Numerical Studies on Fire Hazards of Elevator Evacuation in Supertall Buildings

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Submitted: May 2017

Revised: August 2017

Further revised: December 2017

Abstract

Long evacuation time is a key fire safety concern for crowded supertall buildings. Elevator evacuation appears to be the only choice but fire safety provisions are not specially designed in the elevators. A fire safe elevator system was proposed earlier for supertall buildings by providing elevator accessible on each floor level and passing through the refuge place. The fire hazard associated with this design has been studied numerically through an example building in this paper. Smoke spread to the elevator system was considered in the study. The effect of ventilation of the shaft, stack effect and wind effect on smoke movement were studied by empirical equations in fire engineering and justified by Computational Fluid Dynamics (CFD). Different designs of smoke extraction with pressurization system were evaluated by analyzing the smoke dispersion and pressure distributions. The effect of fire at different heights on smoke spread was also investigated. Results show that the smoke extraction system can only delay smoke spread to the elevator shaft near the fire source for a short time. The "four-floor approach" pressurization system can confine the smoke in the area of fire floor for a sufficiently long time period for safe evacuation.

Keywords: elevator; evacuation; supertall buildings; smoke; computational fluid dynamics

Introduction

Buildings taller than 300 m (984 feet) are regarded as supertall buildings by the Council on Tall Buildings and Urban Habitat[1] in the USA. There are many examples all over the world for these types of buildings.[2] The associated fire hazards have been briefly a concern.[3] Long evacuation time has been identified as a primary concern and an important factor for fire rescue when a crowded supertall building is on fire.[3-5] Full evacuation with stairs alone would require a long evacuation time up to 2 hours as reported in some existing supertall buildings.[5] Phased evacuation or the 'stay-in-place' approach by providing with refuge storeys or refuge areas is then commonly adopted. However, if fire safety management is not implemented properly, firemen have to go inside the building to rescue occupants. Further, occupants are no longer willing to accept delayed egress by staying in the building that is on fire after the collapse of the World Trade Center within 3 hours after the start of a 'not too big' fire as reported. Elevator evacuation seems to be a more efficient alternative means and is starting to be adopted for egress and access in many projects all over the world.[6] The elevator system, including the elevator car and lift shaft, can be an effective alternative if it is reliable, accessible and safe during a major fire. Upgrading the fire safety provisions for the elevator system to stand a large fire is an important step to enhance fire safety of supertall buildings.

A fire safe elevator design for emergency evacuation of supertall buildings was proposed earlier by Chow.[7] Each level is proposed to have at least one refuge place with at least 2-hour Fire Resistance Rating (FRR). Lift shaft is located in the refuge place. Fire safe elevator meeting the requirements of fireman's lift[8,9] will go through the refuge place. Associated protection including direct access to a stair with a standpipe, secondary power, protection of wires and cables, real time monitoring, and communications should be included for the elevator. In the traditional way, the elevator can stop at any storey. If the elevator stops at the fire floor, the smoke would easily spread into the elevator shaft and then spread throughout the building. Therefore, in this proposed design, the elevators are controlled to stop only at those storeys with refuge places to avoid the smoke infiltration due to the elevator door opening to a fire storey without refuge places. Surrounded by refuge places, the elevator can be accessible during major fires. Refuge places can protect both the occupants and the elevator from threats caused by uncertainties of changes of HRR at flashover. Occupants can go to the refuge place first and then evacuate through the elevator there. Then taking elevators, all occupants can evacuate from the refuge places to the ground quickly. The performance of this fire safe elevator system has been evaluated in this paper using an example supertall building. Different arrangements of smoke extraction systems and pressurization systems can be applied and evaluated in new projects. Empirical equations on smoke spread are applied with results justified by Computational Fluid Dynamics (CFD).

Elevator Evacuation

Although elevator is normally not an evacuation means, there are lifts for fireman as specified in many codes.[8,9] In the USA, changes to the International Building Code (IBC) on permitting the use of elevators for occupant evacuation in fires were approved by the International Code Council (ICC) based on recommendations from the National Institute of Standards and Technology (NIST), which were derived from its New York City's World Trade Center (WTC) Towers Investigation.[9] The IBC code[9] contains requirements on provisions for Occupant Evacuation Elevators (OEE). Similar requirements on provisions for elevator systems are specified in National Fire Protection Association (NFPA) 5000 Building Construction and Safety Code.[10] ‘Occupant Evacuation’ is distinct from ‘Means of Egress’ and that neither the ICC nor NFPA recognizes elevators as a means of egress or permits elevators to replace the minimum number of exit stairs in a building.

Both commercial and residential buildings in Hong Kong store many combustibles as surveyed. This is likely the case also in many other densely populated regions in the Far East. The high fire load density could cause much larger fires.[11] The heat release rate (HRR) of most post-flashover room fires depends on the ventilation provisions.[12] Under strong wind, the HRR would increase significantly for a supertall building with the same load of combustibles.[13] Windows might be broken during fires in some buildings with high window-to-wall area ratio.

Besides, in some new supertall residential buildings, such as those in Hong Kong, windows can be opened for natural ventilation purpose. Wind speed increases significantly with height. Under wind action, the airflow rate through openings in a room at 800 m high can be three times the value at the ground level. More air would be supplied to burn the fuel and thus give rise to more serious consequences. For example, if there is sufficient fuel, a bigger fire could be risen. The transient HRR with time might change with time due to different wind conditions.[13] The high HRR when flashover occurs would endanger both the occupants and construction elements of the building. Owing to the high occupant loading in the Far East,[14] practices in overseas cannot be applied directly in this region.

Cheng et al.[15] studied the wind flow patterns around a high-rise building with a refuge floor by CFD simulations. The results showed that there was a smoke hazard potential when smoke dispersed from the rear face of the building at a level closely below the refuge floor. Elevator shaft and stairwell shaft-pressurization systems were studied as a means to prevent smoke migration due to stack effect in a 30-storey model residential building. Simulation using the CONTAM software was carried out by Miller and Beasley.[16] Results showed that large pressure differences across the upper-floor elevator doors were found for all cases. However, smoke could spread to the shaft and then to all parts of the building. Black[17] developed a network model for smoke control in a tall structure. The model was applied to study smoke spread in a standard building with 45 floors under a standard fire. Factors affecting the neutral plane height were discussed. Using CFD and software SIMULEX, Lee and Won[18] recently conducted a study of smoke control in a stair shaft of a ten-storey building. The effect of exhaust fans and fire protection curtain was investigated by analyzing toxic gases induced by fire. The results showed that the exhaust fans were capable of reducing the CO mass flux compared with an ordinary staircase without exhaust fans.

However, the above results might only be good for tall buildings of normal heights and not much progress has been made in implementing these in supertall buildings. Moreover, there are few studies on smoke control in elevator shaft for evacuation. In this study, the performance of fire safe elevator combined with refuge places was investigated by CFD simulations, which was validated by empirical equations.

Smoke Control Strategies

Without the protection of refuge place, if a fire breaks out at the floor without refuge place, the smoke would easily spread into the elevator shaft and then spread throughout the building. Under such circumstances, the effects of stack effect and wind action may be serious in the elevator shafts and stairwells in buildings that are very tall.[19] Thus smoke control in supertall buildings should be seriously considered.

As there are no agreed performance indicators available yet, the smoke control strategies would be evaluated by whether all the vertical passages are kept free of smoke for a sufficiently long time.

According to the Hong Kong Code of Practice,[20] a smoke extraction system should be provided for the fire floor. The minimum extraction rate should be equivalent to not less than 8 air changes per hour of the total compartment volume. The minimum supply or make-up air rate should be 80% of the extraction rate. The travel distance for smoke should not be more than 30 m before smoke entering the inlet to the nearest point of the extraction system. At least one extract point should be provided within each 500 m^2 unit of floor area. The smoke exhaust system should be started 60 s after detection of the fire. Pressurization systems[20,21] should be provided for stairwells, lobbies and elevator shafts.

A pressurization approach known as 'four-floor approach' was first proposed in zoned smoke control by Klote and Milke,[21] and was adopted by the Seattle jurisdiction in the USA.[22] In the proposed control method, the primary fire floor, the floor directly above, and two floors immediately below the fire floor should be included for consideration. The pressure differences across the elevator doors on these four floors would be assumed to be within a certain pressure range. This 'four-floor approach' was adopted in the example case and was compared with the multiple injections pressurization system in the following numerical studies.

A method of analysis for a pressurized stairwell in a building without vertical leakage was proposed in the Society of Fire Protection Engineers (SFPE) handbook.[19] The pressure difference between the stairwell and the building, ΔP_{SB}, can be determined by Equation (1) in terms of the pressure difference at the stairwell bottom, ΔP_{SBb}, the distance above the stairwell bottom, y, the flow area (per floor) between the stairwell and the building, A_{SB}, and the flow area (per floor) between the building and the outside, A_{BO}:

$$\Delta P_{SB} = \Delta P_{SBb} + \frac{by}{1+\left(A_{SB}/A_{BO}\right)^2} \tag{1}$$

The parameter b is determined by Equation (2) in terms of the absolute temperature of outside air T_o, the absolute temperature of stairwell air T_i, the atmospheric pressure P, and the specific gas constant for air R as:

$$b = \frac{gP}{R}\left(\frac{1}{T_o} - \frac{1}{T_i}\right) \tag{2}$$

For a stairwell with no leakage directly to the outside, the flow rate (Q) of pressurization air can be determined by Equation (3) in terms of the pressure difference at the stairwell top, ΔP_{SBt}, the number of floors, N and the flow coefficient, C, which is 0.65 for ρ of 1.2 kgm^{-3},

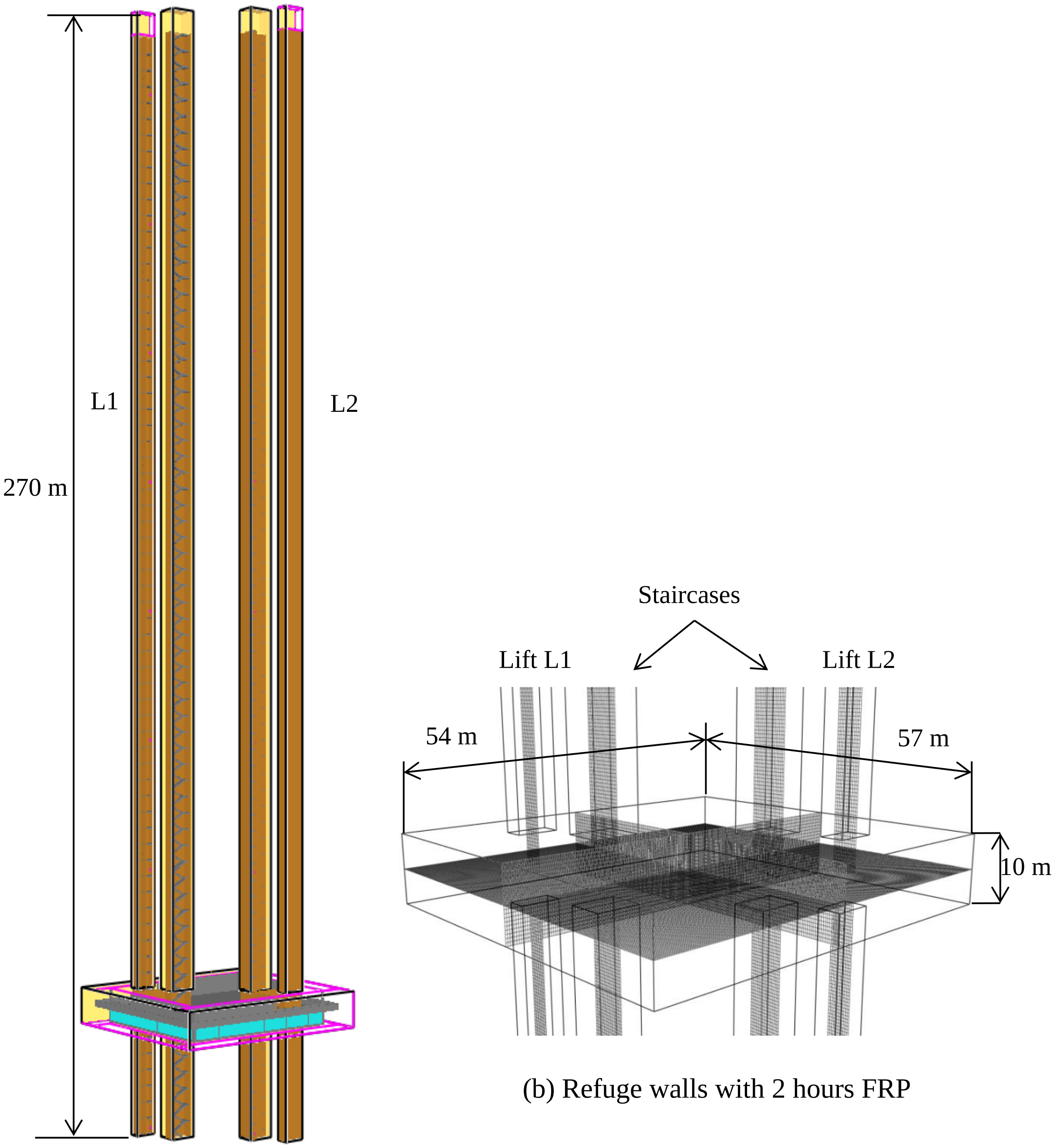
$$Q = \frac{2}{3} NCA_{SB} \sqrt{\frac{2}{\rho}} \left(\frac{\Delta P_{SBt}^{3/2} - \Delta P_{SBb}^{3/2}}{\Delta P_{SBt} - \Delta P_{SBb}} \right) \quad (3)$$

Pressurization for an elevator shaft can be estimated similarly in this way.

In this study, the air flow rate for the pressurization system was calculated using Equation (3), and then different arrangements of smoke extraction and pressurization systems were investigated.

The Example Building for Numerical Study

An example building of height 306 m with 68 storeys was used in this study to illustrate the concept of the design. The CFD software Fire Dynamics Simulator (FDS) version 5.5.3[23] was used for simulations in this study. Each floor was of length 42 m, width 45 m and height 4.5 m. Figure 1(a) shows the side view of the building model. One refuge floor, *one floor with fire below the refuge floor*, and the whole system of fire elevators with lobbies and staircases were included in the model. The building was assumed to contain open-plan offices.



(b) Refuge walls with 2 hours FRP

(a) Typical refuge floor plan of a financial centre

Figure 1: An example case of a supertall building

In our model, there were two fire safe elevators going through the refuge places. Floors with refuge places were located in every eight storeys. Fire safe elevators of length 2.4 m and width 2.4 m with lobbies of length 2.4 m and width 2.4 m were located in the centre of the refuge places. The elevators were controlled to stop only at those storeys with refuge places.

The exterior sides of the refuge places were open to provide adequate cross ventilation. Free boundary conditions were applied to the ventilation vents of lift shafts, and the door cracks link the lift lobbies and refuge place and all the exterior sides of the refuge places. Each refuge place also has an access to a staircase. Assuming a fire resistance period (FRP) of at least 2 hours, the enclosure materials of the elevator shafts and lobbies should be the same as those of the refuge areas.

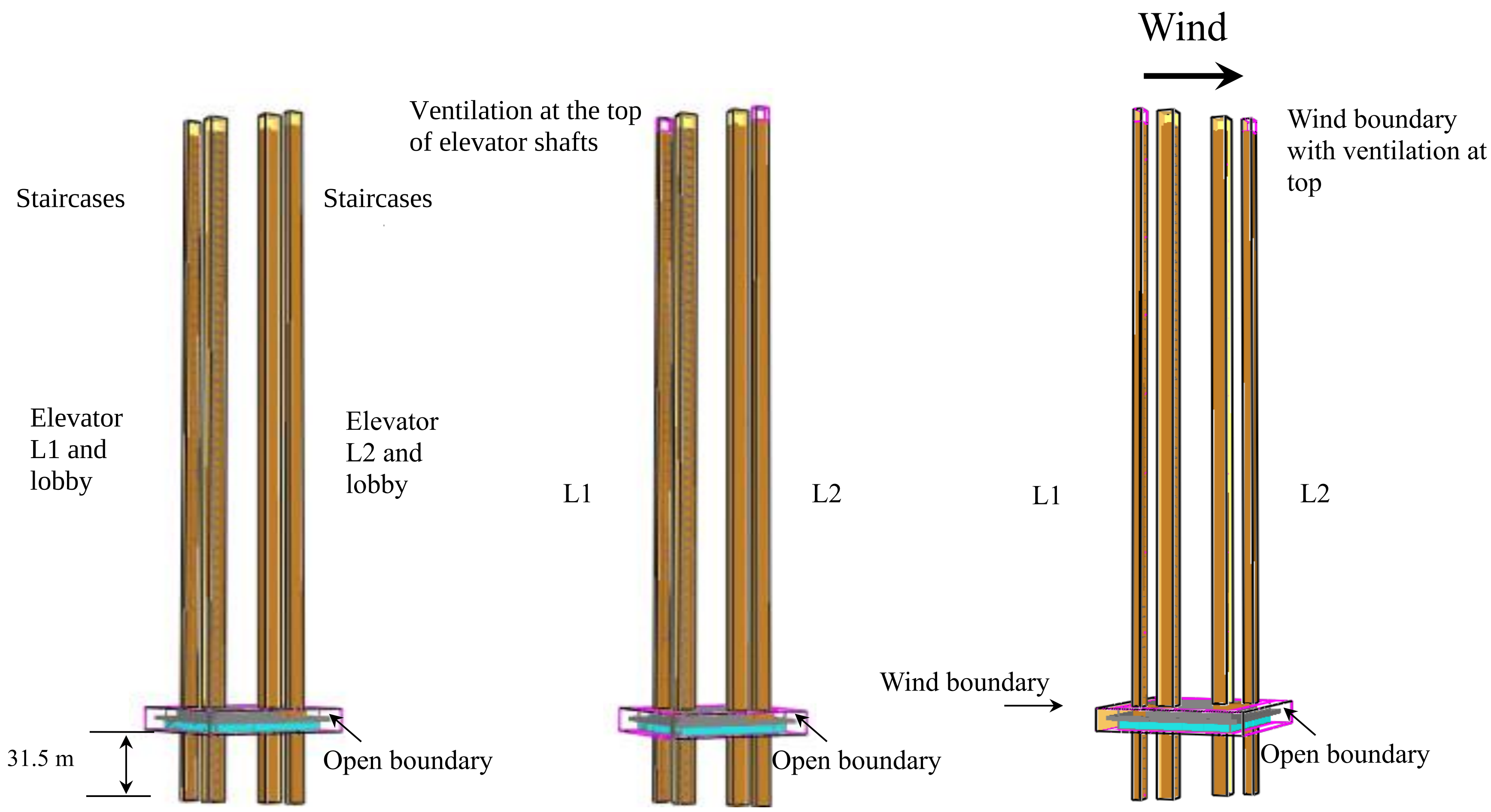
Smoke extraction system for the fire floor and pressurization system for the elevator shafts were studied in the fire scenarios. The multiple injections pressurization system and 'four-floor approach' pressurization system were also investigated.

The piston effect of the moving elevator car is beyond the scope of this paper. The moving elevator car was assumed to have no significant effect on the flow of air through doors and gaps.

Numerical Experiments

The computing domain for the two floors involved was 54 m long, 57.6 m wide and 10 m high in a Cartesian co-ordinate, which was extended to outside the enclosure to capture all movement of air.[24-28] This area comprised a total of 691,200 grid cells each of 0.3 m by 0.3 m by 0.5 m high, as shown in Figure 1(b). Elevator shafts with lobbies were modelled with 250,000 grid cells each of 0.3 m by 0.3 m by 0.5 m high. The staircases were modelled with 300,000 grid cells each of 0.3 m by 0.3 m by 0.5 m high. The total number of grid cells was 1,241,200. Each door was given a one grid size leakage to simulate the door cracks and the openings due to the entry and exit of people. For the door located on the refuge floors, open boundaries were applied to the door cracks.

According to the Code of Practice for Building Works for the Installation and Safe Use of Lifts and Escalators in Hong Kong,[29] openings should be made at the top of a lift well, with a minimum area of 1% of the area of the horizontal cross section of the well (not less than 0.15 m^2 net free area). Three scenarios without fire were first included to study the pressure distribution in the elevator shaft under different ventilation conditions and boundary conditions, as shown in Figure 2.



(a) Scenario NNN (b) Scenario NVN (c) Scenario NVW

Figure 2: Scenarios without fire

- Scenario NNN:

  No ventilation at the top of the shafts, and without wind.

- Scenario NVN:

  Same as scenario NNN, but with ventilation at the top of the shafts.

- Scenario NVW:

  With ventilation at the top of the shafts, and with wind.

Four scenarios with the fire located on the 7th floor (31.5 m above ground level) were simulated in our investigation of the smoke extraction and pressurization systems, as shown in Figure 3. The fire source was placed on the floor below the storey with refuge places, in front of the lobby door of elevator L1. The fire was assumed to be an ultra-fast t^2 fire with a heat release rate of 5 MW.

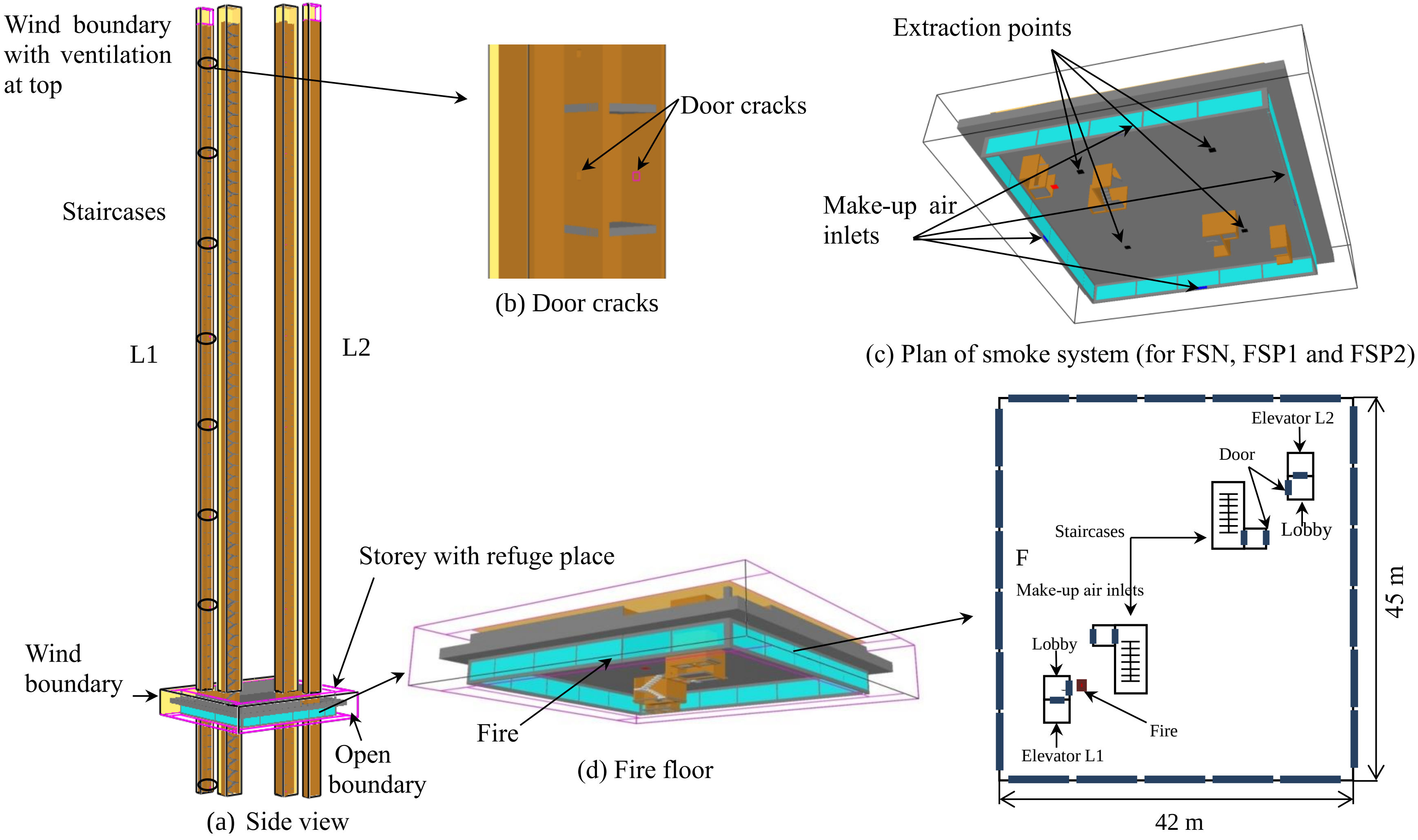


Figure 3: Fire scenarios with fire located on a lower floor

- Scenario FNN:

  Without smoke extraction and pressurization systems.

- Scenario FSN:

  With smoke extraction system on the fire floor, but without pressurization system.

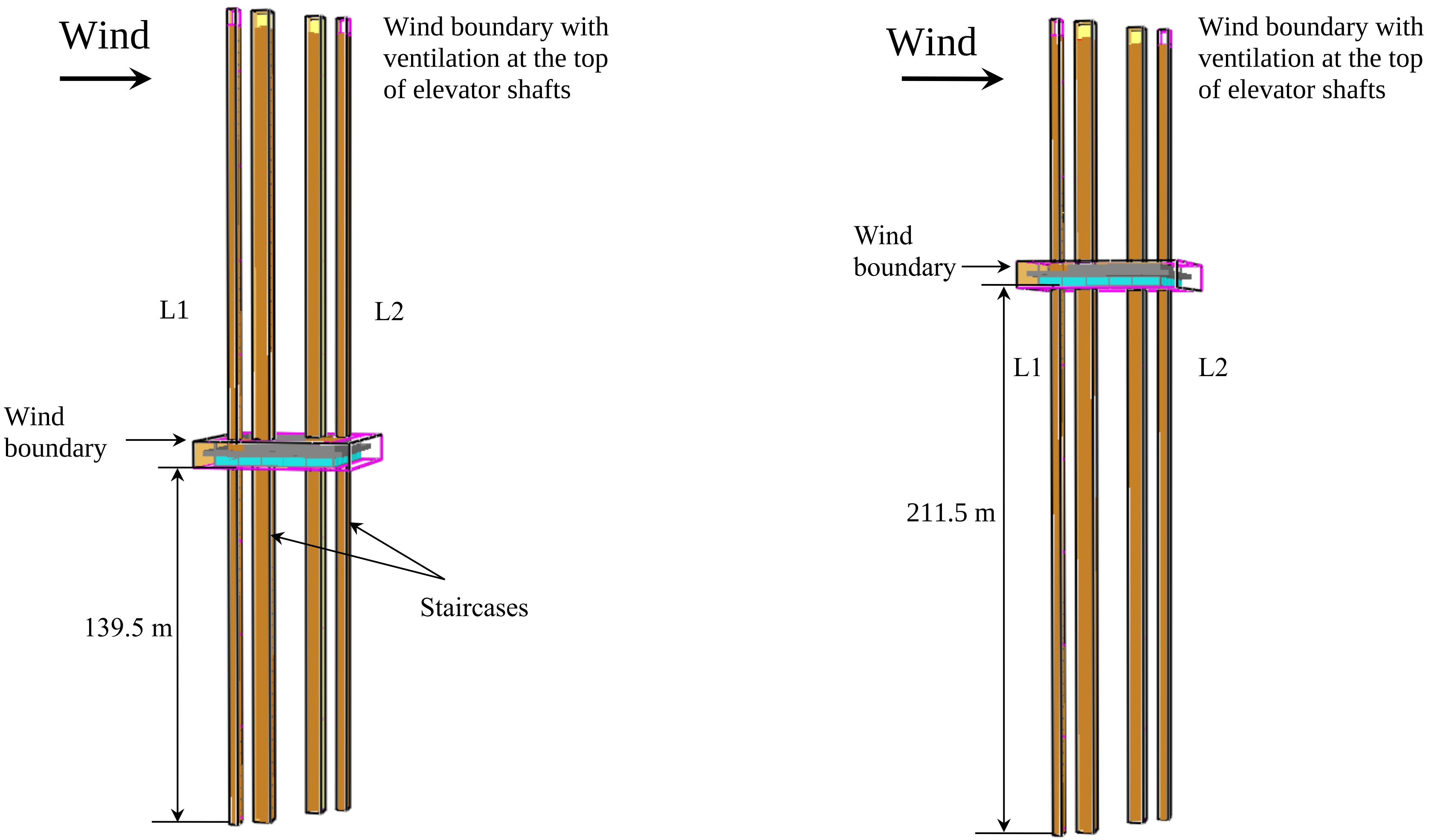
- Scenario FSP1:

  With smoke extraction system on the fire floor, and with pressurization system in the elevator shafts using multiple injection points.

- Scenario FSP2:

  With smoke extraction system on the fire floor, and with pressurization system in the elevator shafts in the way of four-floor approach.

Four scenarios with the fire located on a middle and a high floor were included to investigate the effect of location height of the fire floor, as shown in Figure 4.



(a) Scenarios with fire located on middle floor (MNN and MSP2)

(b) Scenarios with fire located on a higher floor (HNN and HSP2)

Figure 4: Fire scenarios with fire located on a middle floor and a higher floor

- Scenario MNN:

  The fire was located on a middle level at the 31st floor (139.5 m above ground level), and without smoke extraction and pressurization systems.

- Scenario MSP2:

  The fire was located on the 31st floor (139.5 m above ground level), and with smoke extraction system on the fire floor and pressurization system in the elevator shafts in the way of four-floor approach.

- Scenario HNN:

  The fire was located on a high level at the 47th floor (211.5 m above ground level), and without smoke extraction and pressurization systems.

- Scenario HSP2:

  With smoke extraction system on the 47th floor (211.5 m above ground level), and with pressurization system in the elevator shafts in the way of four-floor approach.

Finally, three scenarios with fires of 20 MW located on a low, a middle and a high floor were studied to investigate the effect of large fire.

- Scenario FSP2L:

  The fire of 20 MW was on the 7th floor (31.5 m above ground level), and with smoke extraction system on the fire floor and with pressurization system in the elevator shafts in the way of four-floor approach.

- Scenario MSP2L:

  The fire of 20 MW was located on the 31st floor (139.5 m above ground level), and with smoke extraction system on the fire floor and pressurization system in the elevator shafts in the way of four-floor approach.

- Scenario HSP2L:

  The fire of 20 MW was located on a high level at the 47th floor (211.5 m above ground level), with smoke extraction system and with pressurization system in the elevator shafts in the way of four-floor approach.

All the scenarios are summarized in Table 1.

Table 1 Scenarios for Numerical Simulations

Scenario	Fire Location	Top Ventilation	Smoke Control Strategies
NNN	/	/	/
NVN	/	Y	/
NVW	/	Y with wind	/
FNN	5MW fire on 7th floor	Y	/
FSN	5MW fire on 7th floor	Y	smoke extraction system
FSP1	5MW fire on 7th floor	Y	smoke extraction system and pressurization system using multiple injection points
FSP2	5MW fire on 7th floor	Y	smoke extraction system and pressurization system using four-floor approach
MNN	5MW fire on 31st floor	Y	/
MSP2	5MW fire on 31st floor	Y	smoke extraction system and pressurization system using four-floor approach
HNN	5MW fire on 47th floor	Y	/
HSP2	5MW fire on 47th floor	Y	smoke extraction system and pressurization system using four-floor approach
FSP2L	20MW fire on 7th floor	Y	smoke extraction system and pressurization system using four-floor approach
MSP2L	20MW fire on 31st floor	Y	smoke extraction system and pressurization system using four-floor approach
HSP2L	20MW fire on 47th floor	Y	smoke extraction system and pressurization system using four-floor approach

Scenarios without Fire

Theoretical and numerical studies were first carried out to investigate the pressure distribution in the elevator shaft in scenarios without fire. The effect of ventilation of the shaft, stack effect and wind effect were studied first.

Since the open refuge places are located every eight storeys, the elevator shaft can be considered as a shaft with a continuous opening. The location of the neutral plane Z_n (m) can be determined by Equation (4) in terms of the height of the shaft Z (m), the absolute temperature of air in the shaft T_s (K) and the absolute temperature of outside air T_o (K):[21]

$$Z_n = Z\left(\frac{1}{1+\left(T_s/T_o\right)^{1/3}}\right) \tag{4}$$

If a shaft is ventilated, regardless of whether the vent is above or below the neutral plane, the neutral plane should be located between the height of the neutral plane of an unvented shaft and the vent elevation. The location of the neutral plane can be determined by Equation (5) [21]:

$$\frac{2}{3}A'(Z-Z_n)^{3/2} + A_v(Z_v-Z_n)^{1/2} = \frac{2}{3}A'Z_n^{3/2}\left(T_s/T_o\right)^{1/2} \tag{5}$$

where A' is the area of the opening per unit height (m^2).

Two scenarios were studied first. In scenario NNN, the elevator shaft was not ventilated, air could flow in and out only through the door cracks. In scenario NVN, the elevator shaft was ventilated by one grid size (0.15 m^2) opening on the top. For both scenarios, the outside air temperature was set at 0°C, and the air temperature of the shafts and inside floors was set at 20°C. As the floor plan was symmetric, the pressure distribution of the two elevator shafts should be similar. Therefore, only the numerical results of the shaft of elevator L1 were analyzed in this section. The predicted pressure distributions at the central line of the shaft of elevator L1 are shown in Figure 5. The location of the neutral plane of scenario NVN should be higher than that of scenario NNN. This would be consistent with the theoretical analysis given by Klote and Milke.[21]

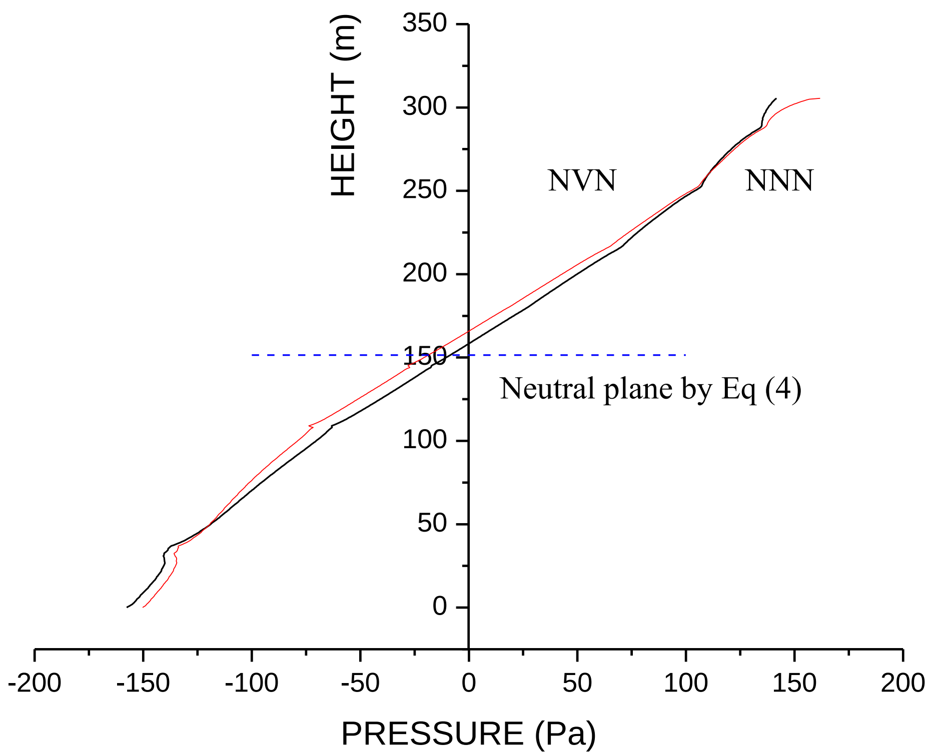


Figure 5: Pressure distributions at the central line of L1 for scenarios NNN and NVN

The theoretical location of the neutral plane for shaft with a continuous opening was calculated by Equation (4) to be 151.5 m. FDS result of the neutral plane location for scenario NNN was calculated to be 158.5 m, with an error of 4.6% compared to theoretical result. The theoretical location of the neutral plane for ventilated shaft was calculated to be 169 m by Equation (5). Corresponding FDS result for scenario NVN was calculated to be 164 m, with an error of 3.0 %.

Openings are required at the top of a lift well in the Hong Kong code.[42] Therefore, in the following cases in this study, all the elevator shafts were ventilated via the top opening of 0.15 m^2 to open air.

To study the wind effect, Scenario NVW was used. A wind profile boundary was put on one side of the computational domain as in Figure 2. In this scenario, the elevator shafts were top vented. Figure 6 shows the pressure distributions at the central line of the shaft of elevator L1 for scenarios NVN and NVW. The effect of wind on both the location of the neutral plane and the vertical pressure distribution in the shaft was insignificant when there was no opening other than door cracks.

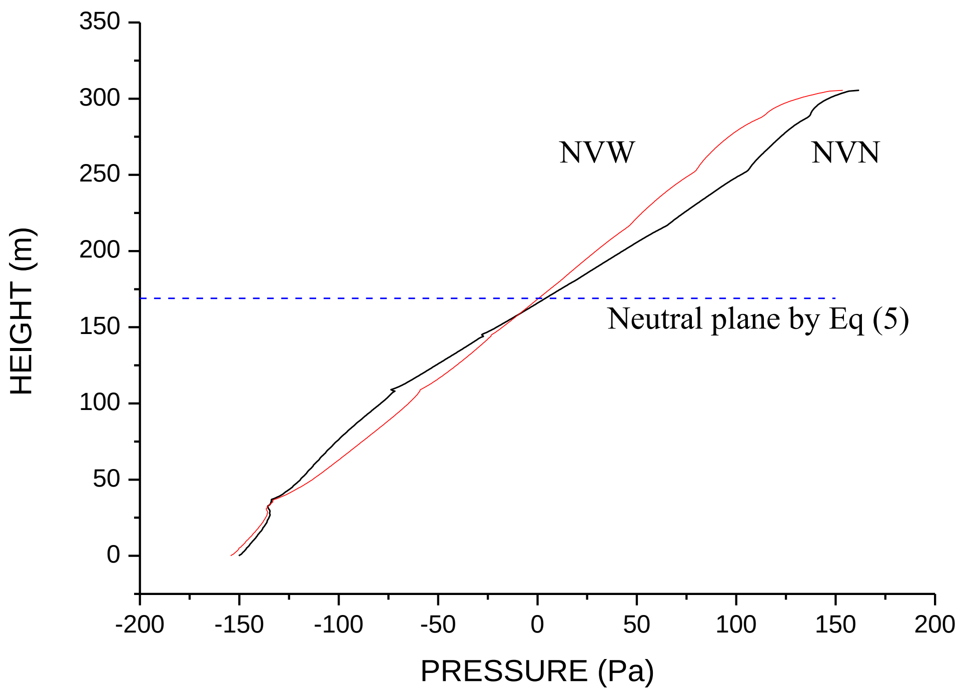


Figure 6: Pressure distributions at the central line of the shaft of elevator L1 in scenarios NVN and NVW

Figure 7 shows the temperature distributions at the central line of the shaft of elevator L1 for scenario NVN at 400 s. Though the initial air temperature of the shaft was assumed to be 20°C, but due to the large amount of cold air flowing into the shaft via door cracks on open refuge places, the temperature in the shaft was dramatically reduced to the outside temperature level. Therefore, without hot smoke entering the shaft, the initial air temperature in the shaft was assumed to be equal to that outside. In the following studies, only the initial air temperature of the fire floor was assumed to be 20°C.

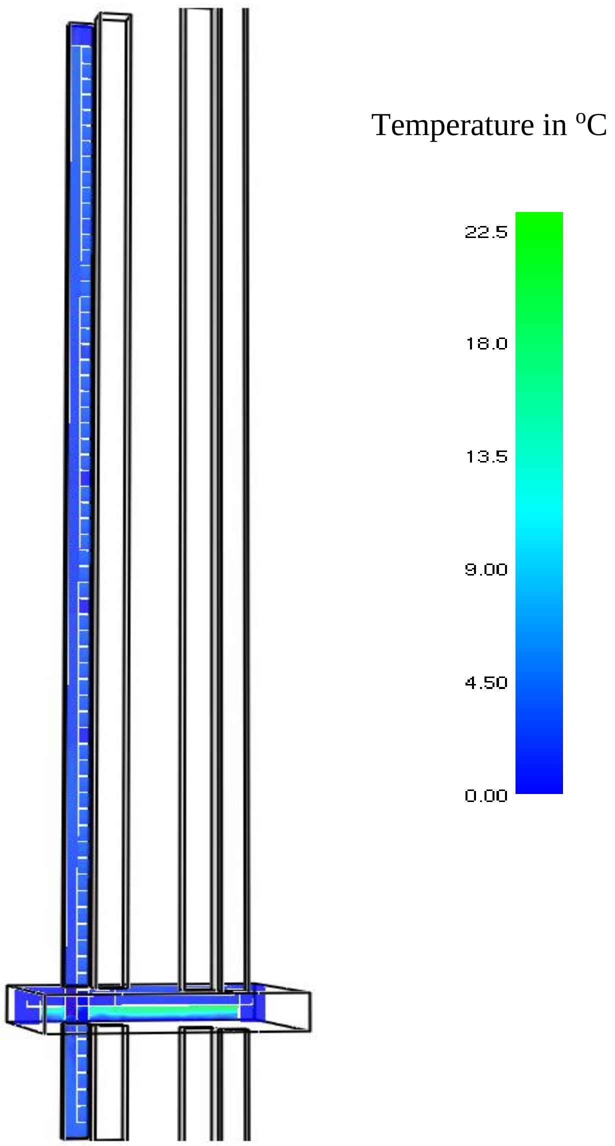
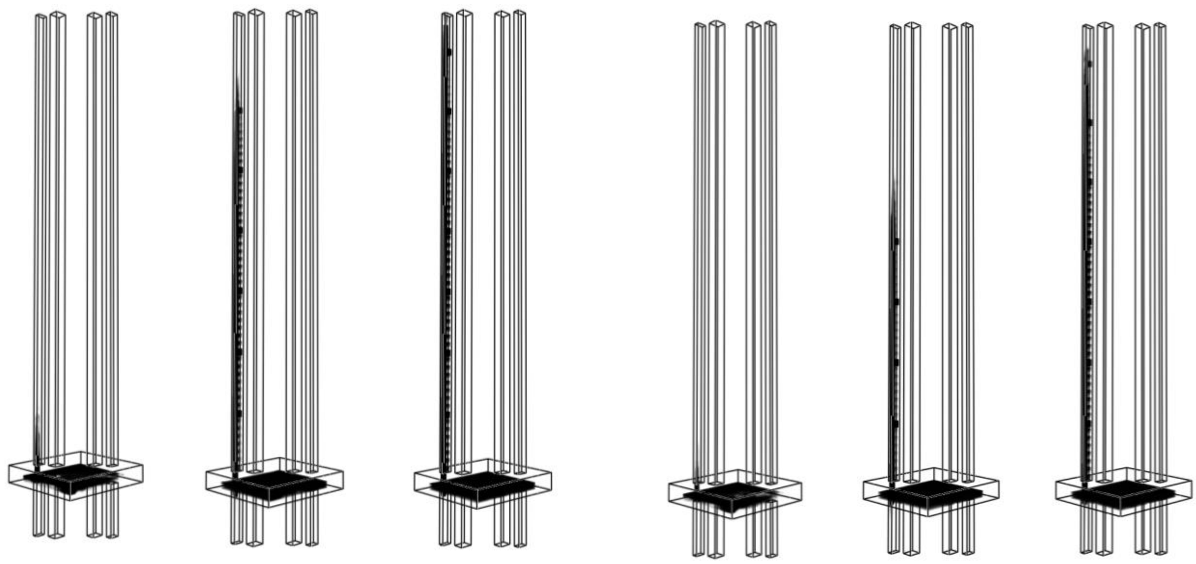


Figure 7: Temperature at the central plane of L1 in scenario NVN at 400 s

Scenarios with Fire

The extraction points of the smoke extraction system were located on the ceiling of the fire floor, and the make-up air inlets were located on the bottom level of walls. For the model building concerned, the volume (42 m by 45 m by 4.5 m) of the fire floor was used to calculate the required extraction rate of 8 air changes per hour (ACH)[20].

Smoke dispersion snaps for scenarios FNN, FSN, FSP1 and FSP2 at fire floor at different times are shown in Figure 8(a) to 8(d). Without ventilation system, the smoke entered the shaft of elevator L1, which was the nearest vertical passage to the fire, and reached the top of the shaft quickly. Although the smoke extraction system could delay smoke dispersion, smoke could still spread fast into the elevator shaft and reached the top of the shaft. In scenario FSP1, though the smoke extraction system with multiple injection pressurization system could keep the elevator shaft free of smoke for a while, smoke began to enter the shaft at 200 s after fire broke out.

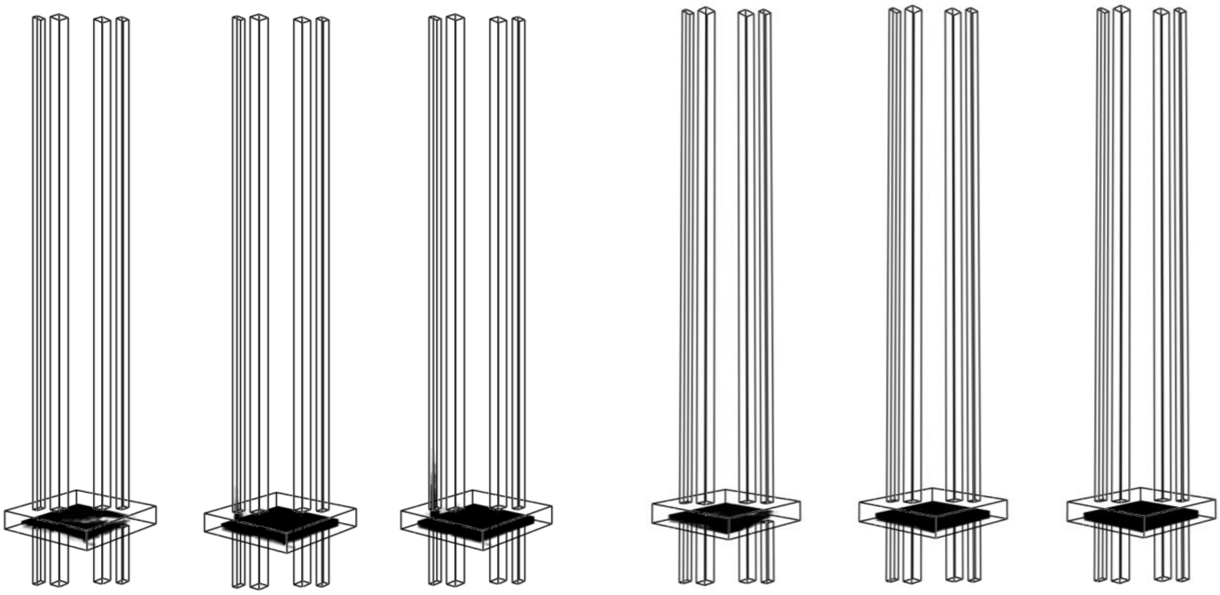


t = 100 s t = 200 s t = 250 s

(a) Scenario FNN

t = 100 s t = 200 s t = 250 s

(b) Scenario FSN



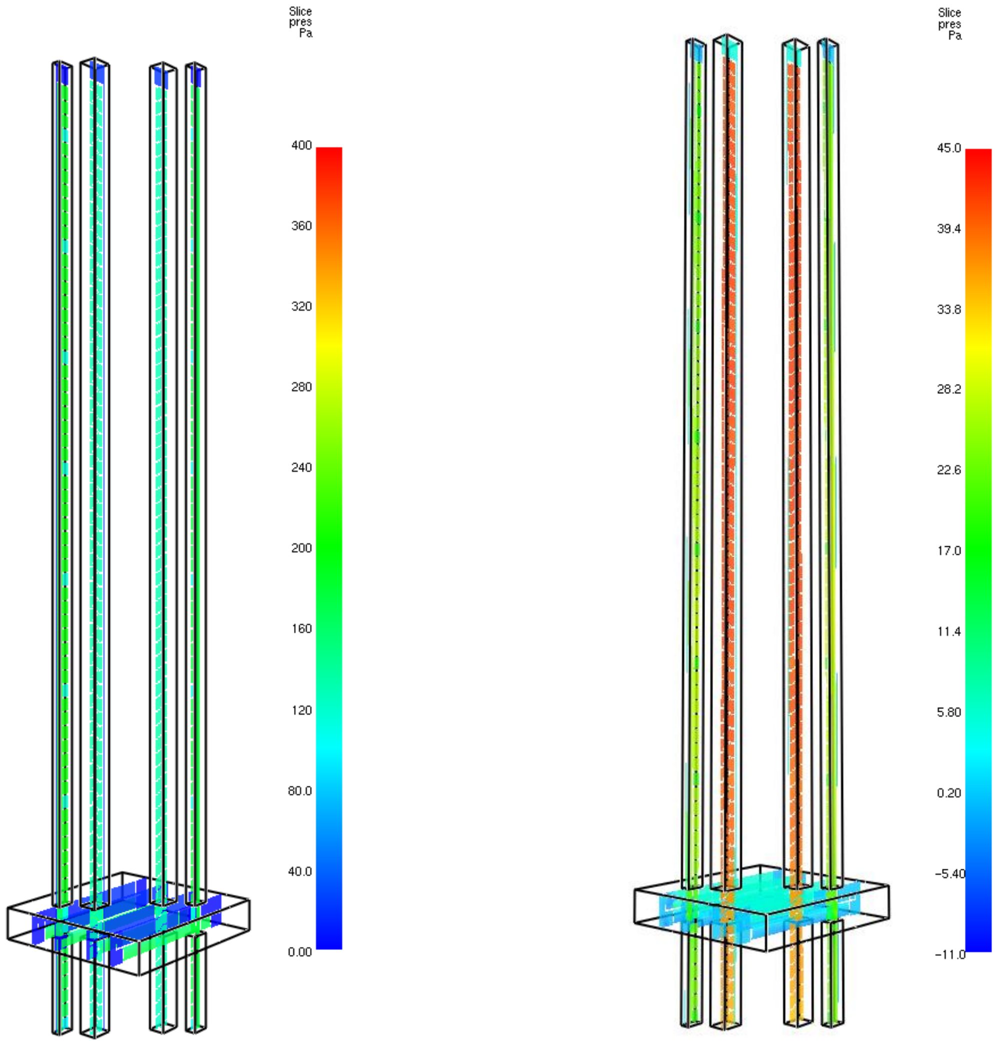
t = 100 s t = 200 s t = 250 s
(c) Scenario FSP1

t = 100 s t = 200 s t = 250 s
(d) Scenario FSP2

Figure 8: Smoke dispersion with fire

Figure 9(a) shows a snap of the pressure distribution in all vertical passages for scenario FSP1. The pressure differentials in both elevator shafts and the fire floor were as high as 240 Pa, although the flow rates of the pressurization system were calculated using a pressure difference of 25 Pa. This phenomenon is consistent with studies by Miller and Beasley.[16] This is because the large amount of pressurized air flows into elevator shafts was required due to the relatively large door leakages. These pressurized elevator air flows exited the shaft and entered the fire floor which also resulted in strong interactions with the smoke extraction system and stairwell pressurization system. In scenario FSP2, relatively large amount of pressurized air flow rates were required for the injection points located in shafts on four fire affected floors, including the fire floor, the floor above with refuge places and two floors below the fire floor. As shown in Figure 8(d), smoke was confined in the area of the fire floor. All the vertical passages, including elevator shafts and stairwells, were kept free of smoke for as long as 1200 s (20 min) when the simulation was stopped manually. The pressure distribution are shown in Figure 9(b).

No over pressurization was observed. Positive pressure differentials of 25 Pa and 45 Pa were kept in the elevator shafts and stairwells respectively. Among these four scenarios above, the way of smoke control adopted in scenario FSP2 yielded the best results.

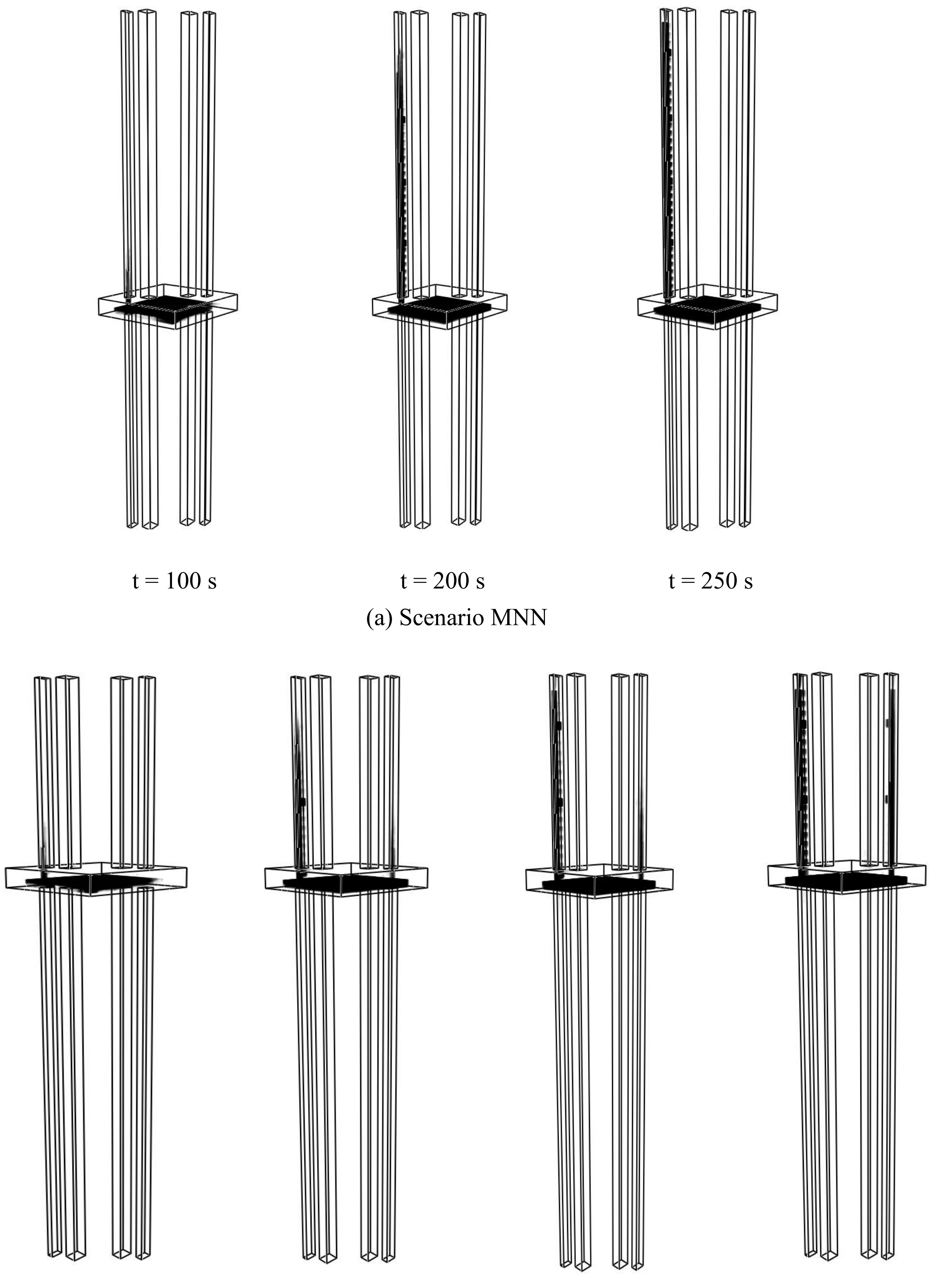


(a) Scenario FSP1 (b) Scenario FSP2

Figure 9: Pressure distribution in vertical passages at 250 s

Without ventilation system, scenario MNN with fire located on a middle level at the 31st floor (139.5 m above ground level), which was near the mid-height of the building and scenario HNN with fire located on a high level at the 47th floor (211.5 m above ground level), were studied first. Then, with the same smoke extraction and pressurization systems as those in scenario FSP2, scenarios MSP2 and HSP2 were studied to investigate the efficiency of smoke control.

Figure 10(a) and 10(b) show the smoke dispersion in scenarios MNN and HNN. In scenario MNN, the smoke entered the L1 shaft and quickly reached the top of the shaft as in scenario FNN. However, a different smoke dispersion pattern was observed in scenario HNN. Smoke not only entered the L1 shaft but also the L2 shaft before the smoke in L1 shaft reached the top. At 600 s, both parts of elevator shafts above the fire floor were full of smoke. The pressure distribution in L1 shaft in scenarios MNN and HNN are shown in Figure 11. The pressure distributions at the central line of the shaft of elevator L1 in scenarios FNN, MNN and HNN are shown in Figure 12. The higher the fire located in the building, the higher the neutral plane of the L1 elevator shaft and the lower the pressure at the top of the L1 elevator shaft. Compared to scenarios FNN and MNN, relatively small amount of smoke entering the L1 shaft would cause a weak stack effect in L1 shaft for scenario HNN. Smoke from the fire floor would then enter the L2 shaft and contaminated the part of the L2 shaft above the fire floor.



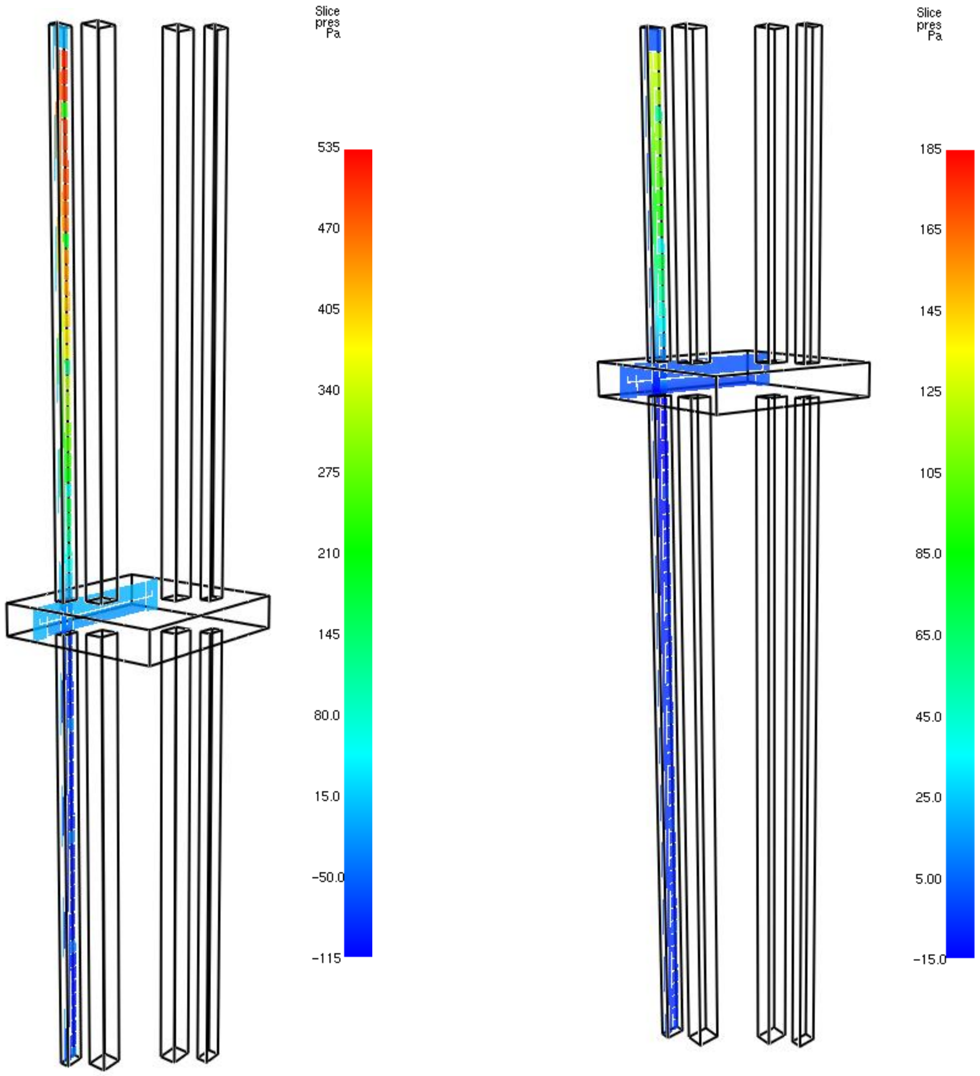
t = 100 s t = 200 s t = 250 s

(a) Scenario MNN

t = 100 s t = 200 s t = 250 s t = 600 s

(b) Scenario HNN

Figure 10: Smoke dispersion in scenarios MNN and HNN



(a) Scenario MNN (b) Scenario HNN

Figure 11: Pressure distribution in L1 shaft at 250 s

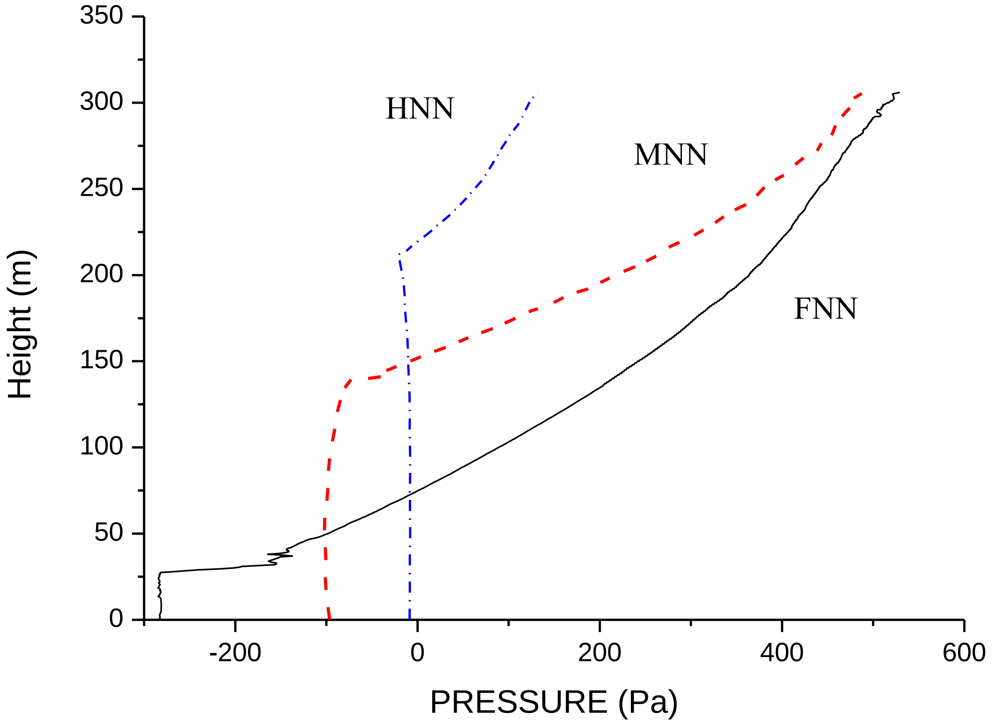
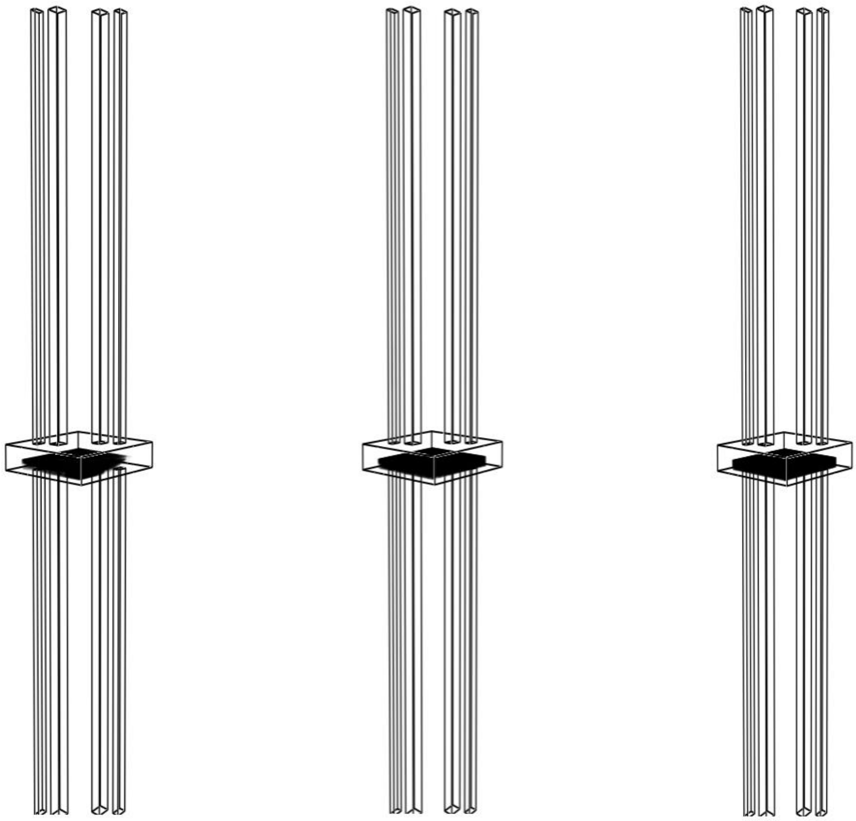


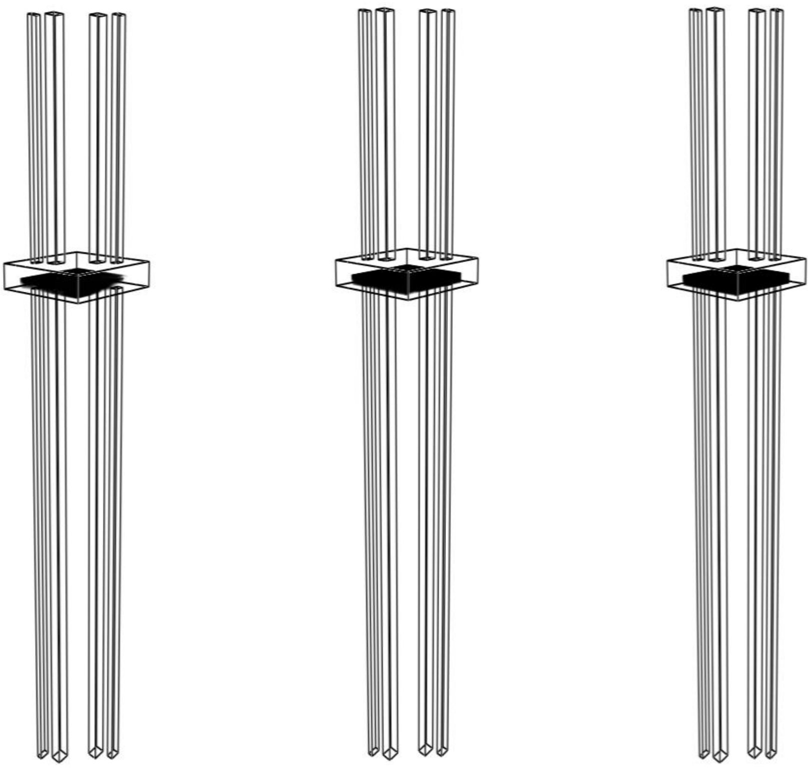
Figure 12: Pressure distributions at the central line of L1 in scenarios FNN, MNN and HNN

Using pressurization in a similar way as in FSP2, the smoke could be confined in the area of the fire floor for both scenarios MSP2 and HSP2, as shown in Figure 13(a) and 13(b). All the vertical passages were free of smoke for as long as 1200 s (20 min) when the simulation was stopped manually. The vertical slices of pressure distribution are shown in Figure 14. Positive pressure differentials around 25 Pa and 45 Pa were kept in the elevator shafts and stairwells respectively.



t = 100 s t = 200 s t = 1200 s

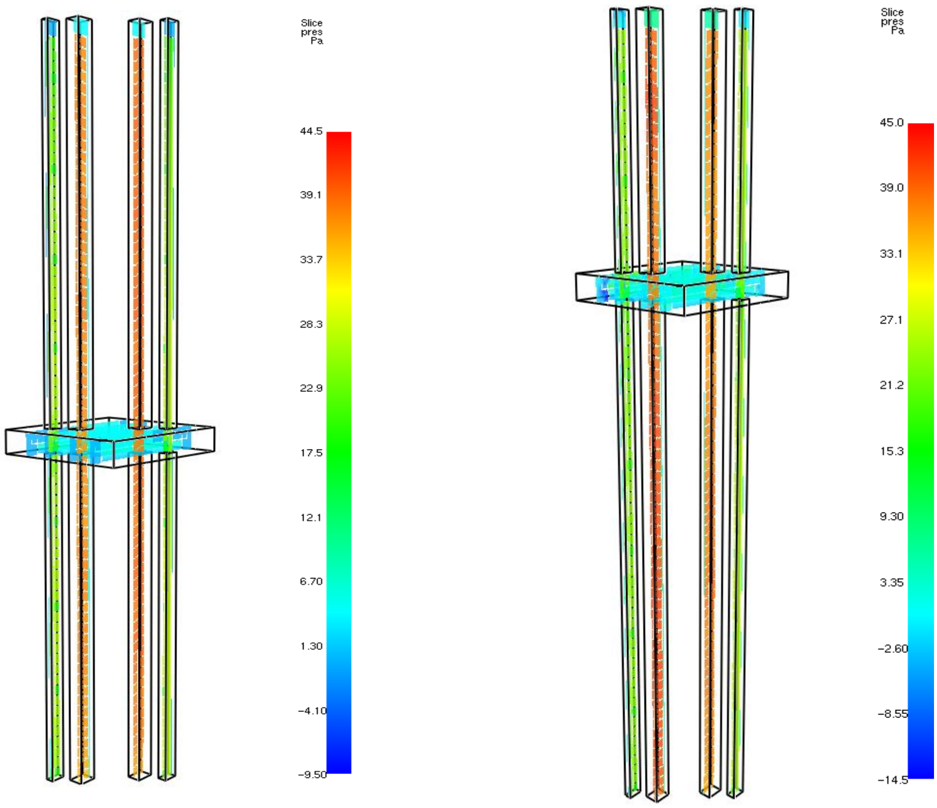
(a) Scenario FSP2



t = 100 s t = 200 s t = 1200 s

(a) Scenario HSP2

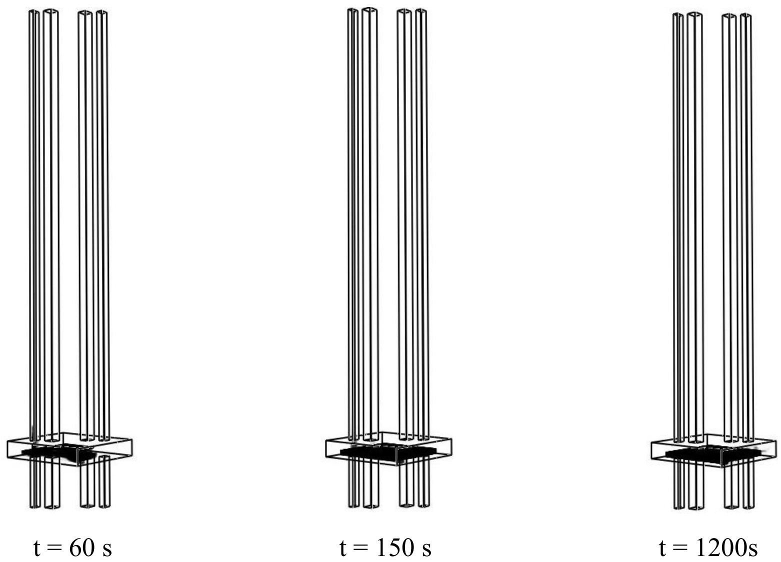
Figure 13: Smoke dispersion in scenarios FSP2 and HSP2



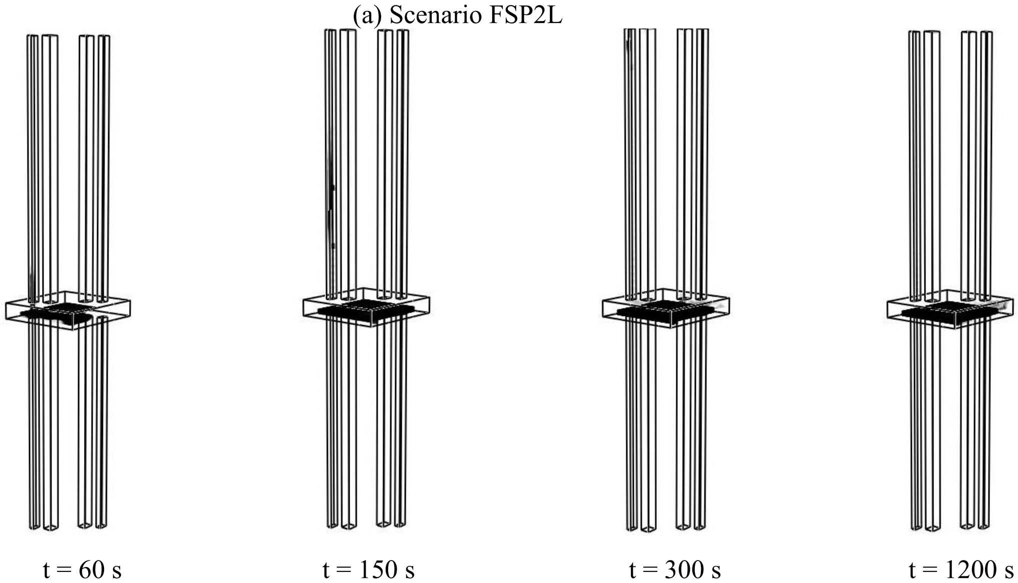
(a) Scenario FSP1 (b) Scenario FSP2

Figure 14: Pressure distribution in vertical passages at 600 s

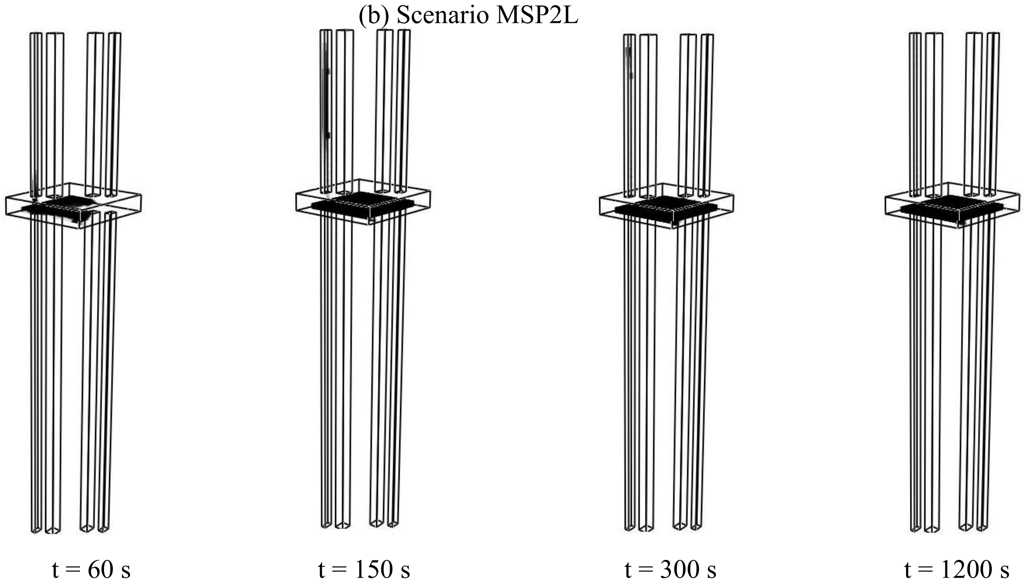
A large fire of 20 MW was used to investigate the effect of fire size. Figure 15 shows the smoke dispersion when the large fire was placed on different heights with the presence of the smoke extraction and pressurization system. In all scenarios, there was smoke in the lift shaft 60 s after the fire was broken out. The extraction system was activated at 60 s, the smoke in the lift shaft was being extracted either from the fire floor for scenario FSP2L or the top of the shaft in the scenarios MSP2L and HSP2L. When the fire was in the lower floor, smoke was extracted from the lift shaft to the fire floor, and all the smoke could be confined in the fire floor. The smoke in the shaft went out from the top of the shafts when the fire was in the middle floor or higher floor, and the rest of the smoke was confined in the fire floor. All vertical passages were found to be free of smoke for as long as 1200 s. Positive pressure differentials around 65 Pa and 35 Pa were kept in the vertical passages in all three scenarios as shown in Figure 16. The pressure differentials in cases of large fire are a little bit higher than those in cases of small fire.



(a) Scenario FSP2L

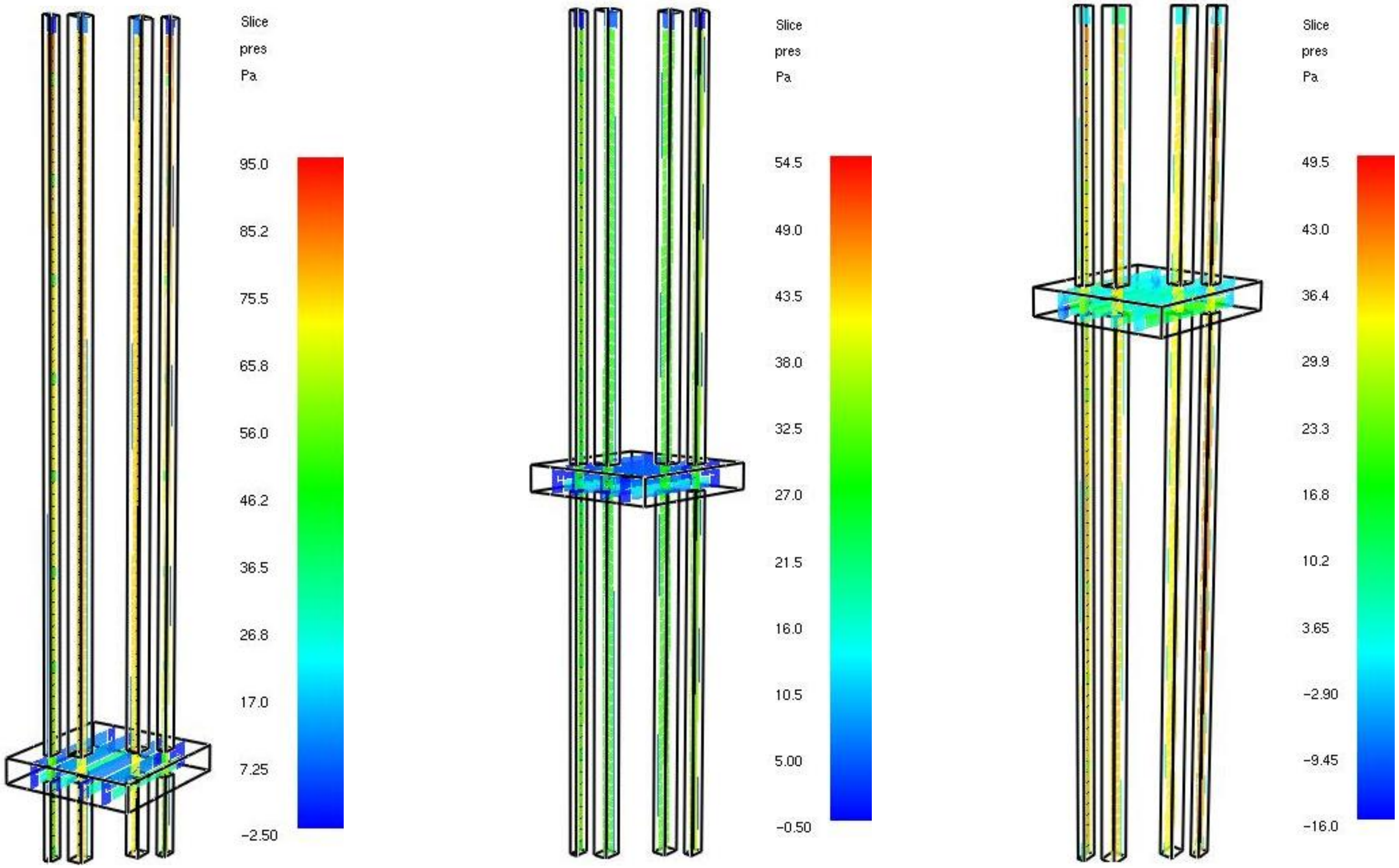


(b) Scenario MSP2L



(c) Scenario HSP2L

Figure 15: Smoke dispersion with large fire



(a) Scenario FSP2L (b) Scenario MSP2L (c) Scenario HSP2L

Figure 16: Pressure distribution in vertical passages at 500 s

Conclusions

The performance of a fire safe elevator system consisting of fire safe elevators and refuge places for emergency evacuation of supertall buildings was evaluated for various scenarios in this study. This design combines the refuge place with fire safe elevator was used for evacuation. Smoke spread from the fire breaking out at other storeys without refuge places was considered. Numerical studies were carried out to study smoke spread in this proposed elevator system:

- For cases without fires, FDS predictions agree with empirical equations that estimated the location of neutral plane and the vertical pressure distributions in the elevator shaft.
- In fire scenarios, the smoke extraction system would delay smoke spread to the elevator shaft near the fire source, but not for a long time.
- Although smoke extraction system with multiple injection pressurization system could keep the elevator shaft free of smoke for a while, overpressure cannot be ignored, which might eventually result in smoke control failure. The 'four-floor approach' of pressurization, which targets the primary fire floor, the floor directly above, and two floors immediately below the fire floor, can confine the smoke in the area of fire floor and keep all vertical passages free of smoke for a sufficiently long time, at least for 20 minutes in this case. This 'four-floor approach' pressurization system is an efficient way for smoke control for elevator shafts in supertall buildings.

Upgrading the fire safety provisions for the elevator system in supertall buildings to withstand a large fire is necessary. Smoke control system for the elevator system in supertall buildings should be evaluated carefully on a case-by-case basis. Further works should be carried out to investigate appropriate evacuation strategy and effects of different age and sex groups of occupants and their familiarity with the evacuation route in evacuation. More experiments on different types of fuels need to be conducted, and further justifications of the CFD predicted results are recommended.

Funding

The work described in this paper was fully supported by a grant from the Research Grants Council of the Hong Kong Special Administrative Region, China for the project "A study on explosion hazards of clean refrigerant propane leaking from air-conditioning units in small commercial flats" (Project No. PolyU 15203414) with account number B-Q42U.

Declaration

The authors declare that there is no conflict of interest.

Both authors contributed equally to this manuscript.

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