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Smoke Prevention and Exhaust System for Buildings Based on Performance-Oriented Design

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ABSTRACT

To improve the efficiency of smoke prevention and exhaust (SPE) system for buildings, this paper analyzes the building space structure, SPE design and equipment, fire control strategy, and smoke features of emerging buildings, namely, metro stations, tunnels, atriums, and underground garages, and evaluates the reliability of water curtain system in SPE design. By analyzing the factors affecting the SPE efficiency of buildings, the authors measured the effect of building SPE plan and evacuation situation, and summarized the keys and technical difficulties in the SPE system research of different types of buildings. Considering building features and SPE optimization strategy, it is recommended to apply water curtain system as fire partitions in metro stations and underground garages. The proposed optimization strategy, coupled with the original SPE system for buildings, marks the research trend of SPE system for emerging buildings in future.

1. INTRODUCTION

Recent years has witnessed the burgeoning of emerging buildings, such as large metro stations, tunnels, atriums, and underground garages. In this context, it is particularly important to optimize the smoke prevention and exhaust (SPE) system for buildings, which plays a key role in protecting personal safety and property.

The SPE system for buildings has mainly been studied through model experiments and simulations. For instance, Zhong et al. [1] summarized the full-scale experiments on metro stations, and identified the deficiencies in experimental methods and evacuation. Using fire dynamics simulator (FDS), Yao et al. [2] numerically simulated a complex metro station, and proposed a reasonable SPE plan for the station. Liu [3] reviewed the smoke flow and control of atriums, and analyzed the factors affecting the smoke flow and smoke control system in atrium fire through numerical simulation and similar model experiments. Barbato et al. [4] reviewed the ventilation systems of highway tunnels, and presented numerical strategies and graphical methods for some situations. Li and Ingason [5] reviewed the fire safety research of underground highway and railway tunnels. Zhang et al. [6] numerically simulated how the ventilation of underground garages affects the fire spread and smoke flow, and divided the fire development into four stages. Tong et al. [7] explored the mixed ventilation mode of large buildings through reduced-size experiments and simulations, and derived a reasonable ventilation and exhaust scheme.

The existing studies on SPE system for buildings started late. Most of them strictly follow relevant codes. However, there is little report that summarizes the research on the SPE system for emerging buildings. To ensure the fire safety of modern buildings, the SPE design and fire equipment layout of emerging buildings must orient to performance [8]. The SPE system for emerging buildings should be designed according to the layout and usage of the specific building.

Therefore, this paper summarizes the SPE systems for four different types of buildings, and evaluates the reliability of water curtain system in SPE design. The research findings shed new light on the SPE system for future buildings.

2. SPE SYSTEM FOR METRO STATIONS

Each metro station consists of a platform layer and a hall layer. Most underground platforms are island platforms. The key difficulties of the SPE system for metro stations include the platform of transfer station, atrium-type station, and the tunnel. Zhong et al. [9] designed an experimental method for metro fire, in which each variable corresponds to multiple sets of experiments. Their research inspires many simulations and experiments.

Despite the growing size of transfer halls in metro stations, there is no mandatory requirement on the area of fire compartments in such a public zone. It is difficult to optimize the SPE design of the platform by setting up fire partitions [10]. The *Code for Design of Metro* (GB50157-2013) [11] stipulates that, in the public area of hall and platform, the size of each smoke zone partition should not surpass 2,000m^2.

The conventional exhaust mode, which turns on the SPE system in the fire area only, might not satisfy the exhaust and ventilation requirements of large transfer stations. If the platform catches fire, the spread of fire smoke could be better controlled by turning on auxiliary exhaust equipment, such as the fans on the platform and in the tunnel [12]. Since the platform and tunnel are closely connected, reasonable fire partitions will effectively improve the efficiency of the SPE system, and curb the spread of smoke.

2.1 SPE for atrium-type metro station

The atrium-type metro station is so named for its atrium-style platform and hall. In large transfer stations, the smoke spread can be effectively suppressed through the natural ventilation by opening roof windows on the atrium ceiling, coupled with mechanical ventilation, thereby lowering the carbon monoxide (CO) concentration in the hall. The mean CO concentration in the hall plunges with the growing size of the windows and the volume of ventilation [13].

Focusing on four smoke zone partitions of an atrium-type metro station, Xu et al. [14] observed the smoke spread at different powers and locations of fire source, and proposed a novel approach to control smoke spread: installing a fire shutter at the junction of the platform and the atrium, and dividing the atrium into two smoke zone partitions, using the flyover on the top of the atrium. For the first time in China, Meng et al. [15] adopted a roll-up smoke retaining screen around the upper atrium of a metro station hall, and demonstrated the compliance of this strategy. The innovation of their strategy lies in the smoke-blocking duct between each set of stairs and escalators. Therefore, fire partitioning is a technical difficulty of the SPE system in atrium-type metro stations.

2.2 SPE at the head of platform stairs

Smoke retaining screens are often adopted in metro stations to divide fire protection units. Once a fire occurs, the stairs from the underground platform to the hall provide the trapped with the only escape route. A reasonable fire partition at these stairs helps to enhance the exhaust efficiency.

Huang [16] recommended to apply the air curtain at the head of the stairs between the platform and the hall of metro stations, and proved that the exhaust efficiency peaks when the jet of the air curtain deviates from the smoke flow direction by 15°-20°, and the fire source power falls in 2-2.5MW. Liu et al. [17] set up air curtains around the pillars of the platform, and thus rationalized the distribution of ventilation speed and temperature on the platform. Compared with mixed ventilation and layered ventilation, their approach creates a healthy and comfortable environment for metro platform.

Li [18] introduced the water curtain system to metro fire compartments for the first time, and proposed a novel fire design concept based on the Japanese practice of opening holes in metro parking lot: the water curtain system should be adopted as fire partitions, if the fire shutter cannot fully block out the fire. Pan et al. [19] deployed the water mist system before the screen door, and explored the impact of water mist on the smoke movement from the tunnel to the platform through the screen door: the water mist can reduce the smoke and dust flow, lower temperature and CO concentration, and increase visibility and oxygen (O_2) concentration.

The water curtain system, often used as fire partitions, falls into fire partition water curtain and protective cooling water curtain [20]. The former is a water wall or water curtain formed by densely arranged nozzles, whose width must be greater than or equal to 6m, while the latter is to spray water to the protected object. Studies have shown [21] that the best protection effect can be achieved by the staggered arrangement of nozzles (Figure 1).

This paper proposes to install the water curtain system as a fire partition at the head of open stairs and on both sides of platform pillars (Figure 2). The nozzles follow staggered arrangement in two rows. The water curtain is perpendicular to the tunnel to stop the smoke from spreading. Compared with conventional fire partitions, e.g., fire shutter and smoke retaining screen, the water curtain system is simple and flexible to deploy, and efficient in smoke blocking. In addition, this system can efficiently lower the ambient temperature, and improve the visibility at the fire scene, providing a solution to the difficulty in dividing fire compartments and setting fire partitions in metro stations.

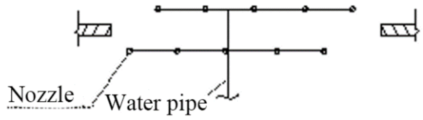


Figure 1. The arrangement of nozzles in water curtain system

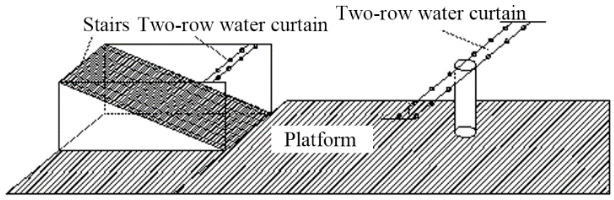


Figure 2. The location of water curtain system on the platform

2.3 SPE and smoke features of metro tunnel

If a metro train catches fire in the tunnel, the smoke will spread from the fire source to both directions along the tunnel. Thus, ventilation shafts should be arranged to curb the spread of smoke and speed up the evaluation. In the fire scene, it is difficult for people to evacuate, when the air inhaled by them is hotter than 60℃, and the visibility is less than 5m.

Studies have shown that exhaust efficiency of the shaft is independent from the lateral position of the fire source in the tunnel. In natural ventilation, the tunnel shaft boasts the best exhaust effect at the aspect ratio of 6 [22].

The return of smoke is a nonnegligible factor in the exhaust design for metro tunnels. The length of the returned smoke can be limited in a small range by setting up shafts in the tunnel. But the returned smoke will be longer, if the dimensionless distance between the fire source and the shaft is greater than 3 [23, 24].

3. SPE SYSTEM FOR TUNNELS

3.1 SPE plan for tunnels

Tunnels are mostly part of highways and railways. The ventilation and exhaust mode of tunnels varies with tunnel structure and length. The common modes of ventilation and exhaust for tunnels are longitudinal, semi-transversal, and full-transversal [25]. Depending on tunnel structure, various alternatives can be selected for exhaust plan: jet fan, ventilation shaft, linear, T-shaped, L-shaped, etc. [26].

Wang [27] verified the feasibility of different tunnel exhaust plans, and suggested the Hongmei Road Tunnel to adopt longitudinal ventilation at ordinary times, and switch to exhaust ducts for centralized exhaust in the event of a fire. Liu

[28] held that semi-transversal linkage and vertical mechanical modes are relatively efficient for underground tunnels in urban areas; once a fire occurs, the shafts of adjacent smoke zone partitions should be opened for mechanical exhaust at the same time; the trapped can be evacuated safely, when the wind speed of the section is 2.5-3.6m/s. As a result, the SPE system needs to be configured according o the length and structure of the tunnel.

3.2 Smoke phenomena and features in tunnels

During centralized exhaust, plug-holing might take place if multiple some vents work simultaneously. The vent far away from the fire source is more likely to suffer from plug-holing. Thus, it is important to select a reasonable rate for centralized exhaust [29].

The critical speed of the tunnel is the minimum air speed to prevent the diffusion of the upstream smoke. After the action of the sprinkler system, the critical speed will decrease by a maximum of 31%. To a certain extent, this speed is affected by the number, position, and pressure of the nozzles [30].

To sum up, the ventilation and exhaust plan hinges on the length and structure of the tunnel, while the exhaust efficiency depends on the smoke features. In actual application, the safe evacuation of personnel also needs to be considered.

3.3 Application of water curtain system in tunnels

The water curtain system can reduce the spread of smoke in the event of a fire. This efficient smoke blocking measure has been widely applied in tunnels. Mehaddi et al. [31] found that, during tunnel construction, the water curtain fails to block the smoke diffusion, but reduces the heat radiation of the smoke by 90%. Wang et al. [32] demonstrated that the water mist curtain (WMC) can effectively prevent the spread of smoke in the early stage of fire, and the reasonable deployment of the WMC in the tunnel can significantly lower the smoke particles and CO gas released by fire. Li et al. [33] learned that, when the wind speed in the tunnel is not less than 3m/s, the low-pressure water mist fire extinguishing system can halt the fire spread and increase the volume fraction of O_2. Zhang et al. [34] concluded that the most energy-efficient and cost-effective linear spray intensity of the water curtain are 8, 14, and 16L/(s*m), respectively, for the tunnel fires with fire source powers of 5, 20, and 30MW. Liang et al. [35] developed a new SPE mode called the smoke control system coupling WMC and transversal ventilation (WMSTV). The WMSTV system can control fire flexibly and effectively, and greatly facilitate evacuation.

The evaporation of water vapor in the water curtain reduces the air temperature in the tunnel. Double-layer tunnels mostly adopt the lateral exhaust mode. The combination of lateral exhaust and water curtain system could effectively inhibit the spread of smoke in the early and mid-stages of the fire, and improve the visibility in the tunnel. Yan et al. [36] and Chen et al. [37] observed that the efficiency of water curtain system increases with the growing exhaust volume and number of lateral vents, and the decreasing interval between the vents. Based on temperature, CO concentration, and smoke layer height, Xu [38] quantified the available safe evacuation time, and summarized the impacts of water mist screen on that time: the water mist curtain reduces the space temperature, lowers the CO concentration, and extends the safe evacuation time; setting up a water curtain system overcomes the difficulty in smoke exhaust and curbing smoke spread in super long tunnels; the trapped can wet their towels with the sprayed water to cover their mouths and noses, preventing the inhalation of smoke. Therefore, the optimal SPE design can be obtained by rationalizing the number, location, spray intensity, and incident angle of water curtains, applying the optimized water curtain system as fire partitions in the tunnel, and fitting the system with the original SPE plan through experiments and numerical simulations.

4. SPE SYSTEM FOR ATRIUMS

4.1 SPE plan for conventional atriums

The atrium is an emerging building that mostly appears in shopping malls and exhibition halls. The *Code for Fire Protection Design of Buildings* (GB50016-2014) [39] stipulates that smoke exhaust facilities should be provided in the atrium. The chimney effect and thermal barrier effect of the smoke are relatively obvious in tall atriums. The fire smoke can reach the top of the atrium at a speed of 2-3m/s. However, the smoke height has a ceiling, due to the high temperature outside the atrium and the low thermal buoyancy of the fire gas. The exhaust effect is optimal, when the supplemental air volume is half of the exhaust volume [40].

Thermal radiation is the key factor of heat transfer in fire. Chow et al. [41] simulated the smoke spread height and air temperature in the atrium, and verified the simulation accuracy through experiments. Yao and Wang [42] numerically simulated a five-floor commercial pedestrian street with four tall atriums, and obtained the best solution as the integrated exhaust between mechanical exhaust and natural ventilation: mechanical exhaust fans on the top of the four atriums, natural ventilation for the pedestrian street, and natural air compensation at the bottom of the atrium. Ayala et al. [43] showed that, under natural ventilation, there is no significant difference in the influence between different fire source powers and atrium roof geometries on the smoke; under exhaust mode, the greater the aspect ratio of the atrium, the greater the visibility and smoke layer decline rate, the chimney effect is relatively obvious under natural exhaust conditions [44].

4.2 SPE plan for irregular atrium

High-rise atriums have an obvious thermal barrier effect. Ou et al. [45] combined centralized exhaust with dispersed exhaust, and implemented a uniform segmented exhaust mode (Figure 3(a)) for the three refuge floors of a 200m tall atrium, which can meet the smoke exhaust requirement by exhausting 45% of the smoke on the roof. Huang et al. [46] discovered the major impact of the vent size, outdoor wind speed, and outdoor temperature on the natural exhaust of atrium, and the exhaust effect of the atrium depends heavily on the arrangement of vents, which are usually deployed on the roof or side walls. This gives birth to the Z-shaped atrium (Figure 3(b)). Experimental results show that the Z-shaped atrium equal or less than 45m in height can effectively exhaust smoke via natural exhaust in Haikou, the seat of southern China's Hainan Province.

Gutiérrez-Montes et al. [47] investigated the influence of different areas, positions, and speeds of air compensation at the bottom of the atrium over the internal conditions of the fire and the decline of smoke layer. Simulation reveals that the compensated air interferes with the flame and smoke flow, and the simulation data deviated from the experimental data by more than 20%. Experimental results show that air compensation to a large unsymmetric entrance makes the flame and smoke plume more disturbed. Some tall atriums are irregular in shape. There are office areas connecting the north and the south on the 8th, 10th, and 13th floor (Figure 3(c)). Lin and Fang [48] adopted a segmented exhaust mode, and installed 6 exhaust fans evenly on the bottom of the functional room, meeting the requirements for safe evacuation.

Irregular atriums differ clearly in structure and exhaust mode. The parameters of roof exhaust and bottom air compensation should be configured based on the actual position, size, and orientation of actual vents, and the structure of the bottom space. The layout of exhaust fans and the size of exhaust volume must be designed as per the actual structure of the special atriums. The ventilation and exhaust system of the atrium is affected by smoke phenomena and features. Thus, it is practical to rationalize the roof exhaust and bottom air compensation based on the structure of the atrium and the features of smoke.

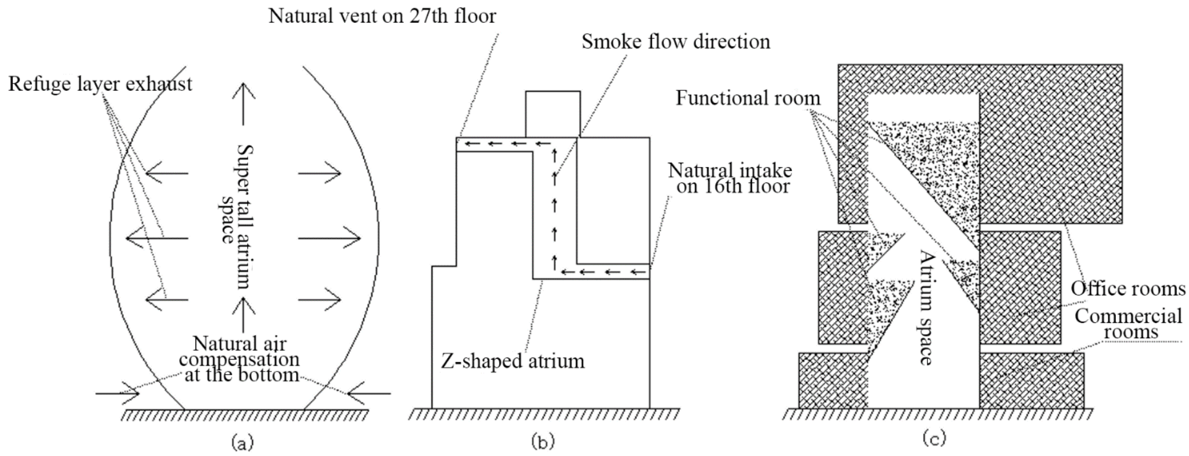


Figure 3. The exhaust plan for an irregular atrium

5. SPE SYSTEM FOR UNDERGROUND GARAGES

5.1 Ventilation system for underground garages

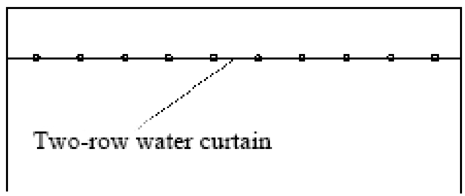
Underground garages have gradually increased with the completion of various largescale complex commercial buildings. More and more attention has been paid to the SPE and ventilation of underground garages. For garages and repair shops, the exhaust system is a must, and each smoke zone partition should not exceed 2,000m^2 [49].

A reasonable design of ventilation system will greatly improve the air quality inside the building. Since CO is the main pollutant in underground garages, how to reduce the CO level is a key issue in ventilation design [50]. Studies [51] have shown that, in many garages, the blocking effect of smoke retaining screens is insignificant, and the smoke zone partitions are too small, adding to the difficulty in integrating ventilation system with exhaust system.

For underground garages, the coupling between mechanical exhaust and natural air compensation can outperform mechanical exhaust and mechanical air supply in efficiency. This is particularly true in winter, when the CO concentration and air age in the garage are smaller than those in summer. Due to the heat pressure between cold outdoor and warm indoor, the natural ventilation in winter is three times as much as that in summer. The heat pressure can be utilized to form natural ventilation, making energy use more efficient [52]. In addition, the depth of the cross and longitudinal beams in underground garage has a major impact on the temperature and the settling time of the smoke in the fire scene [53].

To improve the blocking effect of smoke retaining screen in the underground garage, this paper proposes to install a water curtain system at the smoke retaining screen in the underground garage (Figure 4(a)), which serves as a fire partition in replacement of the conventional approach of dividing smoke zone partitions with the smoke retaining screen. As shown in Figure 4(b), the water nozzles of the water curtain system are arranged in two rows and in a staggered manner. The water curtain system is more flexible and more efficient than smoke retaining screen in putting out the fire. It can effectively improve the efficiency of the SPE system in underground garages. Figure 4(a) was shot in the underground garage of a commercial center in Jinshui District, Zhengzhou, the seat of Central China's Henan Province.

(a) Smoke retaining screen



(b) Two-row water curtain

Figure 4. The location of the water curtain in the underground garage

5.2 Induced ventilation system and SPE system for underground garages

Traditionally, exhaust and ventilation use the same ducts. The main disadvantage of this traditional exhaust mode is that the exhaust ducts occupy a large area of the building, creating blind spots of ventilation airflow. To solve the problem, many underground garages resort to duct-free induced ventilation systems.

In Britain and the Netherlands, jet induced fans are adopted for auxiliary exhaust in underground garages, laying theoretical basis for relevant technologies. Meanwhile, few Chinese scholars have explored induced ventilation and exhaust [54]. In fact, induced fans are mainly used in tunnels under the longitudinal ventilation mode.

Chang et al. [55] evaluated the ventilation and exhaust effects of jet fans in an underground space, noticed that the exhaust effect is better when the fans are arranged evenly in a matrix, and calculated the fan arrangement based on the garage structure by the jet formula. Lu et al. [56] proved that the induced ventilation system can effectively control smoke movement in underground garages with a simple structure, and outshine air duct exhaust in terms of visibility. In the presence of automatic sprinkler system, Tian et al. [57] compared the smoke control effects between air duct exhaust and indued fan exhaust, and made the following discoveries: the induced fan exhaust maintains a high visibility in the upstream of the fire source in a flat underground garage, but achieves a poor exhaust effect in the downstream; the smoke control ability of induced fan exhaust is poorer than air duct exhaust; induced fan exhaust might turn on unnecessary sprinklers. Therefore, it is advised to apply induced exhaust in garages with a small personnel flow. If the automatic sprinkler system is turned on, the smoke will spread across the garage, causing more sprinklers to be activated. This will disrupt the normal operation of the automatic sprinkler system [58].

In summary, traditional air duct exhaust occupies more area, but achieves better efficiency than induced fan exhaust. The latter is suitable for underground garages with a small personnel flow and a simple building structure. In the presence of automatic sprinkler system, the air duct exhaust should be prioritized for the underground garage.

6. ANALYSIS ON WATER CURTAIN SYSTEM

The water curtain system is highly flexible and applicable to various emerging buildings. Despite these advantages, the system has not been studied extensively. GB50016-2014 stipulates that the water curtain system must be deployed in large theaters and stages, and in the case that the firewall or other fire partitions cannot be installed. During tunnel construction, the water curtain system provides a safe environment for evacuees, by reducing the carbon dioxide (CO_2) concentration, and increasing the O_2 concentration outside the curtain [59].

6.1 Previous research on water spray

Willauer et al. [60] have shown that water mist has a certain inhibitory effect on dynamite explosions. The existing water mist nozzles can greatly attenuate the radiation from radioactive sources. Albeit its small flow rate, the water mist boasts better attenuation ability than the automatic sprinkler system. After all, the small water droplets excel in absorbing and scattering radiation [61, 62]. Tang et al. [63] designed an analytical model to quantify the downward flow of the smoke under the action of water spray, and examined the influencing factors like spray angle, droplet diameter, smoke layer temperature, and the cooling effect of the air entrained in water; the results show that the smoke moves further downward, when the droplet becomes smaller, and the smoke layer becomes cooler.

6.2 Optimization of water curtain system

The WMC combines the meris of water spray and water curtain, creating a highly efficient tool of smoke prevention. Li et al. [64] set up an experimental platform to explore the features of the WMC, and observed that the WMC under 2MPa delays the smoke passing time in the fire scene, reduces the optical density of the smoke, improves the visibility of the fire scene, and lowers the smoke temperature. Duanmu et al. [65] improved the nozzles of the WMC, and verified the effect of improved nozzles through experiments and numerical simulations. the results show that the WMC can clearly suppress the ceiling jet flame: a large amount of water vapor is produced through evaporation, and attached to the ceiling in the protection section, which dilutes the concentration of O_2 and combustible vapor in the downstream ceiling.

In this paper, the water curtain system in subway and underground garage is presented in the form of water mist curtain.

7. CONCLUSIONS

(1) The water curtain system can effectively overcome the difficulty in setting up fire partitions in metro stations. There are few studies on water curtains used as fire partitions in metro stations. In most cases, the fire protection units are divided with smoke retaining screens. Therefore, it is promising to reasonably arrange the position of the water curtain, combine the water curtain system with the original fire extinguishing system of the metro station, and evaluate the system effect through numerical simulations and experiments, using multiple interactive variables.

(2) The traditional approach that solely considers the original SPE plan of tunnel and verifies its feasibility lacks persuasive power. The SPE system is greatly affected by smoke features. Early on, some scholars suggested applying water curtain as fire partitions in tunnels. This paper improves the water curtain system, drawing on their results. A key research direction is to couple the optimized water curtain system with the original SPE system of the tunnel, and carry out experiments and simulations in the light of smoke features.

(3) The chimney effect and thermal barrier effect of the smoke are relatively obvious in tall atriums. The ventilation and exhaust of the building hinge on the roof exhaust and bottom air compensation of the atrium. It is of practical significance to reasonably arrange roof vents of the atrium and configure the parameters of bottom air compensation through experiments and simulations, according to the atrium structure and smoke phenomena.

(4) The water curtain system can overcome the difficulty in setting up smoke retaining screens in underground garages. The induced ventilation system of underground garages is similar to the longitudinal ventilation with jet fans in tunnels.

The system is mainly used for ventilation. Before applying the system to auxiliary exhaust, it is necessary to consider the ventilation volumes in winter and summer, the parameters and layout of the fans, and the geometric area and personnel flow of the garage, and to discuss the coupling between the induced ventilation system and mechanical exhaust, in the presence of the automatic sprinkler system.

(5) The WMC combines the meris of water spray and water curtain, creating a highly efficient tool of smoke prevention. The existing studies mostly evaluate the blocking effect of the WMC with the curtain as the only variable. The results are therefore not representative. It is of far-reaching significance to combine the WMC with the original SPE system of the building, and measure the SPE effect under the joint effect of multiple factors.

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