors. In the current study, the mass flow rate was 6.544 kg/s, resulting in a convective heat input of 1,500 kW. In the absence of air, this smoke had a temperature of 535K and a 50% CO_2. The smoke flow rate in the simulations was 6.544 kg/s at the smoke inlet using the Zukoski equation, as described in Equation (1) [28]:

$$M = 0.071 Q_C^{0.333} (z - z^0)^{1.667} \tag{1}$$

where M is the mass flow rate of smoke in kg/s, Q_C is the heat output in W, z is the height of the smoke layer above the base of the fire in m, z^0 is height above the base of the fire of the virtual origin of the smoke plume in meter.

In this simulation, a convective heat input of 1,500 kW was applied to the plume, and the resulting mass flow rate was then calculated using the Zukoski formula with the effective height of the smoke layer above the virtual origin, $z - z^0$, taken as 3.5 m. This smoke temperature was calculated based on the heat output and the determined mass flow rate using the following relationship:

$$T_C - T_{ambient} = Q_C/M \tag{2}$$

where T_C is the temperature of the smoke layer above ambient in K and $T_{ambient}$ is ambient temperature in K. Thus, the smoke flow rate and temperature used as boundary conditions in the simulations were calculated based on an assumed heat output and the Zukoski formula, consistent with fire safety engineering principles [12]. Table 4 summarises the key solver configurations, mesh quality and strategy, and physical property assumptions used in this simulation setup.

Table 4. Summary of category used in simulation setup.

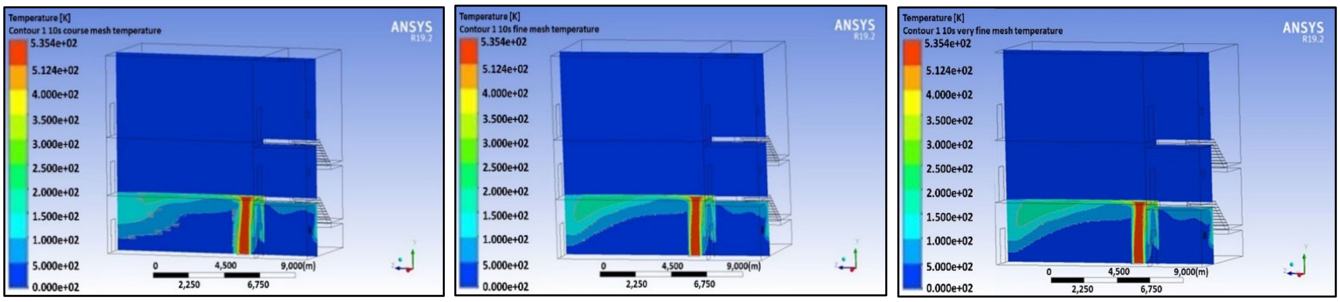
Category	Parameter	Description / Value
Solver Configurations	Solver Type	Pressure-Based
	Velocity Formulation	Absolute
	Time	Transient
	Energy Equation	ON
	Viscous Model	k-omega
	Species Model	Species Transport Mixture-template Diffusion Energy Source (including CO_2, N2, Air, CO)
	Gravity	ON (negative Y-axis)
	Fluid Density	Ideal Gas (to allow stack effect)
	Discretisation Scheme	Second order upwind model for momentum and energy equations
	Turbulence Intensity (at boundaries)	5%
	Turbulence Viscosity Ratio (at boundaries)	10
Physical Property Assumptions and Justifications	Wall Material	Concrete (for walls, floor, and roof)
	Wall Thermal Property	Adiabatic (Heat Flux = 0 W/m²), justified by low thermal conductivity of concrete; no heat transfer through walls considered.
	Wall Permeability	Non-permeable (Zero Diffusive Flux); no gases (N_2, Air, CO) pass through walls.
	Smoke Composition	Represented by 100% gases; CO_2 used as major component to represent all smoke components.
	Flow Type	Assumed to be turbulent due to very high Reynolds number at smoke inlet.
	Natural Convection	Incorporated natural buoyancy or the stack effect.
Mesh Quality and Strategy	Meshing Software	ANSYS Meshing
	Overall Mesh Element Type	Unstructured or hybrid mesh to accommodate complex geometry.
	Total Nodes (Selected Mesh)	3,418,860 (Fine Mesh)
	Meshing Process	Involved refining mesh using progressively smaller cell sizes; assembled all divided bodies into a single part; named selections assigned to various components.
	Quality Assurance Method	Grid Independent Test (GIT) conducted with three mesh configurations (coarse, fine, very fine).
	Mesh Selection Justification	Fine mesh selected because its temperature results converged closely with the very fine mesh while significantly reducing computational time (3 hours vs. 20 hours).

2.4 Grid Independence Test and Comparison Data

A grid independence test was performed to ensure that the simulation results for the current work were accurate. The grid independence test is a crucial step in verifying that the simulation results are consistent with the number of meshes. Thus, three different mesh configurations, namely Coarse Mesh, Fine Mesh, and Very Fine Mesh, were created and simulated separately using the same parameters studied. The mesh counts of Coarse Mesh, Fine Mesh, and Very Fine Mesh are 2.4×10^6, 3.4×10^6, and 3.7×10^6, respectively.

Figure 3 illustrates the temperature contour for coarse mesh (Mesh 1), fine mesh (Mesh 2), and very fine mesh (Mesh 3) at a 10 s-time interval. The temperature contour of fine mesh is nearly identical to that of very fine mesh, especially in Level 1. However, as shown in Figure 3, Mesh 1 (the coarse mesh) had temperature distributions that differed significantly from the finer mesh results, particularly at Level 1.

Furthermore, Figure 4 depicts the temperature profile along height plotted over a 10 s period. Fine mesh and very fine mesh have identical temperatures at heights ranging from 1.5 m to 3.5 m. The coarse mesh temperature slightly underpredicts at the same height. At heights ranging from 0 to 1.5 m, coarse mesh temperature overestimates temperature. The fine mesh shows a slightly higher temperature than the very fine mesh does. Given the comparable temperature profiles obtained with the fine and very fine meshes at heights of 1.5 m and above, the fine mesh was chosen because it required significantly shorter computational time.



Mesh 1 Mesh 2

Figure 3. Temperature contour 10 s for Mesh 1 (course mesh), Mesh 2 (fine mesh), and Mesh 3 (very fine mesh).

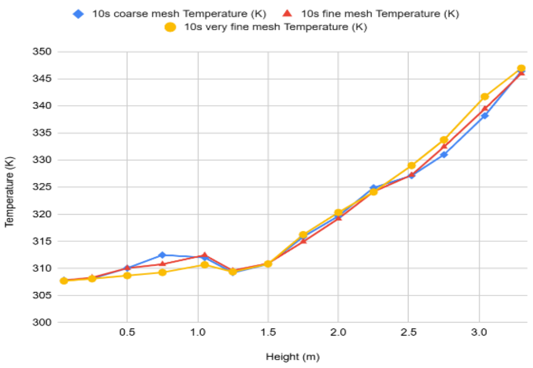


Figure 4. Temperature distribution at various heights for coarse mesh, fine mesh, very fine mesh within a time of 10 s.

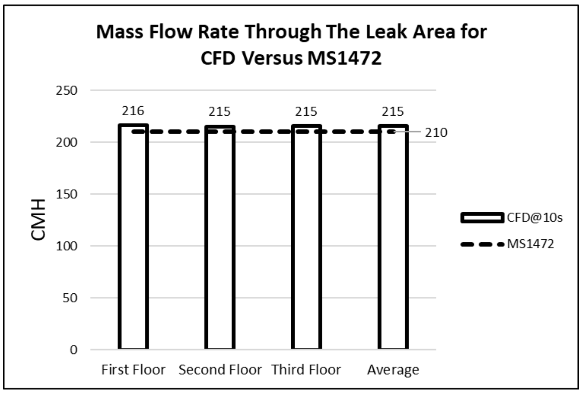


Figure 5. Mass flow rate comparison through the door crack or leak area.

The CFD results' reliability was significantly improved by a critical technical validation process that included a direct comparison with Malaysia Standard MS1472. This validation was critical in ensuring that the CFD model accurately reflected real-world conditions and produced credible results. The comparison specifically utilised data from Table 3 and Table 4 of MS1472, as shown in Table 5, which pertain to fire precautions in the design of buildings, particularly concerning smoke control in protected escape routes using pressurisation. This validation focused on an air pressure setting of 50 Pa, a critical parameter designed to confirm the pressurisation system's ability to prevent smoke infiltration into protected staircases during a fire. Due to the limited availability of experimental results for open doors in existing literature, this particular comparison was performed under a closed-door scenario.

In this specific closed-door configuration, the CFD simulation found an air leakage of 215CMH in average through each of the doors as shown in Figure 5. This result closely matches the MS1472 standard (Case A), which specifies 210CMH for the same conditions of 50 Pa pressure difference. The observed 5CMH (2.38%) deviation is negligible, showing that our CFD model accurately reflects the MS1472 data. This confirms the reliability and robustness of CFD study's findings. Figure 5 depicts the pressure distribution modelled in the simulation by comparing mass flow rates.

Table 5. Leakage area calculation based on 50Pa pressure differential and interpolation of data from Tables 3 and 4 (MS1472).

Case	Type of Door	Size (mm)		Leakage Per Door (CMH)
		Height	Width	
A	Single leaf opening into a pressurised space	2	0.8	210
B	Single leaf opening outwards from a pressurised space	2	0.8	420
C	Double leaf opening into pressurised space	2	1.6	630

3. RESULTS AND DISCUSSION

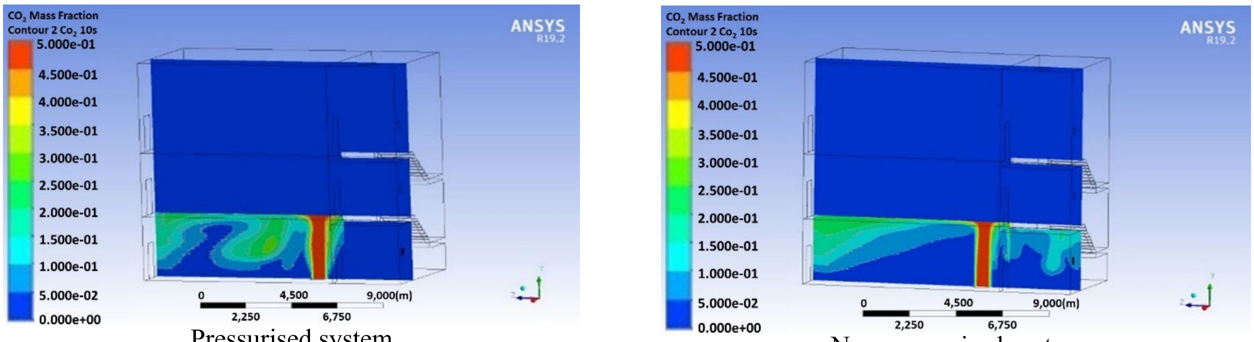
The current study examines CO_2 distribution contour against time, temperature distribution against height, and average air temperature against time, for a staircase with pressurised and non-pressurised system.

3.1 Smoke Gas (CO_2) Distribution Contour

The simulations underscore a substantial disparity in the distribution of smoke gas (CO_2) between the pressurised and non-pressurised scenarios. Smoke gas disseminates rapidly in the non-pressurised scenario. CO_2 occupies the first floor and stairwell within a mere 10 s, attaining a mass fraction of 0.25. The stairwell is devoid of CO_2 in the pressurised scenario, as illustrated in Figure 6, with a mass fraction of 0.00.

The CO_2 contour results exhibit a substantial disparity between the two scenarios at the 300 s time point, as illustrated in Figure 7. The first and second floors of the non-pressurised system were each filled with CO_2, resulting in a maximum mass fraction of 0.5. The third floor was also significantly affected, with a mass fraction of 0.47. This suggests that smoke propagated throughout the building's three floors. On the other hand, the staircase pressurisation system was in operation, resulting in the sole first-floor office area being filled with CO_2 at a maximum mass fraction of 0.42. The first-floor staircase, second floor, and third floor, on the other hand, remained free of CO_2.

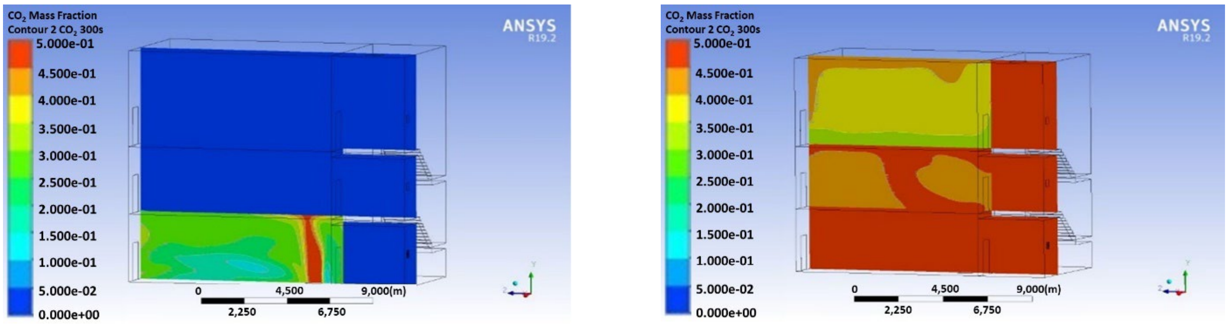
By the time of 600 s, the CO_2 contour results present a stark contrast between the two scenarios. As shown in Figure 8 for the staircase pressurisation system in operation, only the first-floor office area was occupied by CO_2, with a maximum mass fraction of 0.43, while the second and third floors were free from CO_2. However, without the staircase pressurisation system, the entire 3-storey building was completely filled with CO_2, reaching a maximum mass fraction of 0.5. In this condition, smoke had completely occupied all floors within 300 s.



Pressurised system

Non pressurised system

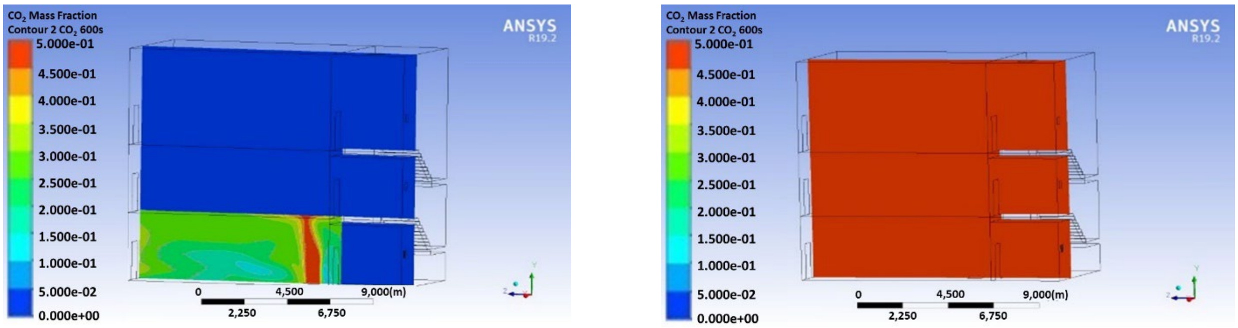
Figure 6. CO_2 mass fraction contour for building with pressurisation system and no pressurisation system at time of 10 s.



Pressurised system

Non pressurised system

Figure 7. CO_2 mass fraction contour for building with pressurisation system and no pressurisation system at time of 300 s.



Pressurised system

Non pressurised system

Figure 8. CO_2 mass fraction contour for building with pressurised system and non-pressurised system at time of 600 s.

3.2 Smoke Temperature Analysis

The study thoroughly examined CO_2 temperature profiles in relation to altitude in both non-pressurised and pressurised systems. The data was systematically gathered on temperature distribution at heights ranging from 0.00 m to 3.25 m, and at time intervals of 10 s, 300 s, and 600 s, at the first-floor staircase. The analysis aims to comprehend the significant influence of the staircase pressurisation system on the temporal trends of hot air temperature. The results sought to offer comprehensive insights for enhancing architectural design and fire safety measures.

The first-floor staircase exhibited distinct temperature patterns within a 10-second time frame of temperature profile in Figure 9, as the pressurised scenario consistently maintained a low temperature of approximately 307K. This suggests that the smoke control and occupant safety measures were effective. In contrast, the non-pressurised condition exhibits substantial temperature fluctuations, with a peak of 365K at 1.25 m, which underlines the inadequacy of the non-pressurised system in containing heat.

Over the course of 300 s as shown in Figure 10, the pressurised system's air temperature remains remarkably consistent and low, averaging approximately 310K throughout the entire height. Conversely, the air temperature of the non-pressurised system has increased and stabilised at a uniform level of approximately 535K, which is significantly higher. This clearly demonstrates that the staircase pressurisation system effectively maintains a tenable, cool environment over time, whereas a system without a staircase pressurisation system becomes dangerously hot, underscoring its critical safety function.

The most impactful occurred in the time of 600 s. Based on the temperature profile in Figure 11, the air temperature for pressurised system remains consistently low, around 310K, across the entire first-floor staircase height, demonstrating its long-term effectiveness in maintaining safe conditions. On the other hand, the air temperature of non-pressurised system stabilizes at a uniformly high temperature of approximately 538K. In comparison to the 10 s and 300 s data, it underscores that pressurisation is essential for sustaining a viable environment, averting significant heat buildup over prolonged durations in a fire situation.

The comparative analysis demonstrated that the staircase pressurisation system significantly restricted temperature from increases within the staircase, leading to notably lower temperatures and safer conditions for evacuation. Quantitatively, after 600s, the air temperature in the non-pressurised system was approximately 228K higher than in the pressurised scenario. The maximum observed temperature dropped from 538K for non-pressurised to 310K for pressurised system, underscoring the system's effectiveness in reducing heat build-up and thermal injuries. These findings confirm that staircase pressurisation systems are a vital component in fire safety design, reliably ensuring that evacuation routes remain clear and safe.

3.3 Effectiveness of the Pressurisation System

The present CFD study underscores the effectiveness of staircase pressurisation systems in a 3-storey building by analysing local smoke temperature inside the staircase at a 2-meter height of the first floor, 1 m away from the smoke inlet. According to the findings, the non-pressurised system's staircases were easily infiltrated by smoke, resulting in high smoke concentrations and elevated temperatures. This would likely impede the ability of occupants to safely navigate safe evacuation routes. Furthermore, during the 600 s, the non-pressurised system had filled all three 3-story levels of the building model with CO_2. In Figure 8, this is illustrated visually. However, the first-floor office area was the primary location of CO_2 concentration for the pressurised system after the same 600 s period. The first-floor staircase, as well as the second and third floors, were kept free of CO_2.

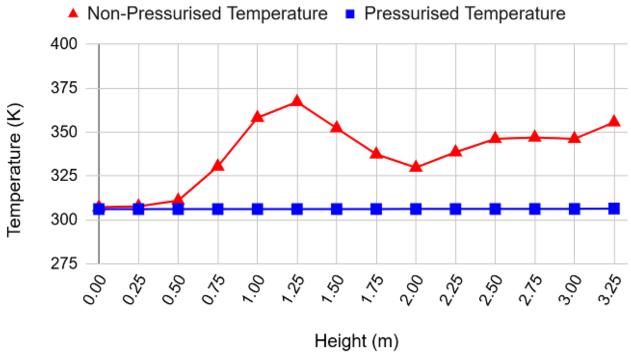


Figure 9. Temperature profile for pressurised system and non-pressurised system at time of 10 s.

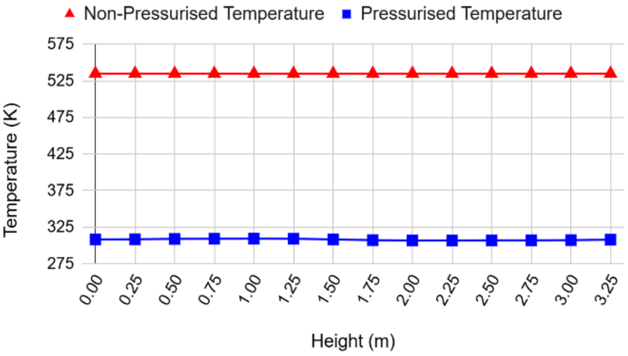


Figure 10. Temperature profile for pressurised system and non-pressurised system at time of 300 s.

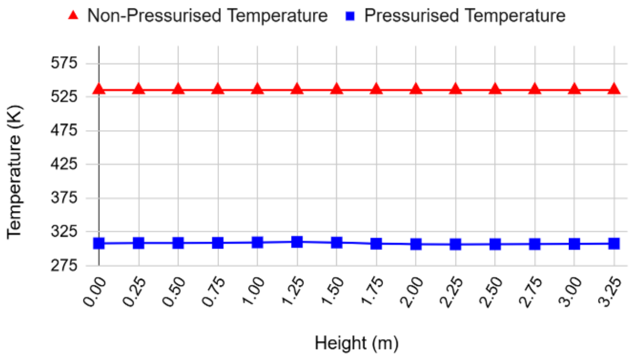


Figure 11. Temperature profile for pressurised system and non-pressurised system at time of 600 s.

Based on Table 6, in the absence of a pressurisation system, the air temperature at a height of 2 m increased markedly and steadily, beginning at around 330K and exceeding 535K within 300 s, maintaining elevated levels thereafter. In contrast, with pressurisation system, the air temperature at a height of 2 m remained remarkably stable and low, fluctuating only slightly around 307K throughout the entire 600 s simulation. This clearly demonstrates the effectiveness of staircase pressurisation in preventing a substantial rise in temperature at a crucial height within the building during a fire.

Table 6. Smoke Temperature at 2-meter height within 600 s.

Time (s)	Temperature (K)	
	Non-Pressurised	Pressurised
10	329.824	306.195
20	368.612	306.788
30	454.595	306.994
60	524.219	307.080
120	533.349	306.994
300	535.077	306.884
600	535.359	306.913

The presented CFD simulations unequivocally demonstrate the critical role of staircase pressurisation systems in enhancing fire safety within multi-storey buildings. The comparative analysis of CO_2 distribution and temperature profiles between non-pressurised and pressurised scenarios reveals a stark contrast in occupant tenability and evacuation viability. In the absence of pressurisation, both smokes, as shown by elevated CO_2 mass fractions, and extreme temperatures quickly permeate the entire building, making evacuation routes impassable within minutes. Conversely, the active pressurisation system effectively contained smoke within the fire-originating floor and maintained consistently low, tenable temperatures (around 310K) within the stairwells. According to international fire safety criteria, safe evacuation is ensured when temperatures remain below 333K (60°C) for at least 10 minutes [29]. In this study, the simulated maximum temperature in the stairwell was around 310K which falls well within tenability thresholds. Furthermore, visibility is a critical evacuation parameter; National Fire Protection Association (NFPA) 92 specifies a minimum clear visibility of 10 m in egress routes [30]. Based on smoke optical density in the CFD results, visibility in the pressurised stairwell exceeded this requirement throughout the simulation as the smoke primarily contained within the first-floor office area. These findings directly translate to extended safe evacuation times and significantly reduced risk of smoke inhalation and thermal injuries for building occupants.

3.4 Novelty, Practical Relevance, and Study Limitations

This study significantly contributes to the field of fire safety engineering, particularly in Malaysian context. Its primary novelty lies in the focused application of high-fidelity CFD simulations to evaluate the performance of staircase pressurisation systems specifically against the requirements of Malaysian Standard MS1472, which requires a 50 Pa differential pressure. Although numerous studies investigate smoke control, there is a scarcity of direct evaluations of CFD models in relation to specific national standards within a localised framework. This research bridges that gap by providing data-driven understanding of how such systems comply with local codes. The findings offer immediate practical relevance for fire safety engineers, architects, and regulatory authorities in Malaysia. They provide concrete evidence supporting the effectiveness of these systems, informing design decisions, aiding in performance-based design approaches, and potentially refining existing fire safety codes to better protect occupants in real-world fire scenarios.

Despite its robust methodology and valuable insights, this study acknowledges certain limitations. The simulations were based on several idealisations, including an ideal fire source with a fixed smoke mass flow rate and adiabatic building surfaces. The omission of furnishings, occupants, and other real-world items was a deliberate simplification to focus the analysis on the fundamental fluid dynamics of smoke and heat propagation, thereby reducing computational complexity and enabling a more direct evaluation of the pressurisation system itself. Furthermore, the simulations were conducted on a specific 3-storey building model, which means that the results may not be directly generalisable to buildings of different heights, complex geometries, or occupancy types without further analysis. The study also acknowledges that its findings are based purely on numerical simulations. While the CFD model was validated against the air leakage requirements of MS1472, direct experimental or real-world field validation of the simulated smoke and temperature distributions would further strengthen the findings of this study. Future research could incorporate such validation to further corroborate CFD predictions and enhance the model's predictive accuracy.

4. CONCLUSION

This study successfully used Computational Fluid Dynamics (CFD) simulations to comprehensively evaluate the effectiveness of staircase pressurisation systems in mitigating smoke and heat propagation in a 3-storey building during a fire. The findings conclusively demonstrate the crucial role of these systems in maintaining safe and tenable conditions within stairwells, which serve as critical evacuation routes.

A stark contrast was observed between non-pressurised and pressurised scenarios in the research. In the absence of a pressurisation system, smoke rapidly infiltrated the entire building within 600 s, as evidenced by the high CO_2 mass fractions. This made all evacuation paths hazardous. Conversely, the pressurised system effectively restricted smoke to the fire-originating floor, thereby guaranteeing that the stairwells and upper floors were clear and safe for egress. It was also found to be highly effective in mitigating temperature. Although the stairwell temperatures reached a hazardous 538K in non-pressurised conditions, the pressurised system consistently maintained them at a safe 310K. This substantial decrease in temperature is essential for the prevention of heat-related injuries and the survival of the occupants.

Furthermore, this study's focused approach on maintaining a 50 Pa differential pressure provides robust evidence of the system's performance under local regulatory requirements, which are consistent with Malaysian Standard MS1472. This work fills a critical gap in the literature by demonstrating the CFD-based assessment of fire safety systems against specific national codes, offering direct practical relevance to Malaysian fire safety engineering and building design practices. In summary, staircase pressurisation systems are essential for improving the safety of buildings by extending the window for safe evacuation by controlling the spread of smoke and maintaining safe temperatures in escape routes. Future research may involve the experimental validation of the CFD model, the investigation of the effects of different fire sizes or building geometries, and the integration of advanced evacuation models.

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DECLARATION OF CONFLICTING INTERESTS

The authors declare no potential conflicts of interest with respect to the research and publication of this article.

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