Influence of Ventilation Factor on Smoke Control through Shaft in High-rise Building Fire

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ABSTRACT

Stack effects have an important influence on smoke movement in high-rise buildings. The stack effect in a room with a shaft causes a negative pressure condition in the room. Smoke can be extracted out of the room through the shaft and fresh air will enter the room through inlet openings. The flow through the inlet may be unidirectional or bidirectional. So, the smoke may also flow out of the room from the inlet for some conditions. The design of the inlet is important to prevent smoke from flowing out. The ventilation factor is a basic parameter to study compartment fires. In this paper, a theoretical analysis was developed to obtain a critical ventilation factor to prevent smoke to overflow from the fire room through an inlet. Numerical simulations with different ventilation factors were also conducted to verify the theoretical model. The results showed that a negative pressure was generated at the bottom of the shaft. The magnitude of the negative pressure difference increased with increasing ventilation factor. However, the negative pressure difference increased at a low rate only within a narrow range of ventilation factors. The magnitude of the negative pressure induced at the opening for supplying air decreased with increasing ventilation factor. At some point, the pressure inside the room was even higher than that outside for some ventilation factors. Consequently, smoke moved out of the fire room through the air-supply opening under a larger ventilation factor. This result illustrated that there is a critical value for the ventilation factor. When the ventilation factor is less than this critical value, there is no smoke flow out of the room. The critical value of ventilation factor was calculated using the theoretical model and verified by numerical simulations.

KEYWORDS: Smoke control, high-rise building.

NOMENCLATURE

H	height of air-supply opening (m)
A	area of air-supply opening (m^2)
$A\sqrt{H}$	ventilation factor (m$^{5/2}$)
S	area of shaft (m^2)
C_p	specific heat (kJ/(kg·K))
h_1	height of the entrance of shaft (m)
h_2	height of the exit of shaft (m)
m_{in}	amount of air supply (kg/s)
m_{out-1}	amount of smoke overflow (kg/s)
Q_c	heat release rate (kW)
T_0	temperature of the air (K)
T_s	temperature of smoke in room (K)
v_1	velocity at shaft entrance (m/s)
v_2	velocity at shaft exit (m/s)
v_3	horizontal flow velocity of point 3 (m/s)
v_4	horizontal flow velocity of point 4 (m/s)
v_0	air supply velocity (m/s)
v_s	velocity of smoke in shaft (m/s)

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m_{out-2} amount of smoke exhaust (kg^3/s)
P atmospheric pressure of the ground (Pa)
P_1 absolute pressure of shaft entrance (Pa)
P_2 absolute pressure of shaft exit (Pa)
P_∞ pressure of neutral plane (Pa)
P_{h1} pressure of shaft entrance (Pa)
P_{h2} pressure of shaft exit (Pa)
ΔP_{s1} smoke flow resistance between the entrance and exit of shaft (Pa)
ΔP_{sd} pressure loss caused by the changes of velocity (Pa)
ΔP_{zs} pressure loss caused by the changes of density (Pa)
y distance between neutral plane and the top of the air-supply opening (m)

Greek

ρ_0 density of air (kg/m^3)
ρ_s density of smoke (kg/m^3)

Subscripts

0 Outside
1 shaft entrance
2 shaft exit
3 point 3 of outdoor
4 point 4 of indoor
s hot smoke

INTRODUCTION

Large amounts of smoke will be emitted by burning plastic synthetic materials in a room fire. Statistics show that hot smoke contains many toxic gases, such as carbon monoxide, which will cause a serious threat to life safety in the building [1-3]. It is important to control smoke movement and confine it effectively. Therefore, smoke spread and control in high-rise buildings should be studied properly. The key point in smoke management is to control the driving force of smoke movement. The pressure difference between the inside and outside of the fire room is responsible for smoke movement from the fire floor to other floors in a tall building. Smoke can be extracted by installing shafts to the room and exploiting the stack effect. The stack effect will give a pressure difference between the bottom and top opening of the shaft, due to the temperature difference between the gas in the shaft and the air in the outer atmosphere.

The stack effect in high-rise buildings will give a lower pressure near the shaft in the burning room than that of outside as in Fig. 1. This negative pressure difference will affect smoke movement in the room. If the negative pressure difference is large enough, smoke will not spread out of the fire room and will be removed by the shaft. On the other hand, cool air can move from the opening into the room.

Smoke control studies [e.g. 4-10] have mainly focused on studying the stack effect in stairwell and shaft, not yet on smoke control of room fires through the stack effect. In China, Zhang [11] studied the feasibility of using a shaft to exhaust smoke in high-rise buildings. Li [12] reported how negative pressure formed by the shaft can be applied to control smoke movement. Zou [13] provided a three-dimensional numerical simulation study of a fire under the effect of a shaft in a highway tunnel. It is obvious that installing a shaft in a room can exhaust smoke and control smoke spread in a high-rise building. However, there are not yet studies on how to confine the smoke to the fire room. Vertical shafts and ventilation ducts installed in high-rise buildings can give a sufficiently strong stack effect for effective smoke control. The role of the room ventilation factor on the effectiveness of smoke control in a high-rise building room as in Fig. 1 will be studied. Using the critical value of the room ventilation factor, the air-supply opening can be designed to exhaust the smoke through the shaft effectively and prevent the spread of fire.

THEORETICAL ANALYSIS

Smoke movement due to the stack effect is analyzed using fluid dynamics. The simplifications and assumptions made are as follows [14]:

- The smoke density is constant in the shaft, and the smoke volume changes in the shaft due to temperature changes are negligible;
- The smoke flow in the shaft section, both inward and outward, is fully developed, and the average flow velocity is taken during calculation.

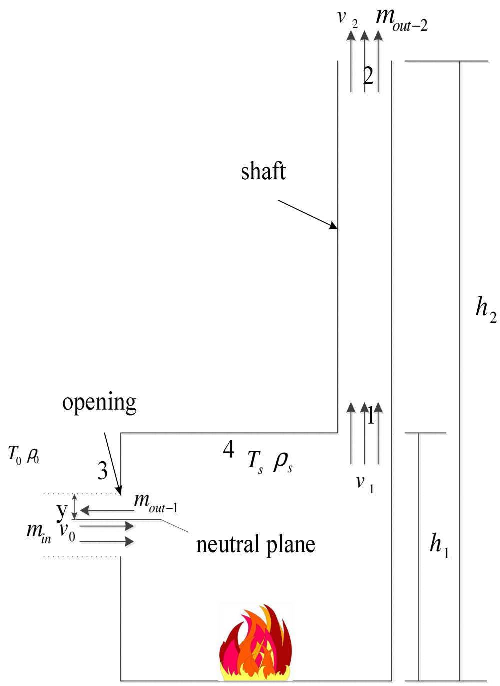


Fig. 1. Hydraulic analysis in shaft

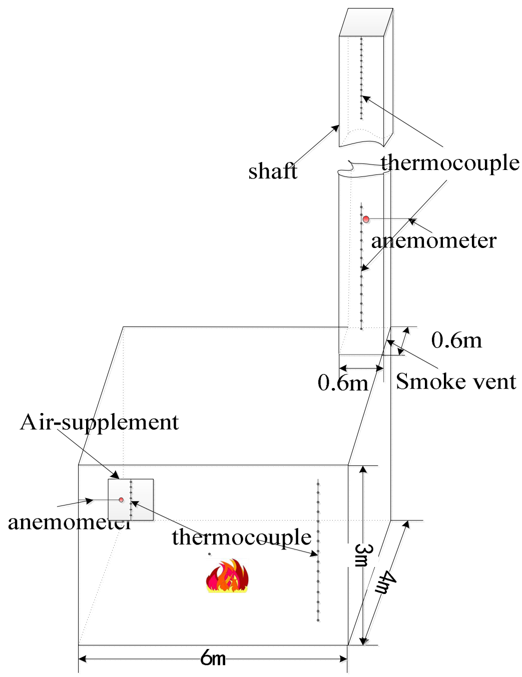


Fig.2. Physical model of smoke control by shaft

For the air flow in the shaft as shown in Fig. 1, the total head can be expressed by the Bernoulli equation:

$$P_1 + \frac{\rho_s v_1^2}{2} + \rho_s g h_1 = \frac{\rho_s v_2^2}{2} + \rho_s g h_2 + \Delta P_{s1} \,. \tag{1}$$

Assuming that the atmospheric pressure at the ground is P, the absolute pressure P_1 of air at any section is equal to the sum of the gauge pressure and atmospheric pressure, that is

$$P_1 = P_{h1} + \left(P - \rho_0 g h_1\right), \tag{2}$$

$$P_2 = P_{h2} + \left(P - \rho_0 g h_2\right). \tag{3}$$

The pressure difference between the entrance and the exit of the shaft is:

$$\Delta P = P_{h1} - P_{h2} = \Delta P_{s1} + \frac{\rho_s}{2}\left(v_1^2 - v_2^2\right) - \left(\rho_0 - \rho_s\right) g \left(h_2 - h_1\right) = \Delta P_{s1} + \Delta P_{sd} - \Delta P_{zs} \,, \tag{4}$$

where ΔP_{zs} is the pressure loss caused by the changes of density, also called as self-generating ventilating force, and can be written as:

$$\Delta P_{zs} = (\rho_0 - \rho_s)\, g\,(h_2 - h_1) = \frac{\rho_s v_s^2}{2} \tag{5}$$

The pressure difference between the entrance and the exit of the shaft determines the direction of air flow in the shaft. From Eq. (4), the pressure difference of two sections is mainly composed of friction loss, speed loss and spontaneous ventilation resistance force. The speed loss is caused by the velocity variation which is caused by the changes of section or temperature of the medium. According to the hypothesis, the impact caused by speed loss can be ignored based on the assumption of air flowing in the shaft without sectional variation. The flow hydraulic loss is the frictional resistance generated by the flow of the medium along the wall, and it is always in the direction opposite to the air flow. Therefore, without external force, ΔP_{zs} has an important role for the direction and magnitude of air flow in the shaft. From Eq. (5), the smoke velocity in the shaft, v_s, can be expressed as:

$$v_s = \sqrt{2(T_s - T_0)\, g\,(h_2 - h_1)/T_0}\ . \tag{6}$$

As shown in Fig. 1, ignoring the mass loss caused by burning, mass conservation gives:

$$m_{in} = m_{out-1} + m_{out-2}\ . \tag{7}$$

When the smoke does not overflow, the mass of air supply is equal to the mass of smoke:

$$m_{in} = m_{out-2} \text{ or } \rho_0 v_0 A = \rho_s v_s S\ . \tag{8}$$

When the smoke does not overflow, the air supply velocity that can block the smoke movement can be calculated from Eqs. (6) and (8):

$$v_0 = \frac{T_0}{T_s}\frac{S}{A}\sqrt{2(T_s - T_0)\, g\,(h_2 - h_1)/T_0}\ . \tag{9}$$

The smoke temperature in the room varies with the height. The temperature near the ceiling is highest. So, the plume centreline temperature is adopted to represent the smoke temperature. Heskestad deduced an expression describing the temperature distribution, and the maximum temperature can be calculated [15] from the following steady-state equation:

$$T_s = T_{\max} = 9.1\left(T_0 / \left(C_p^2 g \rho_0^2\right)\right)^{1/3} Q_c^{2/3} h_1^{-5/3} + T_0 \tag{10}$$

As shown in Fig. 1 in the air-supply opening with smoke flowing, the flow state at a point 4 indoor and another point 3 outdoor can be combined through the Bernoulli equation [15]:

$$\frac{P_4}{\rho_s} + \frac{v_4^2}{2} = \frac{P_3}{\rho_3} + \frac{v_3^2}{2}\ . \tag{11}$$

Velocity v_4 is assumed to be close to zero because the velocity of the indoor mixed gas is very low.

With reference to the neutral plane at pressure P_∞, the pressure at point 4 can be written as:

$$\frac{P_\infty - \rho_s g y}{\rho_s} = \frac{P_\infty - \rho_0 g y}{\rho_3} + \frac{v_3^2}{2}\ . \tag{12}$$

The gas passing through the point 3 comes from indoors with its temperature (and density) the same as that of point 4:

$$v_3 = \sqrt{2(\rho_0 - \rho_s) gy/\rho_s} \ . \tag{13}$$

Therefore, when y equals H, the velocity of the smoke overflow from the air-supply opening is maximum, that is:

$$v_{\max} = \sqrt{2(\rho_0 - \rho_s) gH/\rho_s} \ . \tag{14}$$

When the minimum critical air supply velocity generated from the negative pressure of the interior is greater than the maximum velocity of smoke overflow, natural wind supplement can prevent the smoke overflow. The critical condition for preventing smoke overflow can be obtained from Eqs. (9), (10) and (14):

$$A\sqrt{H} \le \frac{9.1\left(T_0/C_p^2 g\rho_0^2\right)^{1/3} Q_c^{2/3} h_1^{-5/3} + T_0}{T_0\sqrt{h_2 - h_1}} S \ . \tag{15}$$

NUMERICAL SIMULATION

FDS (Fire Dynamics Simulator) was developed by NIST in the USA and is widely used in fire smoke simulations. It solves the Navier-Stokes equations to represent the fluid flow with low velocity driven by heat. It considers the heat losses by conduction, radiation and convection. FDS was used for numerical simulations. The physical model consisted of a room and a shaft, and the smoke shaft was arranged at the top of the room, like a chimney, as shown in Fig. 2. The dimension of the room was 3 m high, 6 m long and 4 m wide. The shaft height affects the stack effect. Our previous research [16] with the same fire room showed that the critical shaft height to prevent smoke overflow was greater than 6 m but less than 9 m. So, the height of shaft was set at 9 m here. In the room, a fire was set at the center of the floor, with the size of 0.4 m×0.4 m, and the maximum heat release rate was 2 MW. The mesh size was uniform with size of 0.1 m×0.1 m.

As shown in Fig. 2, a column of thermocouples with 16 measuring points was evenly arranged in one side of the room from 0.2 to 3.0 m to analyze the temperature distribution in the room. The interval between thermocouples was 0.2 m. The temperatures of hot smoke in the shaft were measured by 13 thermocouples, which were installed at a 0.75 m vertical interval in the center line of the shaft. Besides, 13 pressure probes and 13 velocity probes were also arranged equidistant from bottom to top along the center line of the shaft for measuring the pressure and velocity of hot smoke in the shaft. The first point was 3 m above the bottom of the shaft. Smoke movement was affected greatly by the pressure difference between inside and outside of the fire room in the air-supply opening. A column of pressure probes was arranged in the middle of the air-supply opening. To get more accurate data, seven thermocouples and seven velocity probes were also set in the middle of the air-supply opening, and two flow measuring devices were placed in the air-supply opening and smoke vent to record volume flows.

In order to study the influence of the ventilation factor on smoke control, seven conditions were selected as shown in Table 1.

The vertical distribution of temperature in the fire room and the changes of pressure, velocity and temperature of shaft and air-supply opening were obtained respectively using FDS, as well as the amount of smoke overflow was recorded. The effect of ventilation factor on the stack effect, and smoke control were analyzed.

Table 1. List of simulation conditions

Case	Air-supply opening area (m^2)	Smoke vent area (m^2)	Shaft height (m)	Ventilation factor ($m^{5/2}$)
1	0.4×0.4	0.6×0.6	9	0.101
2	0.5×0.5	0.6×0.6	9	0.177
3	0.6×0.6	0.6×0.6	9	0.279
4	0.7×0.7	0.6×0.6	9	0.410
5	0.8×0.8	0.6×0.6	9	0.572
6	0.9×0.9	0.6×0.6	9	0.768
7	1.0×1.0	0.6×0.6	9	1.0

Effect of ventilation factor on stack effect

The temperature profiles in the fire room with different ventilation factors are shown in Fig. 3. The temperature values were averaged during the steady-state phase of the simulation, and the same was done for the other measured parameters. It can be seen that, with increasing vertical height at the same ventilation factor, the temperature continues to rise. In addition, the temperature shows a rising trend with increasing ventilation factor. When the ventilation factor is smaller, the amount of fresh air from outside is not sufficient, leading to incomplete combustion, so the temperature of the room is significantly lower. However, when the ventilation factor is greater than 0.572 $m^{5/2}$, the temperature at the bottom of the room is gradually reduced, because of the large amount of fresh air from outside, mixed with the lower smoke.

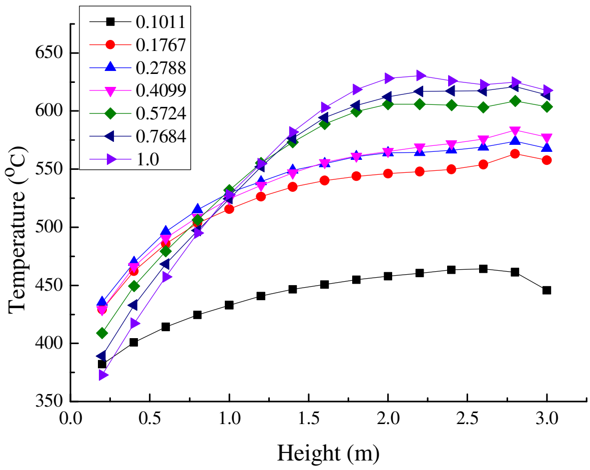
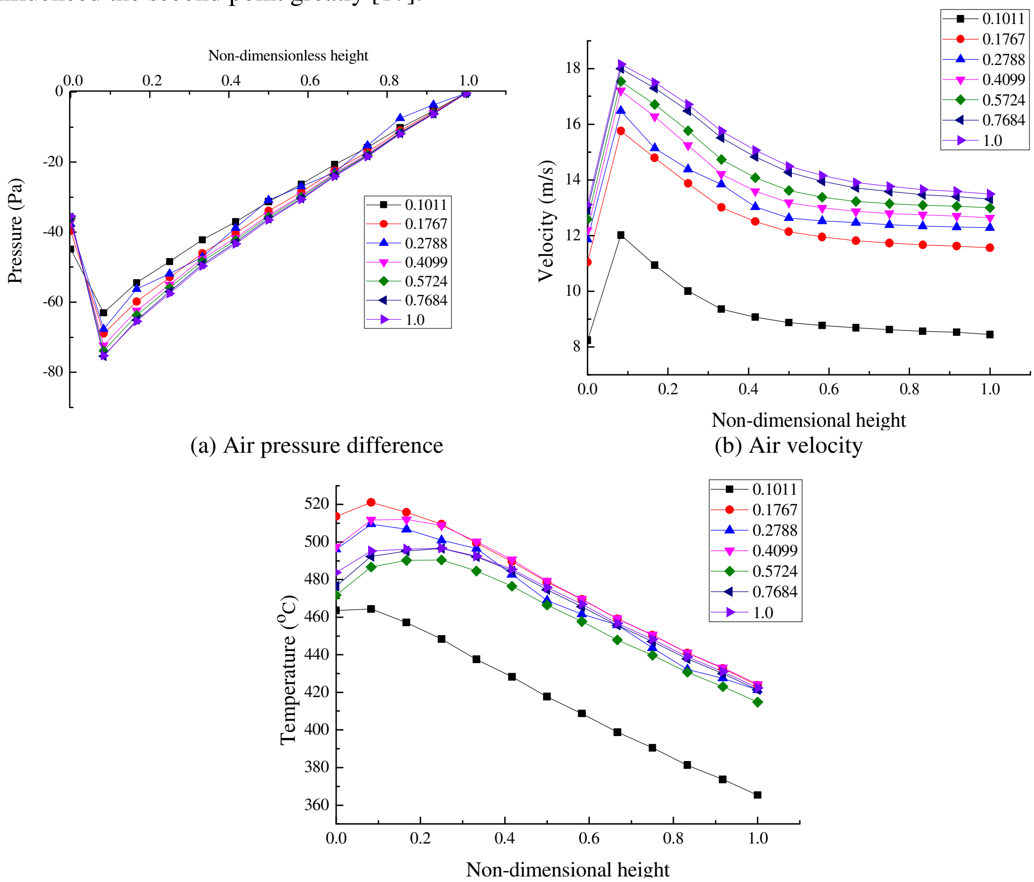


Fig. 3. Variation of indoor temperature with height.

The variations of averaged pressure, velocity and temperature in the center line of the shaft with different air-supply opening areas are shown in Fig. 4a to Fig. 4c. As shown in Fig. 4a, the negative pressure value produced in the shaft presents a trend of decreasing to zero with the increase of non-dimensional height of the shaft in the case of the same ventilation factor. With the increase of the ventilation factor, the negative pressure value at the bottom of the shaft increases, but the variation is very small. It illustrates that, although the stack effect strengthens with the increase of the ventilation factor, the influence of the ventilation factor on the stack effect is not obvious. As shown in Fig. 4b, the velocity of smoke exhaust presents the same trend with the pressure, decreasing with the increase of non-dimensional height of the shaft and increasing with the increase of ventilation factor. However, when the ventilation factor equals 0.101 $m^{5/2}$, the velocity is lower than others apparently. From Eq. (6), it could be seen that the velocity of smoke is reduced with the decrease of indoor temperature at the same condition as shown in Fig. 4. As shown in Fig. 4c, the temperature in the shaft also presents the same trend with pressure and velocity, decreasing with the increase of non-dimensional height in the shaft. Furthermore, when the ventilation factor equals 0.101 $m^{5/2}$, the temperature on the center line of the shaft is lower than others as well as the temperature in the fire room. With the increase of ventilation factor, the maximum temperature at the bottom of the shaft presents a complex variation. Because the fire plume is driven by the stack effect, the smoke flow into the shaft is tilted. Although the stack effect is not particularly strong with the increasing ventilation factor, it does influence the deflection angle of the fire plume and then the angle of the smoke flow into the shaft. It also can be seen from these three figures that the values of pressure, velocity and temperature at the first detection point are lower than at the second point. This effect was also due to the tilted fire plume, which had little influence on the first detection point, but influenced the second point greatly [17].



(a) Air pressure difference (b) Air velocity

(c) Air temperature

Fig. 4. Results at shaft centerline.

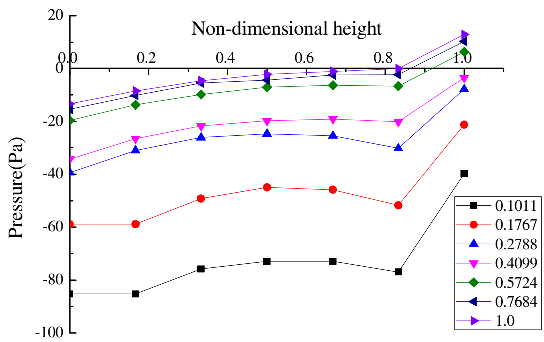
The comparison of the static pressure difference by theoretical calculation and numerical simulation between the top and bottom of the shaft is given in Table 2. The static pressure difference was calculated by Eq. (4). It can be seen that there is a small difference between the theoretical calculation and the numerical simulation for the static pressure difference. With increase of the ventilation factor, the static pressure difference between the top and bottom of the shaft increases by a small amount, which is consistent with Fig. 4a.

Table 2. Comparison of static pressure difference by theoretical calculation and simulation

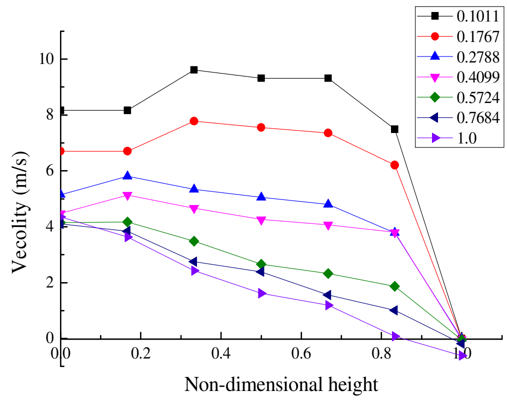
Case	Air-supply opening area (m^2)	Ventilation factor ($m^{5/2}$)	Static pressure difference		Error (%)
			Numerical simulation	Theoretical calculation	
1	0.4×0.4	0.101	67.5	63.0	6.6
2	0.5×0.5	0.177	71.9	68.9	4.1
3	0.6×0.6	0.279	70.6	67.7	4.2
4	0.7×0.7	0.410	73.4	72.3	1.9
5	0.8×0.8	0.572	71.9	73.8	2.5
6	0.9×0.9	0.768	72.6	75.4	3.6
7	1.0×1.0	1.0	73.4	75.3	3.8

Effect of ventilation factor on smoke control

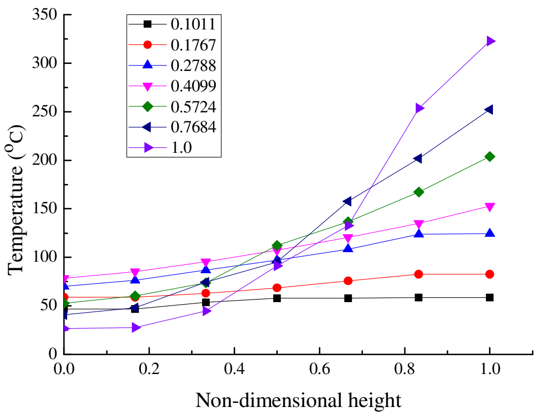
The variations of averaged pressure, velocity and temperature in the vertical center line of the air-supply opening with different ventilation factor are shown in Fig. 5a to Fig. 5c. As shown in Fig. 5a, with the increase of non-dimensional height for the same ventilation factor, the negative pressure at the air-supply opening presents a trend of decreasing, and the variation trend is similar with different ventilation factor.



(a) Air pressure difference



(b) Air velocity

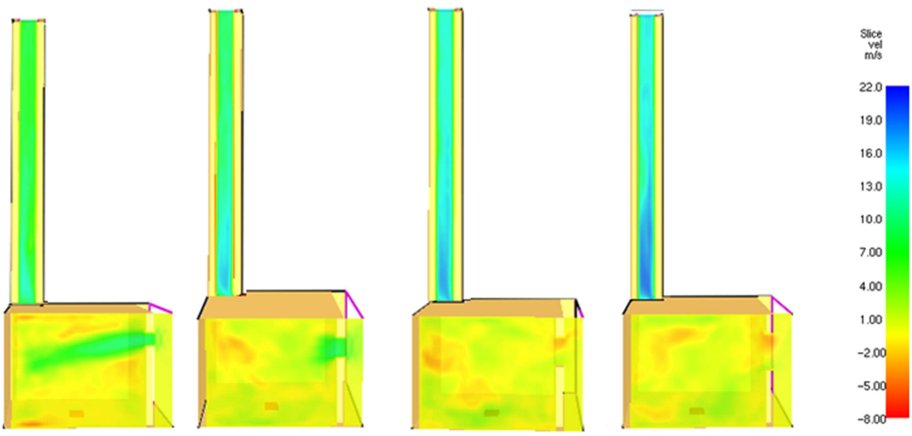


(c) Air temperature

Fig. 5. Results at air-supply opening

The negative pressure value decreases all the time with the increase of ventilation factor. When the ventilation factor is greater than 0.410 $m^{5/2}$, the negative pressure at the top measurement point is greater than zero, but the value is small. This indicates that the smoke could flow out of the fire room through the top of the air-supply opening. As shown in Fig. 5b, the velocity of air flow into the fire room on the vertical center line of the air-supply opening decreases with increase of non-dimensional height in the case of the same ventilation factor, and the velocity decreases with the ventilation factor increasing. When the ventilation factor equals 1.0 $m^{5/2}$, the velocity observed at the uppermost detection point is less than 0, demonstrating that the smoke would overflow from the fire room. As shown in Fig. 5c, the temperature on the vertical center line of the air-supply opening increases as well as the temperature of the fire room with the increase of the ventilation factor. The temperature presents a trend of rising with the increase of non-dimensional height for the same ventilation factor, and the changing rate of temperature becomes gradually large with the increase of the ventilation factor. This is because the smoke flows out of the fire room through the top of the air-supply opening when the ventilation factor is greater than 0.410 $m^{5/2}$.

The velocity distributions in the room with different ventilation factors are shown in Fig. 6. With increasing ventilation factor, the velocity at the opening changes from positive to negative, meaning that the smoke flows out of the opening in cases with high ventilation factor.



(a) $A\sqrt{H} = 0.1011$ (b) $A\sqrt{H} = 0.2788$ (c) $A\sqrt{H} = 0.5724$ (d) $A\sqrt{H} = 1.0$

Fig. 6. The velocity distribution for different ventilation factors.

Table 3. Amount of smoke overflow and smoke exhaust

Case	Ventilation factor ($m^{5/2}$)	Amount of smoke overflow (m^3/s)	Amount of exhaust (m^3/s)	The case of smoke overflow	
				Numerical simulation	Theoretical calculation
1	0.101	0	2.14	No	No
2	0.177	0	2.69	No	No
3	0.279	0	2.91	No	No
4	0.410	0.120	3.00	Yes	Yes
5	0.572	0.104	3.14	Yes	Yes
6	0.768	0.100	3.21	Yes	Yes
7	1.0	0.102	3.26	Yes	Yes

From Eq. (15), it can be determined that the critical ventilation factor to control smoke is 0.36 $m^{5/2}$. That is to say, when the ventilation factor is less than 0.36 $m^{5/2}$, smoke would not flow out of the room. Table 3 gives the amounts of smoke overflow and smoke exhaust, and the cases of smoke overflow. It shows that the results of the numerical simulations agree with the theoretical calculation. When the ventilation factor is less than 0.36 $m^{5/2}$, the smoke cannot overflow from the opening. So, the air-supply opening can be set appropriately to confine the smoke overflow and prevent smoke spread.

CONCLUSIONS

A numerical simulation approach was employed to analyze the changes in the indoor temperature, pressure, velocity, temperature of the shaft and air-supply opening by changing the ventilation factor of the fire room. The amount of smoke overflow with different ventilation factors was also recorded. By comparing with the theoretical calculation results, the effect of the ventilation factor on smoke control in a room of a high-rise building was studied.

1) The principle of the stack effect in a shaft was analyzed theoretically, and the critical condition of controlling smoke overflow was obtained. At the same time, the critical value of ventilation factor under a certain condition was obtained, which was verified by numerical simulation. Results show that, when the ventilation factor is in a certain range, then there will be no smoke overflow out of the fire room.
2) With the increase of the ventilation factor, the indoor temperature increased and the negative pressure value produced at the bottom of the shaft increased by a small amount, as well as the static pressure difference between the top and bottom of the shaft. This result illustrated that the influence of the ventilation factor on the stack effect is not obvious. On the other hand, the negative pressure value produced at the air-supply opening was lower with the increase of ventilation factor, and the pressure between the inside and outside was even greater than 0. Therefore, with the increase of the ventilation factor, once it exceeded the critical value, smoke would overflow, and then spread outward.
3) In engineering practice, when a shaft is used to control smoke in a high-rise building, it is necessary to design the air-supply opening according to the actual situation and theoretical calculation. Thus, smoke can be discharged and confined effectively in the fire room, and people's safety will be protected from toxic smoke.

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