Study of Smoke prevention and Exhaust System for High-rise Buildings

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Abstract: Nowadays, the smoke prevention and exhaust system has not been effectively taken seriously, but smoke in fire disasters have become an important cause of death. In this paper, some problems still exist in smoke prevention and exhaust system will be concluded including design inspection and maintains. Meanwhile, a new method of calculating volumetric flow rate of smoke exhaust in high-rise building will be shown. The results show that the existing prevention and exhaust systems in high-rise buildings have some defects and need to be upgraded. Outdoor wind in high-rise buildings is an important effect of fires. Some significant and easily ignored aspects of inspection and maintains will also be summarized.

1. Introduction
In fire disasters, the main reason of death in fires is caused by smoke, which occupies 80% [1]. Smoke can cause oxygen deficient and generate toxic gases, such as sulfur dioxide and hydrogen sulfide. A high-rise building, denoting as a construction higher than 75 feet, or about 7 stories (National Fire Protection Association, NFPA) [2], includes both the residential buildings higher than 27 m, non-single-storey factory buildings, warehouses, and other civil buildings higher than 24 m (GB) [3]. High-rise building fires are the most frequent ones [4] among all fire types, such as construction site fires, school fires. Fires in high-rise buildings have following characteristics: rapid-spreadingsmoke, hidden fire hazards, long time and evacuation distance, and difficult-extinguished fires [5].

There were 6974 high-rise building fires occurring in 2018 in China, which has increased by 10.6% compared with those occurring in 2017 [4], so the installation of the smoke prevention and exhaust system is of primary importance. Smoke prevention and exhaust system refers to the system composed of all smoke prevention and exhaust facilities, which should be installed in the building following the requirements of the construction regulations.

This study summarizes the smoke prevention and exhaust applications in high-rise buildings. Furthermore, some advice and upgrades on smoke prevention and exhaust systems in high-rise buildings will be given.

These contents shown in the next sections is followed by the problem statement, the design and calculations of smoke exhaust system, inspection and maintains and discussion and conclusions:
- Problem statement
- The principle and types of smoke prevention and exhaust system is shown in the next section. The
investigation and research of the previous researchers would be summarized, and some problems of designing and application of smoke exhaust system in high-rise buildings could be pointed out.

- Design and calculations
  The smoke prevention and exhaust system design and installation will be introduced by using codes and standards, and give some upgrades based on existing smoke prevention and exhaust system. Meanwhile, an experiment and calculations about volumetric flow rate of smoke exhaust of mechanical smoke exhaust system in outdoor wind will be shown.

- Inspection and maintains
  In this part, inspection and maintains of smoke prevention and exhaust system will be shown and give an improvement.

- Discussion and Conclusions
  The result of this paper and discussion will be reveal in this section.

2. Problem Statement

The characteristics of high-rise building fires have been shown above. However, other differences still exist between high-rise building fires and other fires, such as the chimney effect, the occupancy of high-rise buildings, and the outdoor wind. The chimney effect is unique to high-rise fires, which is a phenomenon that the combustion products (including smoke) quickly move to a higher position. The higher of the building is, the greater the temperature difference is along the course of a fire, which will also cause a more evident chimney effect. The chimney effect is an important reason why high-rise building fires are easy to cause death and property loss [6]. Furthermore, high-rise buildings are usually multiple occupancy buildings so that more hazards occur in high-rise buildings. For high-rise buildings, outdoor wind has an obvious affect because the higher the buildings are, the faster of the wind speed is. This will be mainly discussed in the next section.

High-rise buildings have longer escape distances, and people have more opportunities to be enveloped in smoke, that is the reason why so many people die from the suffocation, not from the flame itself. In order to decrease life and property losses, it is necessary to install smoke prevention and exhaust systems. The smoke prevention and exhaust system of fire protection is a special system for supplying, preventing and exhausting ventilation with manual or automatic control, which has the following functions:

- Prevent smoke from spreading in a building;
- Remove smoke and other hazardous gaseous substances in a building;
- Supply fresh air.

Most of smoke prevention and exhaust systems have five components: fans, air ducts, automatic smoke exhaust valves, smoke dampers, and control cabinets. The principle of the smoke prevention and exhaust is that when the fire control center receives a fire signal from a smoke detector, the smoke exhaust fan is linked to a control. The cabinet starts the fan and opens the smoke exhaust valve to discharge the smoke from the air pipe to the outside [7].

By functional features, smoke prevention and exhaust systems have two types: a smoke prevention system and a smoke exhaust system. Smoke prevention systems have two methods to prevent smoke: a pressurization method and an airflow design method. The airflow design method is discussed in this paper. Among designing features, smoke exhaust systems have two types: a natural smoke exhaust system and a mechanical smoke exhaust system. Natural smoke exhaust systems exhaust smoke according to the facilities of the building such as windows, doors, etc. Mechanical smoke exhaust systems drive off the smoke from a building to its outside and supply with fresh air.
For high-rise buildings, smoke prevention and exhaust systems are significant. In this paper, natural smoke exhaust systems and mechanical smoke exhaust systems are introduced emphatically. However, some problems still exist in the smoke prevention and exhaust system for high-rise buildings:

- The natural smoke exhaust systems of high-rise buildings lack reliability
  Most high-rise buildings are multiple occupancy and have many internal areas, which make the internal space structure of high-rise buildings more complicated. A complicated space influences the direction and the speed of smoke [8]. In this situation, the natural smoke exhaust systems used in other buildings may not be suitable for high-rise buildings.

- The effect of outdoor wind
  The speed of wind will increase with the increase of building height, so wind should be considered in designing the smoke prevention and exhaust systems of high-rise buildings. However, outdoor wind is usually be ignored in a design process. Mechanical smoke exhaust system with outdoor wind will thus be shown in the next section.

- Lack of inspection and maintains
  Although some high-rise buildings are equipped with smoke prevention and exhaust systems due to the lack of regular inspection and maintenance, many systems have problems, which makes the fire signal cannot be responded in time.

3. Design and Calculations

The natural smoke exhaust system is a kind of smoke exhaust systems that discharges smoke to the outside in a natural way. The natural smoke exhaust system mainly relies on the convection movement of the cold and the hot air flow inside and outside [11]. Natural smoke exhaust systems can exhaust smoke when power is off. However, this system is easily affected by the wind direction and speed, which causes many unstable factors in the smoke exhaust system. Natural smoke exhaust systems are thus better to be cooperated with automatic fire alarm systems and mechanical smoke exhaust systems.

Natural smoke exhaust windows should be installed when the natural smoke exhaust systems are used. When calculating the effective smoke exhaust areas, window areas are calculated according to the actual opening area, and other windows are calculated according to their opening projection areas [12]. Effective smoke exhaust area $F_p$ is generated from the area of window $F_c$ and the angle of window $\alpha$ [10]. The relevant equation is shown as follows [10]:

$$F_p = F_c \cdot \sin \alpha \quad \text{(Equation 1)}$$

When $\alpha > 70^\circ$, $F_p$ is equal to $F_c$ [11]. By using the equation above, it is better to install a sliding window or any other windows which can be opened above $70^\circ$ in buildings under the condition of $F_p = F_c$. However, in high-rise buildings, the angle of the windows should not be too large so that the effect of natural smoke exhaust systems is limited.

Meanwhile, it should be ensured that all natural smoke exhaust windows in the smoke-proof zones can be switched on in a centralized manner. They should be installed nearby the exits so that the natural smoke exhaust can be reliably opened by manual devices. This can make the effect of smoke exhaust in the situations of power be off and other automatic fire protection systems become invalid.
For high-rise buildings, outdoor wind exists, which can strongly affect smoke exhaust of natural smoke exhaust system. When the outdoor wind is 2.3 m/s, the smoke production is 2.6 times higher than that without wind flows[11].

The mechanical smoke exhaust system is a smoke exhaust system that exhausts smoke by using mechanical devices. These points are advised in the design except for some basic requirements:

- The smoke exhaust fan and the smoke exhaust pipe should be able to continuously work for 30 minutes in 280°C so as to prevent the system break caused by high temperatures.

- The wind speed of the exhaust vent should not be greater than 10 m/s [10]. Excessive intake of ambient air will increase the proportion of air in the exhaust smoke and affect the smoke exhaust. Moreover, the wind pipe is prone to howling and vibration [10], and it easily affects the structural integrity and stability of the wind pipe when the speed is more than 10 m/s.

- In order to ensure that the smoke exhaust fan can operate normally for at least 30 minutes under the smoke exhaust conditions and to prevent the fan from being directly threatened by fire, the smoke exhaust fan should be installed in a safe place [10]. When the conditions are limited, the smoke exhaust fan should be protected by the other fire protection systems such as fire doors, fire stops, etc. Moreover, the volume of this space cannot be too small so that employees can inspect and maintain it easily.

Next, the calculations of mechanical smoke exhaust rate will be shown as follows. Some calculations of mechanical smoke exhaust do not consider the effect of outdoor wind. However, outdoor wind is an important factor of high-rise building fire [11].

Li Sicheng-Chen Ying model [11] chooses to calculate volumetric flow rate of smoke exhaust in a high-rise building, such as: there is a high-rise building in Chengdu city, which has 140 m height. The occupancy of this building is office, each floor is 3.8 m height. The area of each floor is 1650 m², every floor has three smoke control zones, so the area of each smoke control zone is 1650/3=550 m². Meanwhile, each floor has sprinkler system by assuming that the ignition point is on the floor. First of all, the volumetric flow rate of smoke exhaust without considering wind speed is calculated by using GB51251-2017 (Technical standard for smoke management systems in buildings). The mechanical smoke exhaust rate of each floor should be greater than 60 m³/h, so the volumetric flow rate of smoke exhaust is calculated by using

\[ V_0 = 550 \times 60 = 33000 \text{ m}^3/\text{h}, \]

and the minimum volumetric flow rate of smoke exhaust is 15000 m³/h [10]. The steps to calculate volumetric flow rate of mechanical smoke exhaust system are shown as follows:

**Step 1: Calculate wind speed** [11]

\[ \mu = \mu' \left( \frac{H}{H'} \right)^k \]

In above equation, \( \mu \) is wind speed, \( \mu' \) is wind speed of reference height, in this calculation, we assume this value is 1 m/s. \( H \) is the height of floor, and \( H' \) is the reference height, which is usually 10 m in calculation. \( k \) is a constant value, which is usually 0.4 in the city buildings.

**Step 2: Calculate the plume unsteady wind speed and the minimum clear height** [11]

\[ u'_0 = \frac{1.43l}{\sqrt{A}} h_q = 1.6 + 0.1h \]

In this equation, \( u'_0 \) is the plume unsteady wind speed, \( l \) is the distance between fire plume and window, assuming that this value is 5 m. \( A \) is the area of window, assuming that the length is 1.2 m and the width is 1.2 m, so the area of the window is 1.44 m². However, when \( \mu > \mu'_0 \), the model is not suitable. \( h_q \) is the minimum clear height and \( h \) is the height of each floor.

**Step 3: Calculate characteristic height of smoke layer** [10]

\[ Z_B = 0.166 Q_c^{\frac{2}{3}} \]

\( Z_B \) is the characteristic height of smoke layer, \( l \) is the distance between fire plume and window, assuming that this value is 5 m. \( Q \) is the heat output, this value is chosen by 1500 kw for this value by
using GB51251-2017 [10], and $Q_c$ is the convective heat output, which is 0.7 $\dot{Q}$.

Step 4: Calculate smoke production rate [11]

$$m_p = \left\{ \begin{array}{ll} 0.00368Q_c^{0.945}z^{1.782} & \text{if } 1 < z < z_B \\ 0.00834Q_c^{1.084}z^{2.064} & \text{if } z > z_B \end{array} \right.$$ 

In this example, $z \geq h_q$, $m_p$ is the mass flow rate plume at height at $z$, where $z$ is the height of smoke layer, which is 2 m [11]. $\tau$ is a constant value: $\tau = 1$ when $l/\sqrt{A} \leq 8$, while $\tau = 7$ when $l/\sqrt{A} > 8$. In this example, $\tau = 1$ and $\mu$ is the wind speed.

Step 5: Calculate volumetric flow rate of smoke exhaust. [11]

$$V_s = 3600 \times \frac{m_p(T_0 + Q_c/m_pc_p)}{\rho_0T_0}$$

In above equation, $V_s$ is the volumetric flow rate of smoke exhaust, $m_p$ is the mass flow rate plume at height at $z$, and $\rho_0$ is air density, which is usually 1.29kg/m3. $T_0$ is absolute ambient (air) temperature, which is 293.15 K in this example. $c_p$ is the specific heat capacity at constant pressure, this value of air is 1.004kJ/(kg*K)

Next, the calculation is shown in the following sheet:

Table 1: The volumetric flow rate of smoke exhaust in different heights

| H(m) | $\mu$ (m/s) | $\mu'$ (m/s) | $Q$ (kw) | $Q_c$ (kw) | $h_q$ (m) | $z_B$ (m) | $m_p$ (kg/s) | $V_s$ (m$^3$/h) |
|------|------------|--------------|----------|------------|-----------|---------|-------------|----------------|
| 10   | 1.00       | 8.94         | 1500     | 1050       | 2         | 2.68    | 9.92        | 38000          |
| 20   | 1.32       | 8.94         | 1500     | 1050       | 2         | 2.68    | 11.38       | 42000          |
| 30   | 1.55       | 8.94         | 1500     | 1050       | 2         | 2.68    | 12.34       | 44000          |
| 40   | 1.74       | 8.94         | 1500     | 1050       | 2         | 2.68    | 13.06       | 46000          |
| 50   | 1.90       | 8.94         | 1500     | 1050       | 2         | 2.68    | 13.65       | 48000          |
| 60   | 2.05       | 8.94         | 1500     | 1050       | 2         | 2.68    | 14.16       | 50000          |
| 70   | 2.18       | 8.94         | 1500     | 1050       | 2         | 2.68    | 14.60       | 51000          |
| 80   | 2.30       | 8.94         | 1500     | 1050       | 2         | 2.68    | 14.99       | 52000          |
| 90   | 2.41       | 8.94         | 1500     | 1050       | 2         | 2.68    | 15.34       | 53000          |
| 100  | 2.51       | 8.94         | 1500     | 1050       | 2         | 2.68    | 15.67       | 54000          |
| 110  | 2.61       | 8.94         | 1500     | 1050       | 2         | 2.68    | 15.97       | 55000          |
| 120  | 2.70       | 8.94         | 1500     | 1050       | 2         | 2.68    | 16.24       | 55000          |
| 130  | 2.79       | 8.94         | 1500     | 1050       | 2         | 2.68    | 16.50       | 56000          |
| 140  | 2.87       | 8.94         | 1500     | 1050       | 2         | 2.68    | 16.75       | 57000          |

By the calculation above, these values are all greater than 33000 m$^3$/h, so outdoor wind speed has a great influence on the volumetric flow rate of smoke exhaust. Outdoor wind needs to be considered in the calculation of mechanical smoke exhaust system. Moreover, if $m_p > 150$ kg/s, the system cannot exhaust smoke in time [11], so the smoke prevention system and the natural smoke exhaust systems are necessary to be considered in this situation.
Figure 2. The Relationship Between Volumetric Flow Rate of Smoke Exhaust and Height of the building

4. Inspection, Testing and Maintains
Inspection and maintains are as important as design for the fire protection equipment. Some rules of inspection and maintains from GB51251-2017 and NFPA 92(Standard for Smoke Control Systems) is concluded below [10] [12]:

- Inspectors have the responsibility of reliable operation of the system. Only professionals who are familiar with the principles of smoke prevention and exhaust systems and performance operation processes can properly manage, operate, and detect. Therefore, inspectors should be trained and hold a certificate [10].
- Rules of full testing is shown below:
  - Natural smoke exhaust systems should be tested annually, and mechanical smoke exhaust systems should be tested semiannually [10] [12].
- Rules of partial testing is shown in the following table:

| Components     | Inspection and maintains                                      | Period   |
|----------------|---------------------------------------------------------------|----------|
| Pipes          | Check if the pipe is deformed                                 | Weekly   |
| Inert          | Should be switch on in a manual or automatic way and make sure it can work correctly | semiannually |
| Smoke damper   | Should be switch on in a manual or automatic way and make sure it can work correctly | semiannually |
| Exhaust fan    | Should be switch on in a manual or automatic way and check if the fan is rusty or loose screws | Quarterly |
Electrical circuit Confirm whether the circuit is aging Quarterly

| System power | Check if the voltage, current and other values of the power | Weekly |
| Smokebarrier | Should be switch on in a manual or automatic way and check if it can be opened correctly | Quarterly |

5. Conclusions
High-rise building fires increase dramatically in these years [4]. However, many high-rise buildings in China have no smoke exhaust systems or only have unqualified smoke prevention and exhaust systems. Some points waiting to be improved are presented below by some depiction and calculations:
Characteristics of high-rise building fires need to be confirmed, because many differences are between high-rise building fires and fires in other buildings. Furthermore, smoke in high-rise buildings can spread faster than that in the other buildings because of the influence of outdoor wind and the large spaces in high-rise buildings.

- For natural smoke exhaust systems, the angle of the window needs to be chosen carefully in high-rise buildings. The angle should not be too large under the premise of ensuring the smoke exhaust effect. Meanwhile, airflow design method of smoke prevention systems are needed in high-rise buildings. For example, a large volume smoke exhaust zone or smoke-proof corridor can make natural smoke exhaust system work better.
- For smoke prevention systems, smokebarrier need to be checked quarterly to make sure it can prevent the spread of the smoke [10].
- In above calculations, volumetric flow rate of smoke exhaust has been determined. The value is 33000 m³/h without considering outdoor wind. However, all values are greater than 33000 m³/h with considering outdoor wind. It shows outdoor wind need to be considered in high-rise buildings in smoke exhaust systems.
- Inspections, testing and maintains should be resolutely implement by code GB51251-2017, Technical standard for smoke management systems in buildings
- Inspectors should be trained before inspecting smoke exhaust systems [10].

6. Nomenclature
F<sub>p</sub>: effective smoke exhaust area (m²)
F<sub>c</sub>: area of window (m²)
α: angle of window, if α > 70°, F<sub>p</sub> = F<sub>c</sub>
μ: wind speed (m/s)
μ<sub>r</sub>: wind speed of the reference height (m/s), in this calculation, we assume that this value is 1 m/s
H: height of the building (m)
H<sub>r</sub>: reference height (m), which is usually 10 m in calculation
k: a constant value, which is usually 0.4 in city
μ<sub>µ</sub>: plume unsteady wind speed (m/s)
l: the distance between fire plume and window (m), assume that this value is 5 m
A: area of window (m²), assume that the length is 1.2 m and width is 1.2 m, so the area of the window is 1.44 m²
h<sub>q</sub>: the minimum clear height (m)
h: height of each floor (m)
Z<sub>B</sub>: characteristic height of smoke layer (m)
Q: heat output (kw), we choose 1500 kw for this value by using GB51251-2017 [10]
Q<sub>c</sub>: convective heat output (kw), which is 0.7 Q
mₚ: mass flow rate plume at height at z (kg/s)

z: height of smoke layer (m), which is 2 m [10]

τ: a constant value: τ = 1 when \( l/\sqrt{A} \leq 8 \), while \( \tau = 7 \) when \( l/\sqrt{A} > 8 \), so in this example, we choose \( \tau = 1 \)

Vₛ: volumetric flow rate of smoke exhaust (m³/h)

mᵣₚ: mass flow rate plume at height at z (kg/s)

ρ₀: air density, which is usually 1.29 kg/m³

T₀: absolute ambient (air) temperature (K), which is 293.15 K in calculation

\( c_p \): specific heat capacity at constant pressure, this value of air is 1.004 kJ/(kg*K)

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