Effect of Outdoor Wind on the Efficiency of Mechanical Smoke Exhaust in High-rise Building Fires

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Abstract. In this paper, in order to analyze the effect of the outdoor wind on the efficiency of the mechanical exhaust system in high-rise building fires, a 15-floor high-rise building with a long corridor in Nanjing was studied. FDS (Fire Dynamic Simulation) was used to analyze the effect of different smoke exhaust models under the influence of outdoor wind. Without the outdoor wind, the CO₂ concentration in the corridor was 3080ppm, natural smoke exhaust model could meet the need for evacuation. When the outdoor wind speed was 2.4m/s, the CO₂ concentration in the corridor was 5042ppm, which was unable to meet the need for evacuation. Thus additional mechanical exhaust system was necessary to add for reducing the CO₂ concentration in the corridor. Because the outdoor wind speed showed exponential growth with height increased, the CO₂ concentration in the corridor increased with height of fire floor under the same mechanical exhaust system. The smoke exhausting volume should be redesigned, because the traditional mechanical exhaust system was unable to guarantee the people to escape safely when the fire floor was on the 12th floor or above.

1. Introduction
For high-rise buildings, there was no significant effect on internal airflow in the case of high wind speed. However, the windows could be broken during a fire and result in a large amount of fresh air entering the building. The smoke in the building flowed rapidly under the drive of high-pressure wind. According to corresponding statistics, 80% of the casualties were caused by toxic and harmful smoke during a fire.

Given the harmfulness of smoke, it was very necessary to establish a reasonable smoke control model to reduce the damage of the smoke. The corridor was the main way to escape during a fire. In recent years, many scholars have devoted to the study of smoke control models [1-6]. However, these studies have not discussed the influence of wind on the diffusion of smoke. Wind as a natural phenomenon has a serious impact on the diffusion of smoke in high-rise building fires. Therefore, it has great significance to study the influence of wind on the smoke control models in high-rise building fires.

Therefore, the FDS (Fire Dynamic Simulation) was used to analyze the effects of different smoke control models under the influence of wind with the different height of fire floor.
2. Physical model

2.1. Physical Model
As shown in Figure 1, a 15 floors high-rise office building in Nanjing was built. The corridor was 30m length, 2m width and 3m height. On both sides of the corridor were the offices, which were 6m x 5m x 3.2m. The window was 2.1m x 1.8m at the end of the corridor. The door of atria was 1.3m x 2.1m. The window was 4m x 1.8m in the office. The physical model of the corridor was shown in Figure 2.

![Figure 1. Physical model of building](image1)

![Figure 2. Fire layer physical model diagram](image2)

2.2. Boundary condition
The following formula was used to describe the relationship between wind speed and height:

\[ v = v_1 \left( \frac{h}{h_1} \right)^n \text{ m/s} \]

(1)

Where \( v \) was the wind speed at the height \( h \) from the ground, m/s; \( h_1 \) was selected as the reference height which was 10m, and \( v_1 \) was the average winter wind speed in Nanjing which was 2.4 m/s. \( n \) was the wind speed index which was 0.4 in the article[7].

During the simulation, the doors and windows of the fire room were set as the opening. Both the door from the corridor to the atria and the door from atria to the stairwell were opened, and the doors of the first and the fifteenth were used as the escaping door. The doors and windows of other floors were
closed. The initial temperature in of this building was 20°C; the surrounding temperature was 0°C and the pressure was 101.325KPa; the fire source was an unstable volume heat source and the fire heat release rate was 0.046KJ/s². The maximum heat release rate reached 1.5 MW at 180s; the area of fire source was 1m².

2.3. Condition settings
"Code of Design on Building Fire Protection and Prevention" stipulates that: The natural ventilation area of fire room and the corridor was less than 2% of its area. It was not necessary to set up mechanical smoke exhaust facilities. According to the physical model of the high-rise building, the area of the smoke control zone was 90m² in all, including the area of the fire room and the corridor. The mechanical smoke exhaust volume was 5400m³ when the mechanical smoke exhaust was set. A mechanical exhaust outlet with 1.4m × 0.5m was located in the middle of the corridor. A smoke screen with the height of 0.5 m was set, and the distance between the smoke screen and the mechanical exhaust outlet was 1m. Some typical settings were analyzed under the influence of outdoor wind to obtain the optimum setting of smoke control model. Four conditions were taken into consideration to compare the influence of wind speed on the different smoke control model. The setting of the conditions was shown in Table 1.

| Condition | Wind speed (m/s) | Mechanical smoke exhaust | Smoke screen |
|-----------|-----------------|--------------------------|--------------|
| Condition one | 0 | N | N |
| Condition two | 2.4 | N | N |
| Condition three | 2.4 | Y | N |
| Condition four | 2.4 | Y | Y |

3. Numerical simulation criterion

3.1. Time criterion
There was a fire alarm device in the corridor. After the fire occurred for the 60s, the alarm was issued and the mechanical exhaust system started to run. The occupants’ response time was 120s. The evacuation speed of the occupants in the rooms and corridor was 1m/s and 0.6 m/s respectively. The minimum required safety evacuation time for the fire floor was calculated as 240s.

3.2. Temperature and concentration criteria
This simulation mainly focused on the temperature and CO₂ concentration at the characteristic height of occupants’ eyes. The characteristic height of occupants’ eyes was selected as 1.6 m. The corresponding study showed that occupants could only survive 5 min when the temperature of smoke was 140°C, and the CO₂ concentration should be less than 5000 ppm during the evacuation. Therefore, the temperature of 140 °C and the concentration of CO₂ of 5000 ppm were used as the risk criteria [8].

3.3. Smoke efficiency calculation
Mechanical exhaust efficiency referred to the ratio of \( m_e \) to \( m_p \), as shown in equation (2):

\[
\eta = \frac{m_e}{m_p} \tag{2}
\]

The mass flow rate \( m_e \) of the mechanical smoke exhaust can be calculated using formula (3):

\[
m_e = \rho_e V_e = \frac{1.29 \times 273}{T_r + 273} V_e \tag{3}
\]
η was the mechanical smoke exhaust efficiency; \( m_p \) was the mass flow rate of the smoke that diffuses into the corridor, and \( m_e \) was the mass flow rate of the smoke emitted from the mechanical smoke exhaust. \( T_s \) was the average temperature of the smoke and \( V_e \) was the flow volume of the fan.

4. Results analysis

4.1. The effect of outdoor wind with natural smoke exhaust
The windows could be broken due to the high temperature and high pressure during a fire. On the one hand, the fire plume was more likely to induce the fresh air, which generated a lot of smoke. On the other hand, the wind restrained the phenomenon that the smoke rush to the outside. Thus, a large amount of smoke diffused from the fire room to the corridor. Figure 3 and Figure 4 showed respectively the CO\(_2\) concentration and temperature distribution in the corridor at 240s under condition one and condition two. Without the wind, the average CO\(_2\) concentration was 3080 ppm. With the increase of the wind speed, the smoke was restrained from the window to the outside, which made more and more smoke diffuse to the corridor. The average CO\(_2\) concentration in the corridor increased by 65.2% compared with the condition one, which was unable to keep people evacuate safety.

The average temperature in the corridor was 15.3 \(^\circ\)C without the wind speed, and the average temperature in the corridor was 46.7 \(^\circ\)C when the outdoor wind speed was 2.4m/s. At the right end of the corridor, there was smoke reflux due to the occlusion of the atria. Consequently, the highest temperature near the atria was up to 62.4 \(^\circ\)C due to the smoke accumulation.

![Figure 3. Distribution of CO\(_2\) concentration in the corridor](image-url)
4.2. The effect of different smoke control models

From 4.1, natural smoke exhaust was unable to meet the occupants’ evacuation when the wind speed was 2.4 m/s. Therefore, it was necessary to add the mechanical exhaust system to reduce the smoke concentration in the corridor. Figure 5 and Figure 6 respectively showed the CO₂ concentration and temperature distribution in the corridor at 240s under three different conditions. When the outdoor wind speed was 2.4m/s, mechanical smoke exhaust was set in the corridor to discharge a large amount of smoke under condition three. As a result, the CO₂ concentration and smoke temperature in the corridor decreased significantly. The average CO₂ concentration was 3247ppm, which was 35.6% lower than the condition two, and the average temperature in the corridor decrease by 16.3℃. The smoke accumulated in front of the smoke screen under condition four. When the smoke layer was lower than the height of the smoke screen, the smoke could spread in the corridor. The CO₂ concentration and temperature of smoke near the smoke screen increased due to the accumulation of the smoke, and the average CO₂ concentration and the average temperature of smoke decreased from smoke screen to the atria obviously because mechanical smoke exhaust discharged a large amount of smoke.

Figure 5. Distribution of CO₂ concentration in the corridor
4.3. The effect of wind on the mechanical exhaust system of the different fire floor

In order to analyze the effect of wind on the mechanical exhaust system of different fire floors, the fire locations of 7th, 10th and 13th floor were investigated respectively. The smoke exhaust models in the corridor were the same as condition four. Figure 7 and Figure 8 showed the distribution of CO₂ concentration in the fire floor corridor with different height at 240s. From the Figure 7, the average CO₂ concentration and temperature of smoke in the corridor increased with the height of the fire floor significantly. The average CO₂ concentration in the corridor of the 7th, 10th and 13th floor were 4456ppm, 4635ppm and 5161ppm respectively and the average temperature in the corridor were 42.1℃, 44.9℃ and 49.8℃ respectively. When the fire floor was the 13th floor, the CO₂ concentration in the corridor was over 5000ppm, which could be harmful for the evacuation.

Figure 6. Temperature distribution in the corridor

Figure 7. Distribution of CO₂ concentration in the corridor
In order to find out the fire floor that mechanical exhaust modes could be unable to satisfy the escape for occupants, the fire floors of 11th, 12th, 14th and 15th were added respectively. From Figure 9, the average CO$_2$ concentration in the corridor were 4785ppm, 5080ppm, 5257ppm and 5359ppm respectively with different fire floor. Besides, the mechanical smoke exhaust efficiency of the fire floors on the 12th floor and above were 47.4%, 45.7%, 44.8% and 44.2% respectively, which indicated that the efficiency of mechanical smoke exhaust in the corridor decreased with the height of the fire floor. When the wind speed increased with the height of the fire floor, the volume of smoke that spread from the opening of the building to the outside was reduced and that spread to the corridor increased. Therefore, the mechanical exhaust efficiency decreased when the height of fire floor increased.
Figure 10. Mechanical smoke volume and floor fitting

When the CO$_2$ concentration in the fire floor corridor exceeded the critical concentration, different mechanical smoke exhaust volume was selected according to formula (4)

$$v(z)c_0(z) - v_0c_0(z) = \frac{V_a(c(z) - c_0(z))}{\eta}$$

(4)

Where $c(z)$ was average CO$_2$ concentrations in different fire floor corridor when it exceeded the critical concentration, $c_0(z)$ was the critical criterion for CO$_2$ concentration inside the corridor, $V_a$ was the total volume of the corridor, $v$ was the mechanical smoke exhaust volume which was selected with the area of smoke control zone, $\eta$ was the mechanical smoke exhaust efficiency, $t$ was the time from the start of mechanical smoke exhaust to time for judgment. Through equation (4), the relationship between the required mechanical smoke exhaust volume and the fire floor was calculated: $v(z) = 0.0426z + 1.0204$.

The average CO$_2$ concentration in different fire floor corridors at 240s was shown in figure11. The average CO$_2$ concentration in the corridors of the 12th ~ 15th floor were 4882ppm, 4839ppm, 4895ppm and 4928ppm respectively. They were all lower than the critical concentration of 5000ppm, meeting the need of evacuation for occupants.

Figure 11. Average concentration of CO$_2$ in the corridor
5. Conclusion
Without the wind, the CO$_2$ concentration and the average temperature in the corridor can meet the need of evacuation for occupants by the natural smoke exhaust. When the wind speed was 2.4m/s, the CO$_2$ concentration in the corridor under natural smoke exhaust increased by 65.2% and the temperature increased by 31.4℃, which was unable to meet the need of evacuation for occupants.

Under the influence of wind, the concentration of CO$_2$ and average temperature in the corridor increased with the height of fire floor. When the fire floor was below the 12th floor, the traditional mechanical smoke control model can meet the needs for escaping. When the fire location is on the 12th floor or above, the traditional mechanical smoke exhaust model was unable to meet the need for escaping. The volume of mechanical smoke exhaust should be increased.

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