NUMERICAL STUDIES ON STAIRWELL SMOKE MOVEMENT INDUCED BY AN ADJOINING COMPARTMENT FIRE

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ABSTRACT

Compartment fire smoke movement in an adjoining six-storey stairwell and its dynamics behavior are investigated using the Fire Dynamics Simulator (Version 4.07). Smoke temperature and velocity field are analyzed. Longitudinal distribution interior pressure in stairwell is researched, and location of neutral plane is also surveyed. It is found that smoke temperature decreases distinctly with the height in stairwell, yet the maximum temperature does not exist in the lower grand-level due to air supply. The neutral plane ascended with time and the relation of interior pressure with height fit logarithm well. And meanwhile, the heat release rate has obvious effect on distributions of smoke temperature and velocity. The maximal smoke temperature in stairwell ranged from 87.6^{o}C to 130.3^{o}C under HRR from 500 kW to 1000 kW respectively.

KEYWORDS: Fire-induced flow, Vortices, Stairwell, Neutral plane, Stack effect

INTRODUCTION

Stairwell is the connection of different floors of building, which can be an important vertical travel pathway for occupants and smoke under fire. The smoke's vertical spread can be accelerated due to stack effect, which also enhances fire development and air supply. Consequently, the stairwell plays an important role in heat and mass transfer and the control of contaminants in the interior of buildings, which attracts a growing international interest.

A number of studies related to these phenomena have been reported. With a special geometrical size, the vertical air movement occurring in stairwells is one of the most important mechanisms of interzone transfer in the interior of buildings. Thermal buoyancy is one of the factors that induce such flow processes, especially in naturally ventilated buildings. The importance of the temperature effect on these phenomena has been indicated in studies performed in a multi-storey real building[1]. Zohrabian et al.[2] conducted experimental study of buoyancy-driven flows of mass and energy in a half-scale model of a stairwell. The reduced scale stairwell model formed a closed system, within which the circulation of air is maintained by the continuous operation of a heater placed in the lower floor. The overall features of the flow were also described. The results included the velocity and temperature distributions and the circulating volume flow. The effects of heat input rate on these parameters were also discussed. Their own finite-volume programs were used to predict the two-dimensional buoyancy-driven flow in a stairwell model. Klobut and Siren[3] carried out laboratory experiments to explore the influence of several parameters on combined forced and density-driven air flows through large openings in a horizontal partition. The two-way flows in the opening were monitored using a tracer gas technique. They investigated variable parameters including the direction and rate of the net flow, the temperature difference between the zones, and the dimensions of the large opening. Reynolds[4] conducted experiments in a one-half scale model of a typical stairwell to define the influence of a Reynolds number characteristic of the flow. He investigated the air flow through an inclined channel connecting the two compartments of the model. Mass and heat flow rates driven by heater source were estimated from the measurements of air temperature and air velocity at various cross-sections of the model. Reynolds and Mokhtarzadeh-Dehghan[5] carried out an earlier investigation of scale effects on buoyancy-driven recirculating flows in stairwells of the kind adopted in domestic accommodation. A technique was developed to introduce explicitly the fraction defining the way in which the energy loss from the system was divided between the regions above and below the stairway. Furthermore, they also extracted a mathematical model for the phenomenon by applying dimensional analysis, in which it was shown that a single empirical constant suffices to complete relationships among key of the processes of heat and mass transfer. Further consideration was given to the role Reynolds number, which proved to have unexpected features. Ergin-Ozkan et al. [6] conducted a similar numerical study of three-dimensional buoyancy-driven flow in a stairwell and compared predictions with experimental data. Riffat and Shao[7] performed a study concerned with CFD modeling of natural convection through a horizontal opening between two zones. A simplified geometry was chosen for the numerical analysis of only one case, due to the lack of information regarding boundary conditions. Comparison of the predicted air flow rate and that based on experimental measurement showed good agreement, with a relative difference of 10.5%. Qin et. al.[8,9] studied the smoke movement and ambient airflow in a stairwell under fire scenarios using large eddy simulation. Numerical investigation was performed on a typical two-storey confined stairwell, with an open door on the top floor and a fire source on the ground floor. Results showed the existence of fairly distinct layers of hot smoke and ambient air under different fire scenarios. It was found that heat release rate had a remarkable effect on distributions of smoke temperature, velocity and oxygen concentration. Peppes et al.[10] conducted a series of experiments in order to study the coupled flows of mass and heat between the three floors of a full-scale residential building in which buoyancy-driven air flow through a stairwell occurred. A single tracer gas decay technique was adopted. Air flow rates through the specific stairwell were estimated using the computational fluid dynamics (CFD) method. These rates showed very good agreement with the corresponding values provided by the formulas, proposed in an earlier study. The objectives of these above-mentioned works were to study the buoyancy-driven air movement through a typical stairwell that connected the two floors of a full-scale building, to compute the heat and mass transfer between the interconnected floors, to analyze this situation using CFD and compare the predicted and measured values, to consequently improve the existing predictive methods of such processes.

It is worth noticing that almost all the prior studies referred to experimental and numerical work carried out in small-scale geometries. The aim of this work is to develop more accurate descriptions with confined multi-storey for the estimation of smoke flow induced by buoyancy in a close stairwell, by focusing on the impact of several parameters on the phenomenon, such as smoke temperature, upward spread velocity, and interior pressure distribution.

NUMERICAL METHOD

Brief Introduction of the FDS Procedure

In the stairwell, fire-induced smoke movement is a compressible physical phenomenon. The speed of smoke flow is much slower than the speed of sound. Therefore the movement of smoke is considered as flow with low Mach number. Meanwhile, an approximate form of the Navier-Stokes equations appropriate for low Mach number applications is used in the hydrodynamic model in Fire Dynamics Simulator[11]. The approximation involves the filtering out of acoustic waves while allowing for large variations in temperature and density.

Grid and Mesh

The computational domain is a six-storey stairwell with an adjacent room. The stairwell has a base of 2.5 m (x-axis) by 5.5 m (y-axis) and extends to a height of 29 m, and the adjacent room has a dimension of 2.0 m (x-axis) × 4.0 m (y-axis) × 3.0 m (z-axis) with windows on its side walls. A schematic diagram of the building is presented in Fig. 1. An orthogonal, equally spaced grid system with a cell 0.3 m × 0.3 m × 0.3 m is used. Scalar quantities are assigned at the centre of each grid cell while vector quantities at the cell faces. All spatial derivatives are approximated by second-order central differences and flow variables are updated in time using an explicit second-order Runge-Kutta scheme, with the time step appropriately determined by the CFL condition.

The ambient temperature is 20°C and the initial velocity is 0 m/s in the simulation.

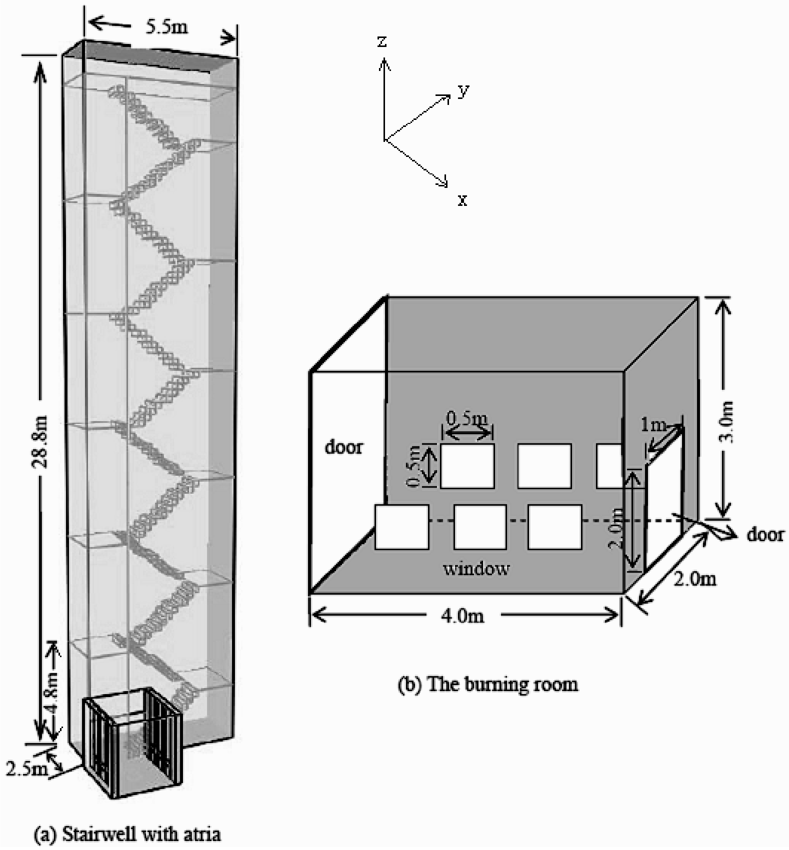


FIGURE 1. Schematic diagram of a typical six-storey stairwell with room

Design Fire

During the simulation, the fuel is kerosene and six different power fires are utilized. According to the experimental results of the combustion process, the fires are designed as three stages. Firstly, the fire sharply increases to a stable situation with great HRR, and then keeps the steady value for a period, and lastly the HRR of the fire source gradually decrease as shown in Fig. 2.

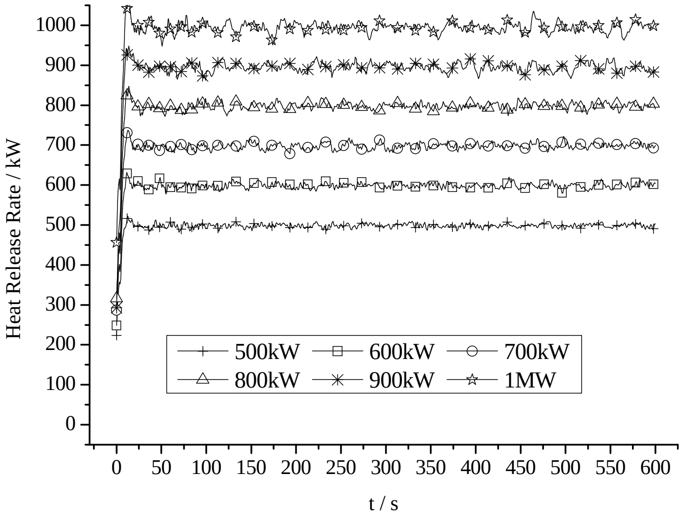
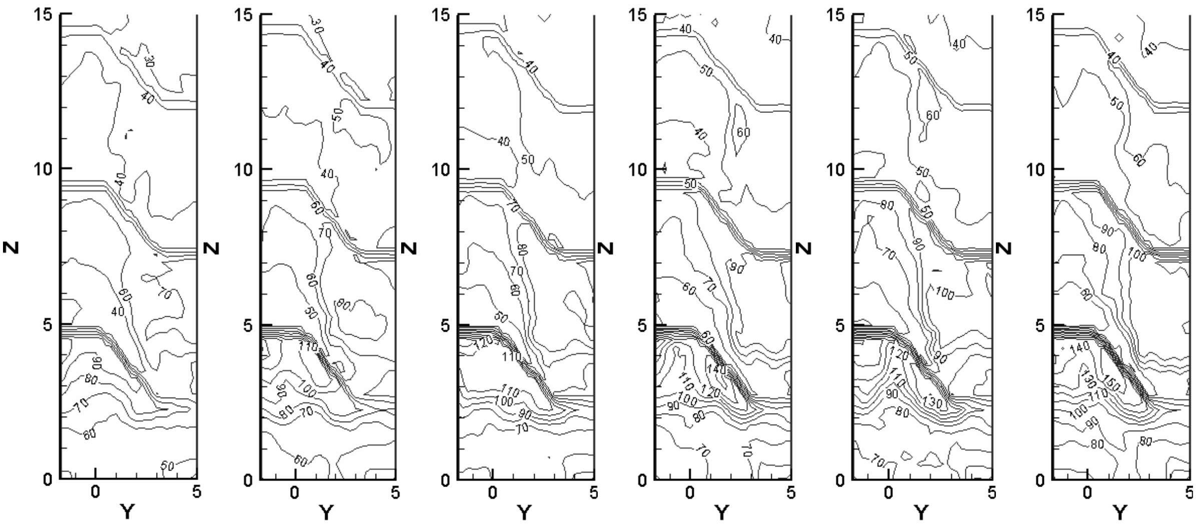


FIGURE 2. Fire scenarios designed for simulation

RESULTS AND DISCUSSION

Temperature Field

As time-dependent simulations proceeded, the mass and heat transfer between the six floors caused variations in smoke temperature and velocity distribution. Fig. 3 shows the smoke temperature field at different heat release rate at 300s (x = 0.5 m). In each floor, the upper-layer temperature near the upside floor is higher than the corresponding one of the lower part. The higher is the floor, the less is the temperature difference between the upper and lower zones, which obviously affect the size of eddies formed in each floor.



(a) (b) (c) (d) (e) (f)

FIGURE 3. Isotherms of smoke within the first three floors at (a) HRR = 500 kW; (b) HRR = 600 kW; (c) HRR = 700 kW; (d) HRR = 800 kW, (e) HRR = 900 kW; (f) HRR = 1 MW, t = 300 s

With the time proceeding, the temperature gradually increases to a steady value in correspondence with the design fire curve, and the temperature increases with height in the stairwell on the whole (Fig. 4), except that the highest one is not in the lowest grand but in a higher level of the first floor due to air supply. As shown in Fig. 5, as a result of fresh air supply, the lower zone of the first floor is filled with cooler air which cools down and dilutes the smoke, so that the maximal temperature is not in the first thermal-couple at 1.2 m but in the second one at 2.4 m (Fig. 4). The tendency of the temperature is in accordant to experimental results by Peppes[10] in his three-storey configuration.

Smoke Flow in Stairwell

The close stairwell has a complex geometry and instruments, so that the temperature field in the stairwell is strongly affected by these instruments, which together determine the velocity distribution in the stairwell. Fig. 6 shows the vertical component of smoke velocity (W) obtained from these simulations. The velocity curves indicate that the vertical components of smoke velocity increase to a peak value in the third floor (at the level z = 12.6 m in Fig. 6), this is attribute to a greater temperature gap between the upper and lower zone of the floor which show very good agreements with the big temperature gaps between the levels z = 10.8 m and z = 13.2 m in Fig. 4.

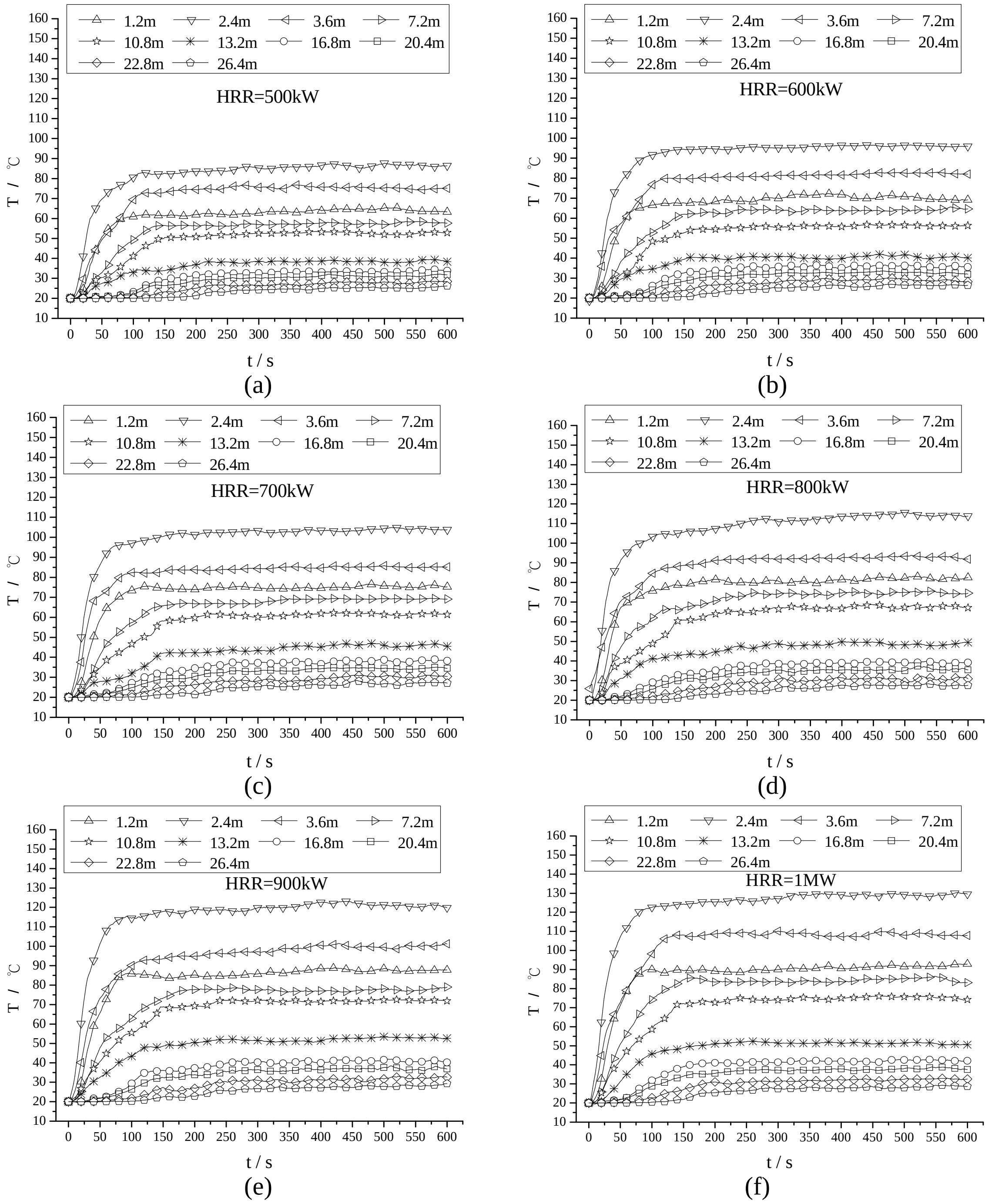


FIGURE 4. Temperature curves in the stairwell at various HRR (a) HRR = 500 kW; (b) HRR = 600 kW; (c) HRR = 700 kW; (d) HRR = 800 kW, (e) HRR = 900 kW; (f) HRR = 1 MW

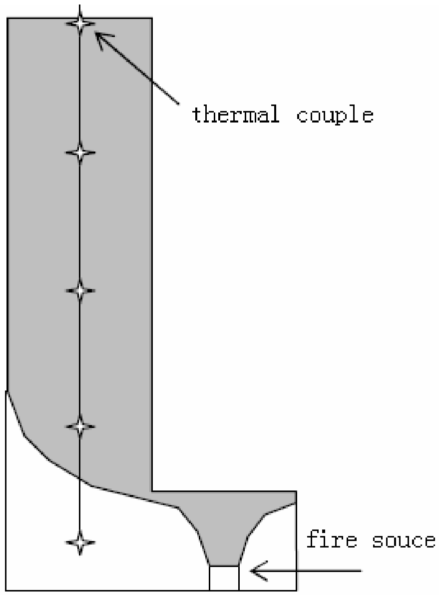


FIGURE 5. Schematic diagram of smoke in stairwell

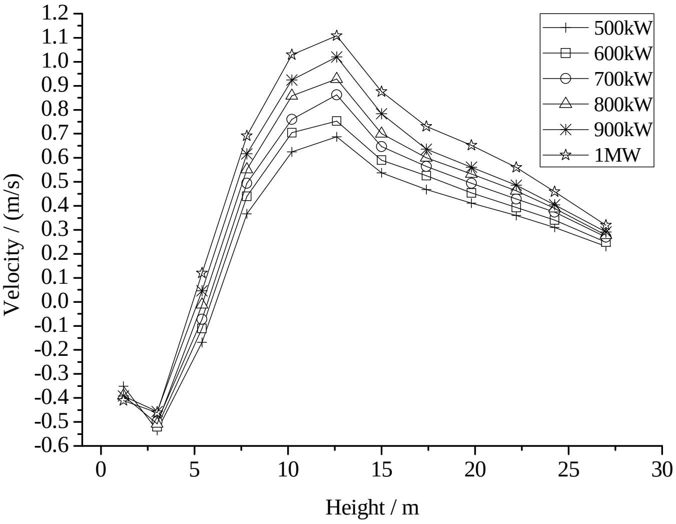


FIGURE 6. Average smoke upward velocity in the stairwell for various HRR

The simulation also indicates that the velocity does not vary much during the fire, and no stack effect is found to affect on the smoke spread. This is mainly owing to the close structure without openings to the outside, and the obstructions also weaken the formation of stack effect by cooling and obstructing. It is worth noticing that the velocity in Fig. 6 denotes the smoke seeped through the middle gap between the stairs.

The presence of stairs has great impact on velocity field in the stairwell. From Fig. 7, it is clear showed that the velocity is greater in the vortices, this attribute to greater turbulences in these regions. Concerning the flow pattern in the stairwell, the lower floors are dominated by many vortices, which promote heat transfer and uniformity of temperature and concentration level within the stairwell (Fig. 8). A similar situation is found in the upper floors. The higher is the temperature difference, the more intense are the eddies. As shown in Fig. 8, the eddies are largest at 120 s when the temperature difference between the lower and upper floors is highest, comparing the little eddies at 240 s on account of less temperature difference. The results are coincidental to the results of temperature (Fig.

4) and velocity field (Fig. 7). In addition, the simulations indicate that the flow patterns did not change significantly with time.

The smoke velocity value in the first floor is negative (Fig. 6), this is cause by the turbulent mixing and air supply in this region. As the stairwell is only open at the bottom through the air supply windows, the transport of mass and energy occurs because of a turbulent mixing process that is driven by the positive density gradient in the vertical direction. This produces a gravitational unstable configuration that feeds energy into a turbulent motion in the smoke within the stairwell. The upper cool air flow downstream to fill in the turbulent mixing process and make the air in the middle gap between the stairs also flow downward. In addition, the fire-induced flow also accelerates the air entrainment and makes the fire incline to the stairwell, and the obliquity increases with the HRR (Fig. 9).

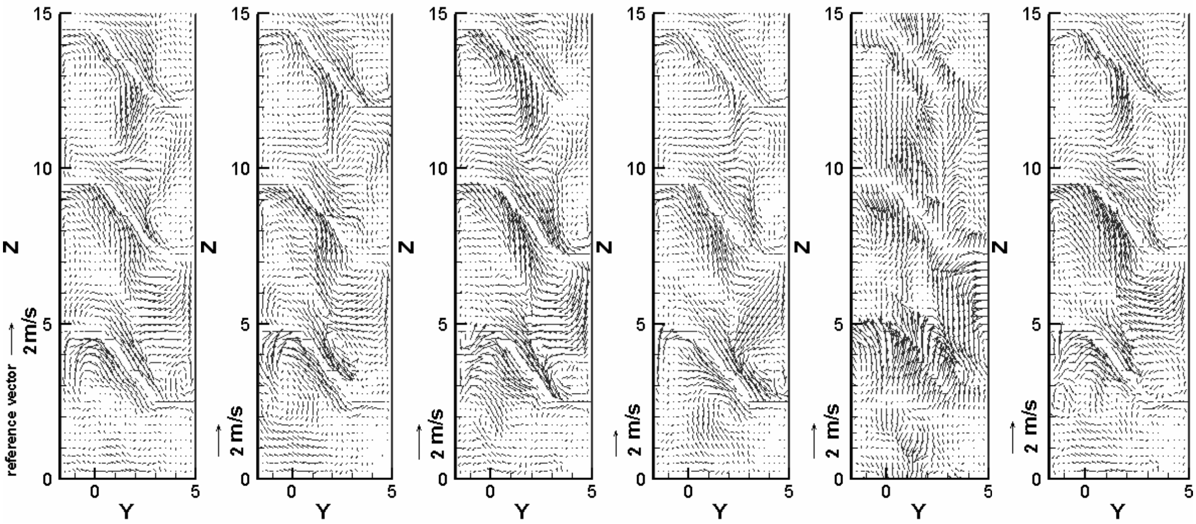


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FIGURE 7. Velocity vector of smoke within the first three floors at (a) HRR = 500 kW; (b) HRR = 600 kW; (c) HRR = 700 kW; (d) HRR = 800 kW, (e) HRR = 900 kW; (f) HRR = 1 MW, t = 300 s

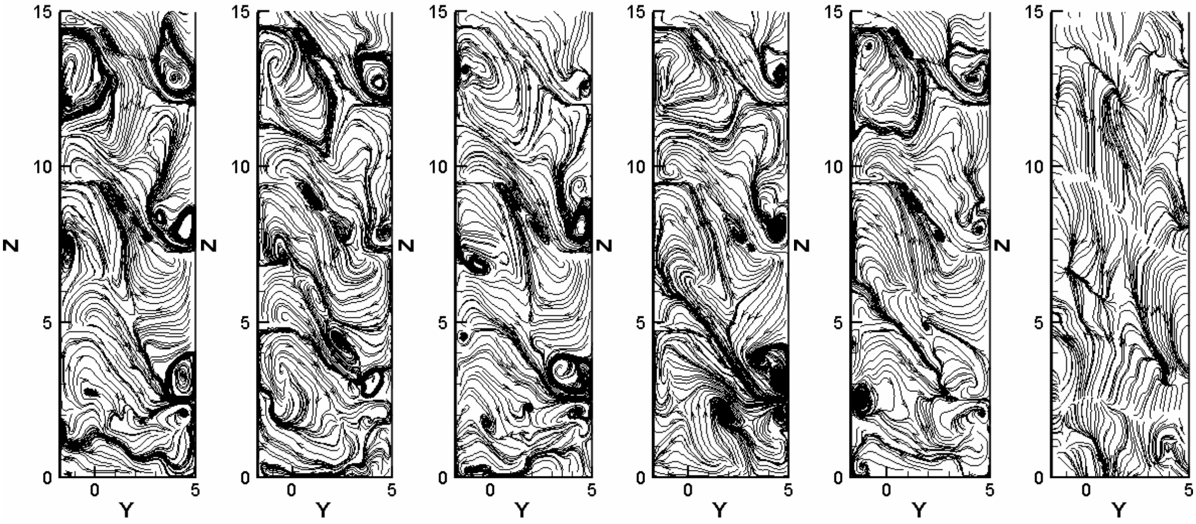

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FIGURE 8. Streamlines within the first three stories at (a) HRR = 500 kW; (b) HRR = 600 kW; (c) HRR = 700 kW; (d) HRR = 800 kW, (e) HRR = 900 kW; (f) HRR = 1 MW, t = 300 s

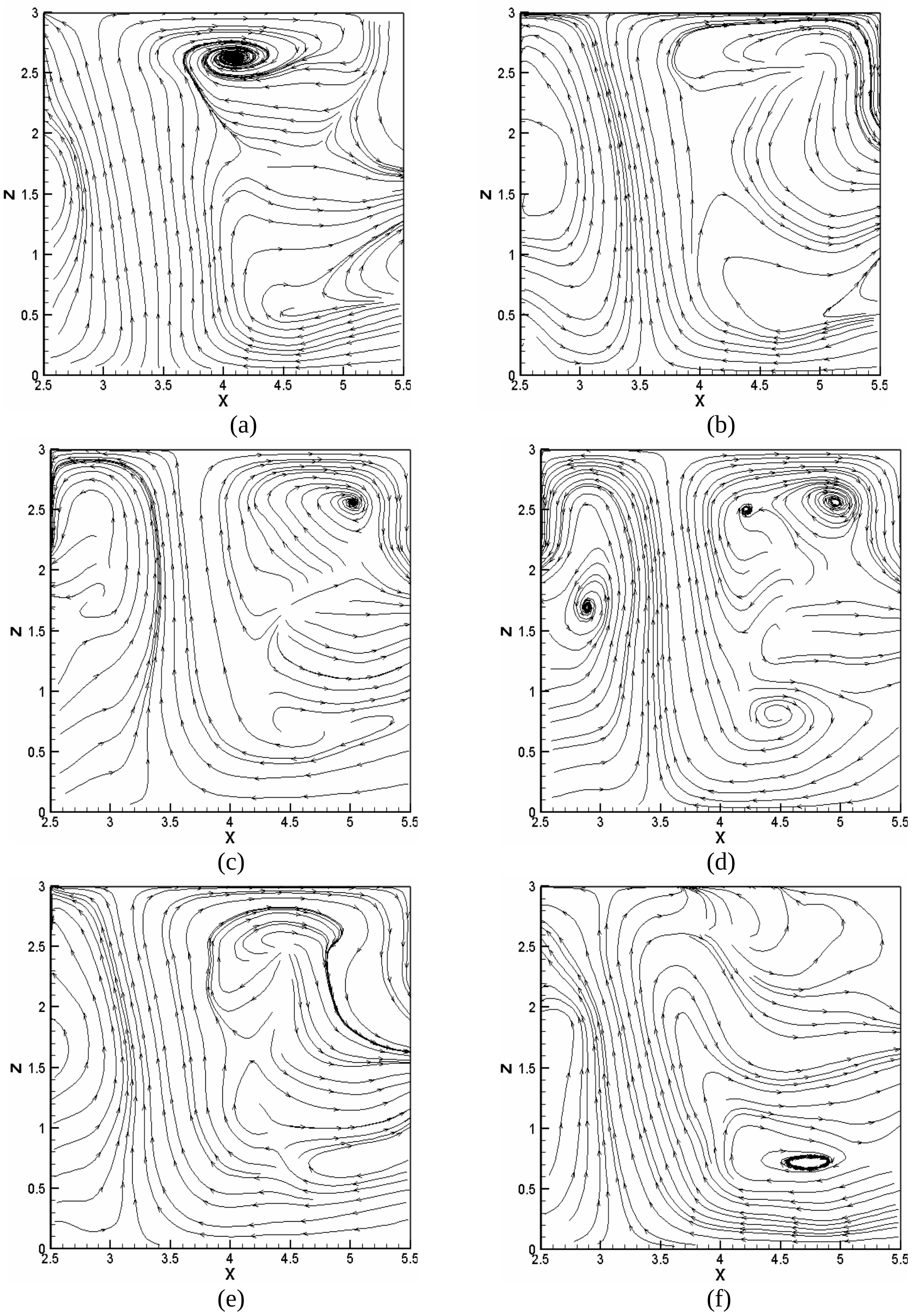

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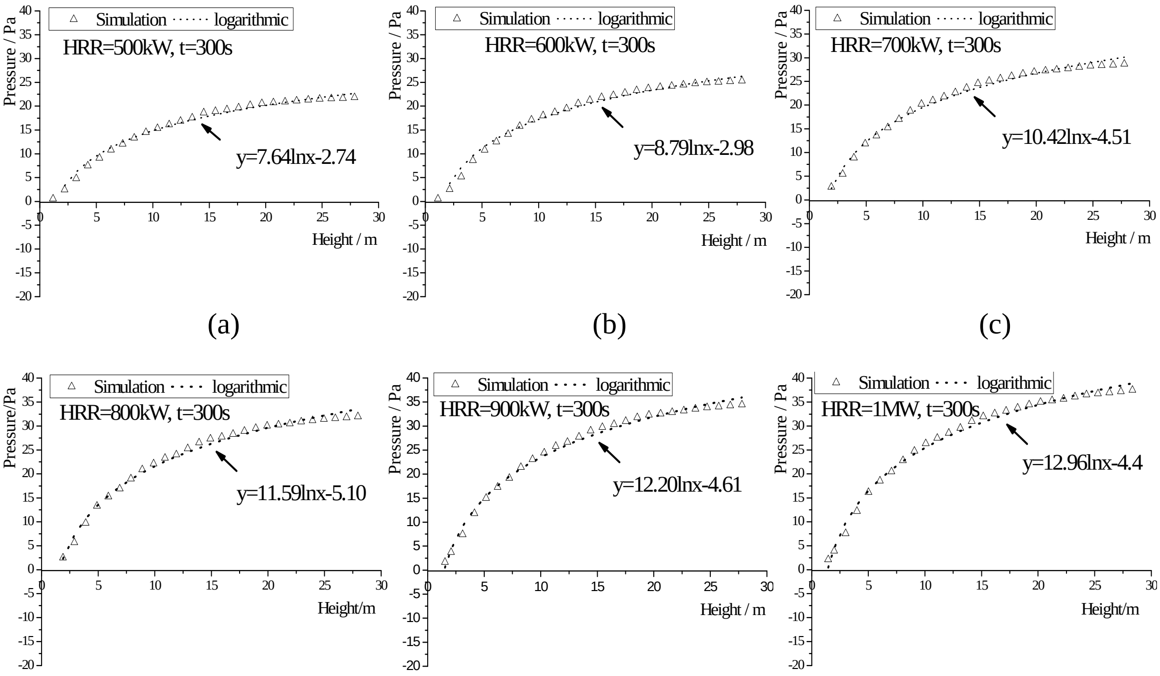
FIGURE 9. Streamlines within the fire room at (a) HRR = 500 kW; (b) HRR = 600 kW; (c) HRR = 700 kW; (d) HRR = 800 kW, (e) HRR = 900 kW; (f) HRR = 1 MW, t = 300 s

Pressure Distribution

Referring to the former literature by Klote[12], in the shaft, the location of the neutral plane and the pressure distribution are weak functions of temperature and strong functions of the size of openings.

And in the work by Harmathy[13], in a bottom-venting shaft, for the entire height of the building, that is, for $0 \leq z \leq H$(where H is the shaft height), the pressure for the whole building is higher than the bottom one (and, in fact, the atmosphere pressure), so that the neutral plane is in the bottom when the opening is located in the bottom. Similarly, the bottom pressure in the stairwell is equal to the atmosphere pressure (Fig. 10). As shown in Fig. 10, the pressure in the stairwell approximately fits logarithmic with height, not linear relationship as predicted in shaft with openings; it can also be concluded that the pressure increase slowly in the entire stairwell.



(a) (b) (c)

(d) (e) (f)

FIGURE 10. Stable longitudinal pressure distribution in the stairwell at (a) HRR = 500 kW; (b) HRR = 600 kW; (c) HRR = 700 kW; (d) HRR = 800 kW, (e) HRR = 900 kW; (f) HRR = 1 MW, t = 300 s

As the stairwell is a close framework without openings to outside, the pressure in the stairwell is consequently dominated by the smoke temperature. Therefore, during the fire, the temperature slowly decreases which leads to pressure decrease, and as a result of the below hot gas’s pushing and heating, the pressure of the upper layer raises. In addition, with the increase of HRR, the overall pressure is higher, which forms a bigger and hotter fire balloon in the upper zone than the corresponding one under small fire. But meanwhile, the lower zone is still hotter than the upper zone, the two hot gas streams rival ship each other, so that the whole pressure increases quicker when the upper zone smoke temperature is lower under small fire.

Effect of Heat Release Rate

In order to study the effect of the heat release rate (HRR), six fire sources ranging from 500 kW to 1MW are utilized. In general, when the HRR increases, the increase of the air drawn into the stairwell accelerates the spread of the hot smoke. So the driving force for the flow is the energy input from a fire located in the lower compartment in the close stairwell. The maximal smoke temperature and velocity in each floor at different HRR are listed in Table 1. Obviously, the smoke temperature and velocity is dominantly determined by the HRR in such a close geometry, and ultimately have impact on the pressure distributions.

TABLE 1. The maximal smoke temperature and average velocity in each floor at different HRR

Heat release rate		500kW	600kW	700kW	800kW	900kW	1MW
Maximal temperature /°C	Floor1	87.6	96.6	104.9	115.7	123.1	130.3
	Floor2	58.4	65.6	69.4	75.7	79.0	86.4
	Floor3	53.5	56.8	62.2	68.8	72.5	76.1
	Floor4	34.5	36.7	38.9	39.7	41.9	42.8
	Floor5	28.6	30.1	31.1	32.3	33.1	33.8
	Floor6	26.3	27.0	28.4	28.4	29.3	29.3
Average velocity /m/s	Floor1	-0.54	-0.52	-0.50	-0.51	-0.46	-0.46
	Floor2	0.37	0.44	0.49	0.55	0.62	0.69
	Floor3	0.69	0.75	0.86	0.93	1.02	1.11
	Floor4	0.41	0.45	0.49	0.53	0.56	0.65
	Floor5	0.31	0.34	0.37	0.39	0.40	0.46
	Floor6	0.23	0.25	0.27	0.28	0.29	0.32

CONCLUSIONS

Smoke flow induced by fire buoyancy in a closed stairwell is investigated in this article, by focusing on the impact of several parameters on the phenomenon, such as smoke temperature, upward spread velocity, and interior pressure distribution. Forced by the energy input from a fire located in the lower compartment, an upward flow of hot smoke propagates away from the fire source to the closed stairwell, and meanwhile cooler air drawn from the air supply windows into the stairwell accelerates the spread of the hot smoke, so the energy generated by the fire source is the dominating driven force of the upward hot flow in the stairwell via heated the air. The complex geometry of stairs has great effect on the flow pattern. The smoke flow is dominated by many vortices. The higher the temperature difference, the more intense the eddies, and it has roughly uniform flow patterns with time except the magnitude of the velocity and vortices size. During the fire, the pressure neutral plane is stable in the bottom and no stack effect is formed as there is no opening in the stairwell to the outside. Furthermore, the pressure in the stairwell approximately fits logarithmic with height.

ACKNOWLEDGEMENT

This work is supported by the CAS and the Croucher Fund of Hong Kong under project “Active Fire Protection in Supertall Buildings”.

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