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Effect of shaft height on smoke control in tall building fires

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Abstract. Smoke exhausting through shaft from fire room with an opening was theoretical analysed and numerical simulated. The critical shaft height to control smoke not overflowing the fire room was induced. The influence of shaft height on the variation trend of pressure, velocity and temperature in shaft and air supply opening as well as indoor temperature was studied. With the increase of shaft height, the static pressure difference between the top and bottom of the shaft increases, so the stack effect is more obvious, and the smoke spillage from fire room through opening decreases, therefore the smoke can be controlled effectively and confined within the room finally. That is to say, under certain conditions, when the shaft height reaches a certain value, the smoke does not overflow. And on the other hand, the stack effect increases continuously until it reaches a critical state, so the stack effect also has another critical state with the increase of shaft height. The results of theoretical analysis and numerical simulation agreed well.

1. Introduction

Fire's damage will increase with smoke movement in the high-rise building with special structures. Once the fire occurs, fire and smoke are easily to overflow rapidly from fire room[1,2], and the toxic substances will cause a serious threat to occupants in the building. It is very important for preventing fire spread and protecting people's safety to control smoke movement and confine it in a certain area timely and effectively. Therefore the research of smoke control method in high-rise building is very important. The key to control smoke spread is to control the driving force. The pressure difference between the inside and outside of room is one of the main driving forces for smoke movement.

Stack effect is a main factor that cause the smoke spread in the high-rise building fire. The chimney is an architectural structure to exhaust smoke in daily life. It could control smoke effectively using the theory of stack effect correctly. When the shaft connected with room in high rise buildings, the stack effect can be formed and then the negative pressure will be formed in the fire room. The existence of negative pressure will have a significant impact on the smoke flow in the room[3]. When the negative pressure is large enough, the smoke can't spread out of the fire room, so as to achieve the purpose to prevent the spread of smoke and protect people's safety. Many scholars[4-9] have studied the stack effect in buildings, especially in stairwell. For example, Sun X.Q. et al[4] studied the smoke movement in a full-scale stairwell with the fire located in an adjacent room. Qi D. et al[9] established analytical solutions in term of dimensionless numbers for smoke spread through high-rise shafts during fire and testified the dimensionless analytical solutions with results of two scaled shaft experiments. Xu X.Y. et al[10-11] deduced the models to predict the neutral plane in shaft. These researches focused on the smoke movement by stack effect. But studies on smoke control using stack effect were less involved. Zhang J.Y. et al[12] studied the feasibility of using shaft to exhaust smoke



in high-rise building, Li J. et al [13] researched the feasibility of using negative pressure formed by shaft to control the smoke, realized the shaft can be used to control the spread of smoke. The study by Sun H. et al[14] showed although the fire power could make the smoke expanding outward, the negative pressure induced by stack effect could successfully control smoke overflow. The effect of smoke control can be influenced by many factors, and the design of the shaft is one of the most important factors. In this paper, the work is to study the influence of shaft height on the effect of smoke control in high rise building room using the simulation methods.

2. Theoretical analysis

As shown in Figure 1, the pressure loss, ΔP_{zs} , caused by the changes of density inside and outside shaft is a driving force for natural ventilation, which can be written as

$$\Delta P_{zs} = (\rho_0 - \rho_s) g (h_2 - h_1) \quad (1)$$

Without external force, ΔP_{zs} has an important role for the direction and magnitude of air flow in the shaft. According to the formula (1) and ideal gas equation, the smoke velocity of shaft v_s can be achieved:

$$v_s = \sqrt{\frac{2(T_s - T_0)g(h_2 - h_1)}{T_0}} \quad (2)$$

Ignoring the mass variation caused by burning, the following relationship can be obtained according to mass conservation equation,

$$m_{in} = m_{out-1} + m_{out-2} \quad (3)$$

When the smoke does not overflow, it means there is no smoke flowing out of fire room from opening. There is only air-supply through the opening. Then the air-supply volume is equal to the smoke exhaust rate.

$$\rho_0 v_0 S_1 = \rho_s v_s S_2 \quad (4)$$

Where S_1 and S_2 are areas of air-supply opening and smoke vent, respectively (m²).

When the smoke does not overflow, the average air supply velocity can be obtained based on formula (2) and (4):

$$v_0 = \frac{T_0 S_2}{T_s S_1} \sqrt{\frac{2(T_s - T_0)g(h_2 - h_1)}{T_0}} \quad (5)$$

As shown in figure1, in the air-supply opening with smoke flowing, the flow state at outdoor 3 and indoor 4 can be combined through Bernoulli equation, that is

$$\frac{P_4}{\rho_s} + \frac{v_4^2}{2} = \frac{P_3}{\rho_0} + \frac{v_3^2}{2} \quad (6)$$

Where v_3 and v_4 are horizontal flow velocities of point 3 and point 4 over the neutral plane, respectively (m/s). v_4 is assumed approximate to zero because the directional velocity of the indoor mixed gas is very low.

Regard the neutral plane as the datum plane, so equation (6) can be written as following according to the pressure of neutral plane P_∞ .

$$\frac{P_\infty - \rho_s g y}{\rho_s} = \frac{P_\infty - \rho_0 g y}{\rho_0} + \frac{v_3^2}{2} \quad (7)$$

Where y is the distance between neutral plane and the upper of the air-supply opening (m).

The smoke passing through point 3 is just flowing from indoors, so its temperature and density are same to the point 4.

$$v_3 = \sqrt{\frac{2(\rho_0 - \rho_s)gy}{\rho_s}} \quad (8)$$

Therefore, when the neutral plane locates at the bottom of opening, y equal to h_w , the height of opening, the velocity of smoke flowing out from the top edge of the opening is maximum.

$$v_{\max} = \sqrt{\frac{2(\rho_0 - \rho_s)gh_w}{\rho_s}} \quad (9)$$

In order to prevent smoke from fire room, the velocity of air v_0 should be not less than maximum smoke velocity $v_{\max}$. Then based on equations (5), (9) and ideal gas equation, the critical condition to prevent smoke from overflowing the opening is gained.

$$\frac{T_0 S_2}{T_s S_1} \sqrt{h_2 - h_1} \geq \sqrt{h_w} \quad (10)$$

Alpert[15] deduced the relational expression to describe the temperature distribution. For any radial range where $r > 0.18h_1$ under the room ceiling, the maximum smoke temperature can be described by the steady state equation as following.

$$T_s = T_{\max} = \frac{5.38}{h_1} (Q/r)^{2/3} + T_0 \quad (11)$$

Where Q is heat release rate(kW), r is the radial distance from the center line of the shaft to the fire(m).

Then the critical shaft height H for preventing smoke overflowing can be obtained by equations (10) and (11).

$$H = h_2 - h_1 \geq \frac{S_1^2}{S_2^2} \left[\frac{5.38}{h_1 T_0} (Q/r)^{2/3} + 1 \right]^2 h_w \quad (12)$$

3. Simulation

FDS(Fire Dynamics Simulator) was developed by NIST of American and widely used in fire smoke simulation[16,17]. It intends to solve Navier-Stokes equations to represent the fluid flow with low velocity driven by heat. The physical model was shown in Figure 2. The size of room was 6 m×4 m×3 m, the smoke shaft was set at the top of room. This main purpose of this paper is to study the influence of shaft height on smoke control. So the fire was changeless. According to the Chinese Code of smoke control[18], the fire heat release rate for office and public area are 1.5MW and 2.5 MW, respectively. So a wood fire was set as 2 MW and located at the central of the room ground. 16 temperature measuring points were set vertically from 0.2 m to 3.0 m with the interval of 0.5 m, which can analyze the temperature distribution in the room under different conditions. The sizes of the air-supply opening and smoke vent were both 0.6 m×0.6 m. In the center line of the shaft, 12 detecting points of pressure, temperature and velocity respectively from bottom to top were arranged. Some detection surfaces also were set to record smoke volume. In the vertical center line of air-supply opening was equidistant arranged 7 detecting points of pressure, temperature and velocity. Some flow detection surfaces were also set to measure the volume flow rate. Two cut planes were settled to record the velocity contours in the air-supply opening and the pressure contours in the shaft, as shown in Figure 2.

In order to research the influence of shaft height on the effect of smoke control in high rise building room, 9 simulation conditions were arranged, with shaft heights of 3m, 6m, 9m, 12m, 18m, 24m, 30m, 36m, 42m, respectively. The changes of pressure, temperature and velocity in shaft and air supply

opening were achieved respectively using FDS, as well as the amount of smoke overflow. The effect of shaft height on stack effect and smoke control were analyzed.

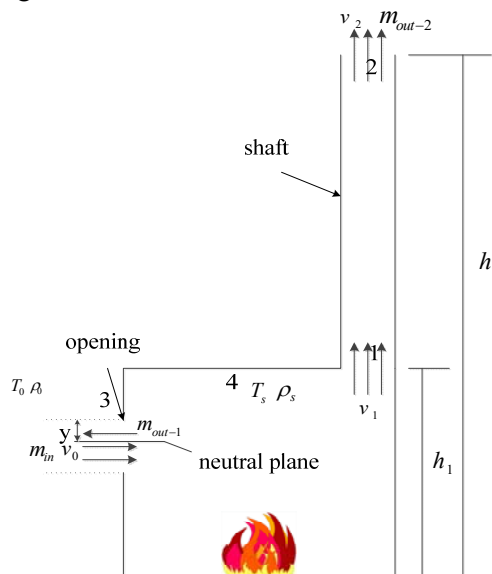


Figure 1. Hydraulic analysis in shaft.

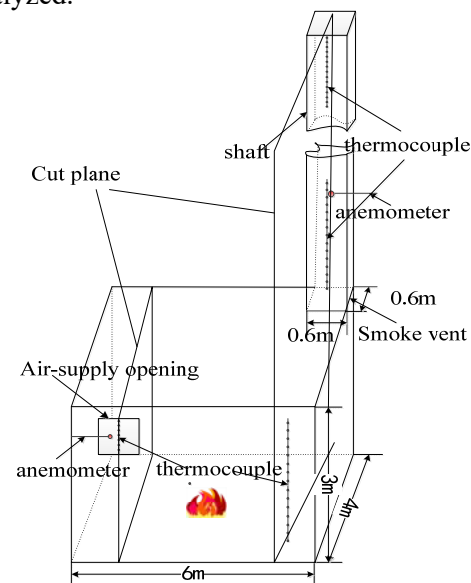


Figure 2. Sketch of physical model.

4. Effect of shaft height on stack effect

As shown in Figure 3, the vertical distributions of temperature in the fire room with different shaft heights were obtained. The temperature was the average value when the fire reached a stable state, as well as other measured parameters in the passage. It can be seen from Figure 3, with increasing of the height at same shaft height, the temperature rises, and the variation trend of temperature is same. The temperature shows a trend of rising with the increase of shaft height. The change of temperature is more obvious when the shaft height is lower, and when the height of shaft is higher than 12 m, the changes is not large. This is because the shaft is too low, the stack effect is not obvious, the supplement of fresh air is not enough, incomplete combustion is caused.

The variations of pressure, velocity and temperature in the center line of the shaft with different shaft height are shown in Figures 4, 5 and 6 respectively. The negative pressure was produced as well as the spontaneous ventilation capacity at the bottom of shaft and the stack effect was obviously with different shaft heights. When the shaft height was 3 m, the negative pressure value was very small, as well as the velocity in shaft. With the increase of shaft height, the negative pressure value increased, the static pressure difference between the top and bottom of the shaft increased, and the velocity of smoke flowing to the shaft also increased. Under different shaft heights, the maximum temperature of smoke at the bottom of shaft only had little difference, but the difference at the exit of the shaft was large. Because of heat loss to wall, the shaft height was higher, the temperature of smoke at the exit of the shaft was lower. But when the shaft height was higher than 30 m, the variation of pressure, velocity and temperature in shaft was small. Values of all parameters at the first point of the shaft were lower than the second. This is because the tilted flame plume is induced by stack effect, which has little effect on the first point, but would affect the second point significantly[19].

The comparisons of static pressure difference by theoretical calculation and simulation between the top and bottom of shaft are listed in table 1. It can be seen that, there are a little errors between theoretical calculations and numerical simulations for static pressure difference. With the increase of shaft height, the static pressure difference between the top and bottom of the shaft increased quickly at the beginning, and then the growth became slow. It illustrates that with the increase of shaft height, the stack effect increases, but it does not keep on increasing with the increase of shaft height, it will

remain unchanged after reaching a critical value. That is to say, the stack effect would not enhance the smoke extraction rate when the shaft is higher than a critical height of 30 m as deduced in this paper.

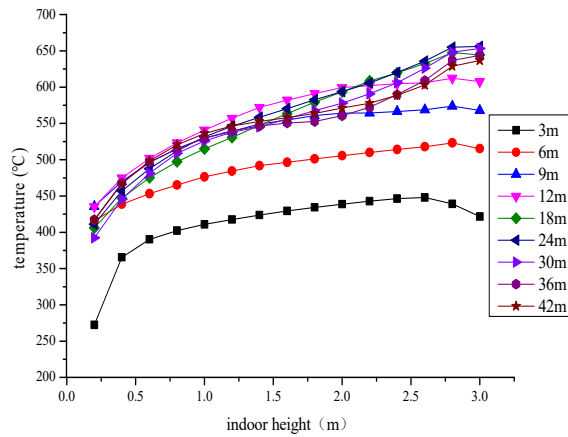


Figure 3. Variation of indoor temperatures with different shaft heights.

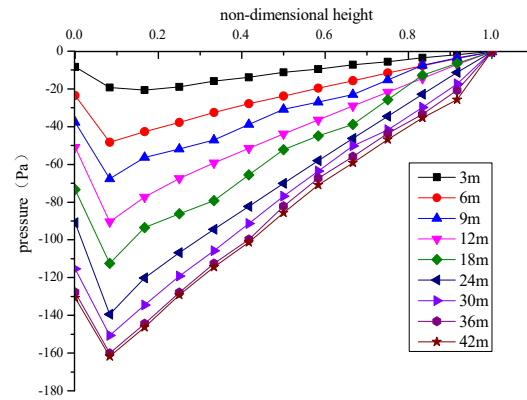


Figure 4. Variation of pressure in the shaft with different shaft heights.

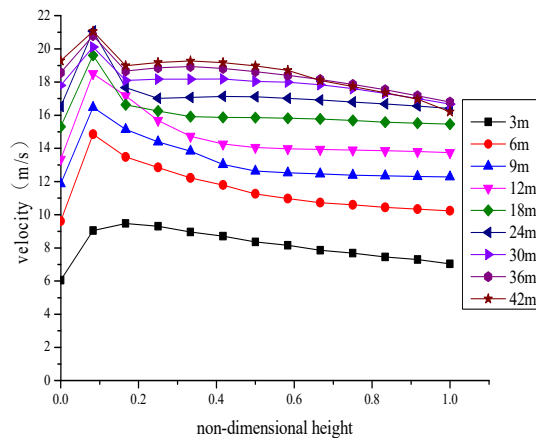


Figure 5. Variation of velocity in the shaft with different shaft heights.

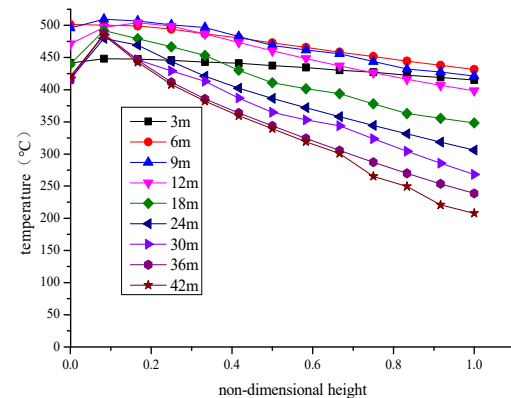


Figure 6. Variation of temperature in the shaft with different shaft heights.

Table 1. Comparison of the static pressure differences between the top and bottom of shaft by theoretical calculation and simulation.

Case	Shaft height (m)	Area of smoke vent (m ²)	Maximum static pressure difference (Pa)		error (%)
			Theoretical calculation	FDS simulation	
1	3	0.6x0.6	21.436	20.6254	3.7
2	6	0.6x0.6	50.172	48.2359	3.8
3	9	0.6x0.6	70.974	67.6716	4.6
4	12	0.6x0.6	95.176	90.3966	5.0
5	18	0.6x0.6	110.366	112.495	1.8
6	24	0.6x0.6	137.113	139.448	1.6
7	30	0.6x0.6	152.737	150.657	1.3
8	36	0.6x0.6	165.383	160.121	3.1
9	42	0.6x0.6	170.364	161.751	5.0

5. Effect of shaft height on smoke control

The variations of pressure, velocity and temperature in the vertical center line of the air-supply opening with different shaft height are shown in figures 7, 8 and 9 respectively. It can be seen from these figures, the negative pressure is formed in the air supply opening. This means the flow through the opening is inward. With the increase of shaft height, the negative pressure value increases. This shows the stack effect increases. It can be seen also that the pressure value at opening top is least. This indicates the smoke is easy to overflow from the opening top. In these cases, only in case 1, the pressures at opening top is positive. This shows that the smoke can overflow from the room in this case. As shown in Figure 8, the velocity of top point of case 1 is less than zero. It also illustrates that there is smoke overflow obviously, and it also can explain why the temperature of case 1 is much greater than others in Figure 9. Because of contacting with smoke, the temperature of air-supply opening is greater than the environment temperature. With the increase of shaft height, the air-supply velocity increases, air-supply volume increases, and the temperature of air-supply opening decreases.

From the equation (12), the critical shaft height is 6.27 m. That is to say, there is no smoke overflow if shaft height is higher than 6.27 m. The result of numerical simulation shows when the shaft height is less than 6 m, the smoke overflows from opening. When the shaft height is larger than 9 m, the smoke cannot overflow from opening, as shown in table 2. So the critical shaft height is higher than 6m but less than 9m. The result of numerical simulation agrees with theoretical calculation. This also shows that the smoke can be confined in the fire room and does not overflow by increasing the shaft height at the condition of natural smoke venting.

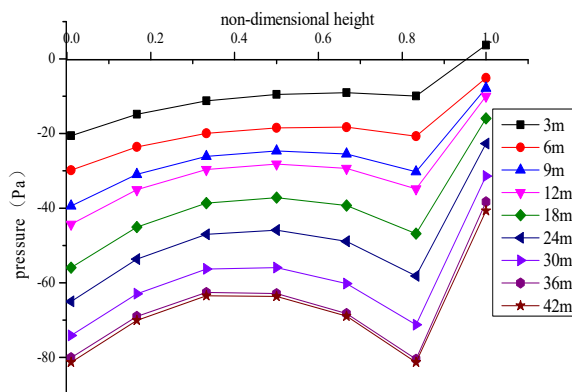


Figure 7. Variation of pressure in air supply supply opening with different shaft heights.

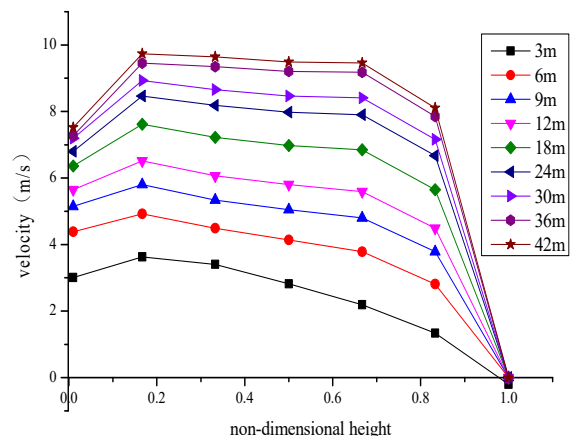


Figure 8. Variation of velocity in air opening with different shaft heights.

Seen from table 2, we can also know that with shaft height increasing, the smoke exhaust rate increased when shaft height was less than 30m. Because the stack effect enhanced with shaft height, the smoke velocity increased obvious as shown in figure 5. But when the shaft height increased to some critical height, 30m in this simulation, the smoke exhaust rate almost stabilized with little variation, even decreased. With the shaft height increasing, the heat loss to the shaft wall was more and more, the temperature decreased as shown in figure 6, and the smoke velocities had little changes as shown in figures 5. So the smoke exhaust rate did not keep increasing.

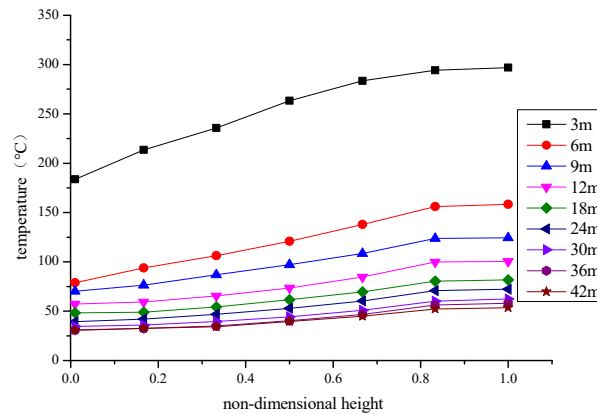


Figure 9. Variation of temperature in air supply opening with different shaft heights.

Table 2. List of the amount of smoke overflow and smoke exhaust under different shaft heights.

Case	Shaft height(m)	Smoke spillage (m ³ /s)	Smoke exhaust rate (m ³ /s)	Smoke overflow	
				Numerical simulation	Theoretical calculation
1	3	0.178394	1.875468	Yes	Yes
2	6	0.102997	2.558896	Yes	Yes
3	9	0	2.9101	No	No
4	12	0	3.115695	No	No
5	18	0	3.342528	No	No
6	24	0	3.449815	No	No
7	30	0	3.49383	No	No
8	36	0	3.506505	No	No
9	42	0	3.452969	No	No

6. Conclusions

Theoretical analysis and numerical simulation method were used to study the influence of shaft height on the smoke control by stack effect. Variations of indoor temperature, and pressure, velocity, temperature in the shaft and air-supply opening under different shaft heights were analyzed. The smoke spillages with different shaft heights were also recorded. The influence of shaft height on stack effect and smoke control in the fire room were discussed.

(1) The critical shaft height condition for smoke control using stack effect was induced and verified by numerical simulation. The results show that with the increase of the shaft height, the value of negative pressure at the air-supply vent increases. The critical shaft height by theoretical equation is 6.27m. The results of numerical simulation shows the critical shaft height to prevent smoke overflow is higher than 6m but less than 9m.

(2) With the increasing of the shaft height, the static pressure difference between the top and bottom of the shaft increases continually until the shaft height reaches a critical height, as well as the stack effect. When the shaft was higher than 30 m, the static pressure difference verified a little. It illustrates, when the shaft height is higher than the critical value, stack effect will not be strengthened more.

(3) Seen from equation (12), besides shaft height, the critical condition to control smoke not flowing out of the room is relevant with many other factors, such as heat release rate, areas of smoke vent and air-supply opening and so on. Therefore the actual situation must be considered to design the shaft scientifically.

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