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March 28, 2018

Numerical Study on the Smoke Control Effect of the Air Outlet Setting in the Vestibule of High-rise Building

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Abstract

In this paper, the smoke control effect of mechanical pressurization system in the vestibule of high-rise building are studied based on numerical simulation. The diversity of the actual air outlet setting of mechanical pressurization system is considered. The relative position of air outlet and fire door opening is investigated in our research, which is divided into three cases: directly opposite, diagonally opposite and perpendicular. The method of numerical simulation is used to study the influence of the relative position of the air outlet and door, as well as the installation heights of air outlet of the fire-induced smoke prevention system. The smoke control effect in the case of fire and the cold state without fire are compared and analyzed; the setting position of air outlet is optimized. The conclusion of this paper can provide some references for the specific setting of the air supply system in the vestibule, and it has a certain engineering practical significance.

Keywords: mechanical pressurization system, vestibule, air outlet, relative position, smoke control effect

1. Introduction

When the high-rise building fire occurs, the trapped mainly evacuated through the corridor, vestibule and staircase. When the smoke penetrates into an evacuation stairwell through a gap of the compartment structure or the opening of a fire door, it can cause a large number of casualties [1, 2]. As a buffer area for evacuation, the vestibule can prevent the intrusion of high temperature fire-induced smoke into the vertical shaft such as stairwell. It should ensure it is free of smoke intrusion when fire occurred primarily. For this reason, smoke control systems are institutionalized in many countries to prevent smoke diffusion and ensure the safety of evacuation [3-5]. There are many smoke control methods. At present, Among them, the method common used in the smoke control of the vestibule to cut off the spread of smoke is the mechanical pressurization system [6]. But there are no explicit illustrations about the specific settings in the criterion. And the location, installation heights and format of the air outlet are dissimilar. So it is necessary to study the smoke control effect of the air supply system in different settings.

Kim et al.[7] analyzed the features of airflow through open door in pressure differential system based on numerical simulation. Kim and Shin[8] analyzed the pressurization system which was designed according to standard and pressure field of compartments in whole building induced by pressurization system for a model building of 20 stories using the network model. Ryu et al.[9] carried out actual and computational fluid dynamics measurement on the study of back-flow to stair-lobby at upper vestibule. They found that in the case upward 45 gradient of supply damper's blade, the simulation results that air flow of upper vestibule is steady but back-flow phenomenon occurred at the bottom. Seo and Shin[11, 12] investigated the characteristics of air flow in the vestibule with multiple fire doors in an apartment building and the damper location for uniform air egress velocity in the case of two fire doors by using the method of CFD numerical simulation. Their research found that when the damper in the vestibule is located at the center of the wall opposite to two fire doors, the uniform air egress velocity can be obtained. Additionally, it was found that the reverse flow occurs when the damper position in vestibule is not appropriate. You et al.[13] evaluated the effects of the real-time changes of a damper's wing and the fire door on the pressure difference in an injection and pressurization smoke-control system. Gai and Cancelliere[14] conducted experimental tests and numerical simulations with the objective of characterizing the pressure evolution in a small compartment under different conditions and through a cycle of door opening. They study on the pressurization and depressurization during steady state and transient phases to identify if there are airflow profiles typical of some geometrical configurations.

The focus of previous research is mainly on the distribution of the air egress velocity in the cold state without fire. In their study, the effective smoke control area is an important factor to measure the effect of the air supply in the pressure differential system on fire-induced smoke prevention. However, when the actual fire occurs, due to the existence of high

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temperature fire-induced smoke, the movement of air flow in the vestibule must be different from the cold state. The influence of the air outlet setting on the effect of fire-induced smoke prevention should be further studied. It is necessary to study the fire-induced smoke prevention effect of different settings of mechanical pressurization system in the vestibule of high-rise building to provide some reference for the design of building smoke control system. In this paper, aiming at the diversity of the actual air outlet setting, the relative position of it and fire door opening is divided into three cases: directly opposite, diagonally opposite and perpendicular. The method of numerical simulation is used to study the influence of the factors such as the relative position of the air outlet and door opening, as well as the installation heights of air outlet vent. The smoke control effect in the case of fire and the cold state without fire are compared and analyzed; the setting position of air outlet is optimized. The conclusion of this paper can provide some references for the specific setting of the air supply system in the vestibule, and it has a certain engineering practical significance.

2. Numerical modeling

2.1. Physical model

In order to study the effect of relative position of fire door opening and air outlet setting in vestibule of high-rise building on the prevention of fire-induced smoke, this study established the physical model as shown in Fig 1. The plane diagram of physical model is shown in Fig 1. In this model, the fire door position is fixed. Air outlet 1 directly opposite to the fire door opening. Air outlet 2 which has 0.4 m horizontal distance from air outlet 1 diagonally opposite to the fire door. Air outlet 3 set in the middle of the side wall of vestibule. Different relative position between the air outlet and fire door opening is realized by different height setting of air outlet on the vestibule walls in different directions. The fire room and the vestibule are connected by a corridor of size $16 \times 2 \times 3 \text{ m}^3$. The stairwell and other areas of the high-rise building are omitted. The fire room is located at the right end of the corridor, and a fire source is set inside it. Between the fire room and corridor opened a fire door of size $1 \times 2 \text{ m}^2$. The door is open when the fire occurs. At the other end of the corridor, the external air flowow is set. The external air flowow is open when the fire occurs which can be used for static smoke exhaust. The vestibule is of size $5 \times 3 \times 3 \text{ m}^3$. The door between vestibule and corridor is 1.4 m wide and 2 m high. When the fire occurs, the door is open because of the evacuation of the trapped occupancies in building.

Fig. 1. (a)Physical model and (b) plane diagram to investigate the effect of relative position of fire door opening and air outlet in high-rise building vestibule on the prevention of fire-induced smoke.

2.2. Numerical set-up

The problem studied in this paper belongs to the fire prevention and control of high-rise buildings. It is applicable to the Technical Specification for Building Smoke Control (DGJ08-88-2006). According to the clause 4.2.1 of Technical Specification for Building Smoke Control (DGJ08-88-2006) [15], the fire release rate (HRR) of fire in the room of an office building or hotel room with sprinklers should be estimated by 1.5 MW. Therefore, in our simulation study, a fire source with a power of 1.5MW is set in the fire room. Because the focus of this paper is not the chemical reaction in the combustion process, the volume heat source (VHS) is used to set up the fire source. The fire source in the actual situation is assumed to be a source of heat and energy. The heat release rate, the type and generation rate of the product are set up respectively. In this simulation, the fire source is simplified to a cube of $1 \times 1 \times 1 \text{ m}^3$. It is assumed that the main components of the fire-induced smoke are CO, CO₂ and air, in which the air accounts for 95% of the total mass and 5% for CO₂. In addition, the mass of CO is 5% of the mass of CO₂. The formation rate of fire-induced smoke is determined by the relationship with the heat release rate.

The Fluent 15.0 is adopted to conduct the numerical study in our research. In this study, the hexahedral structured grid is applied. In the fire room and the corridor, the grid size of 0.1 is adopted. In the vicinity of the vestibule and in the vestibule, the grid size of 0.05 is adopted. The computational domain contained a total of 714,000 grid cells.

Our research focuses on the effect of different air outlet setting on smoke control, so it ignores the influence of some minor factors on smoke control effect to simplify complex problems. The following assumptions are made in the numerical

simulation: 1) there is no other obstacle in the vestibule, which affect the movement of the air; 2) no consideration is given to the effect of escape people on air flow during the evacuation process; 3) neglecting the possible air leakage in the elevator and the stairwell; 4) the temperature of the air supply is consistent with the ambient temperature.

The specific boundary conditions are set as follows: 1) the flow uses a double equation turbulence model with buoyancy correction; 2) the fire source adopts the VHS combustion model, and the size is 1.5 MW; 3) the ambient temperature is 300K, the density is 1.225 kg/m³, and the wall is adiabatic wall; 4) the radiation uses the DO radiation model; 5) the boundary condition of the air outlet is set to Velocity-inlet; 6) the external air flowow is defined as outflow, and the percentage of air mass flow is 100%; 7) the pressure correction method of SIMPLE is used to solve the discrete equation.

In the actual building, the geometry of the air outlet is rather complicated. There are many forms such as the strip air outlet vent and the louver air supply vent. If we want to simulate the geometry parameters of the air outlet accurately, we need to divide the grid to the millimeter level, which will greatly increase the computation load. Because the focus of our research is not the influence of air supply vent structure on the effect of air supply, in order to facilitate the research, we use the traditional simplified method to simulate the air supply of the air outlet. The air outlet vent in the actual building is simplified as a rectangular shape opening in this study. The air supply volume is 10, 000 m³/h. The inlet air flow velocity is defined by the Velocity-inlet model. The inlet air flow velocity is defined as Eq. (1):

$$V = \frac{Q}{A} \quad (1)$$

Where Q is the air volume and A is the air outlet area.

2.3. Fire scenario

This paper mainly focuses on the difference of the smoke control effect under the different setting position of the air outlet. The main variables are installation height of air outlet in vestibule and the relative position between air outlet and fire door opening. Ten fire scenarios are investigated in our research (shown in Table 1). Three relative positions between air outlet and fire door opening are studied for different installation height of air outlet.

Table 1. Table of fire scenarios

Scenario	Relative position	Height of air outlet (m)
1	1: Directly opposite	0.2~0.8
2		1.4~2
3		2.3~2.9
4	2: Diagonally opposite	0.2~0.8
5		1.4~2
6		2.3~2.9
7	3: Perpendicular	0.2~0.8
8		0.8~1.4
9		1.4~2
10		2.3~2.9

2.4. Reliability verification of numerical simulation

In the numerical simulation, the actual building is simplified when the physical model is established, and the boundary conditions are set according to the results of previous researchers. The establishment of model and the setting of boundary conditions have great influence on the final simulation results. Therefore, it is very necessary to verify the accuracy and reliability of numerical simulation results.

In order to verify the reliability of the numerical simulation, the 1/3 scale experiment model which is exactly the same as the numerical simulation model is established. Compared with the 1/3 scale experimental scenarios, the numerical simulation of different air outlet settings was carried out respectively. The comparison between the numerical simulation and experiment results of airflow velocity in corresponding measuring point of vestibule fire door are conducted. Due to the large number of experiment scenarios, only the comparison of the scenario in which the air outlet installation height is 0.5 m and the relative position is directly opposite are selected in this paper to avoid unnecessary redundancy. The comparison between the small scale experiment and the numerical simulation in the typical scenario is shown in Fig 2.

Fig. 2. Comparison of velocity results between experimental and numerical simulation.

It can be seen from the Fig 2 that the numerical simulation has a good similarity with the experimental results. The trend of the results is consistent and there is only a difference in the specific value. The main reason for this difference is due to the unavoidable air leakage in the stairwell and elevator shaft. In addition, the multi-channel anemometer probes need to be perpendicular to the air flow direction. It is difficult to implement this absolute perpendicular state in the actual operation of the experiment. The numerical simulation ignores the effect of air leakage and overcomes the disadvantages of anemometer, so the airflow velocity is smaller than numerical simulation. By comparing the measured airflow velocity and the simulated test point airflow velocity, it can be seen that the model and boundary conditions in this paper has good feasibility.

3. Results and discussion

3.1. Directly opposite

The contour map of temperature distribution in the fire door central section for air outlet set at different height is shown in Fig 3. It can be seen from the Fig 3, the numerical simulation temperature result is much higher than the experimental measured temperature. The main reasons are as follows: 1) numerical simulation ignores the heat transfer of building wall, which is simplified as adiabatic wall, while the main body of the experimental device is steel structure, which has good thermal conductivity and some heat will be absorbed by the steel structure; 2) although the experimental device has been sealed in the connection of components, there are still certain gaps, which lead to heat flowing through these gaps to other parts of the experimental device; 3) liquefied petroleum gas (LPG) was used as fuel in the experiment. The fire power is determined by controlling the LPG flow. However, the actual operation of the LPG flow cannot be absolutely maintained at the set value. The actual temperature, which is influenced by room temperature, will inevitably be lower than the set value.

However, the numerical simulation can avoid the above problems. Therefore, the measured values are lower than the temperature values in the simulation. This paper focuses on the comparative analysis of the advantages and disadvantages of different air outlet settings. So we ignore the detail difference between the experimental and the numerical results, and directly compare and analyze the temperature distribution under different conditions.

It can be seen from Fig 4 that, when the air outlet is set at 0.2-0.8 m, only the temperature in the lower region (in the range of outlet height) of vestibule maintains at about 320 K. In the upper space of vestibule temperature reached above 500 K, where the temperature rises is more than 200 K. It indicates that a large number of high temperature fire-induced smoke spread into the vestibule. It will jeopardize the safety of the evacuation. This result is in agreement with the conclusion of air flow velocity distribution in cold state simulation without fire. When the installation height of air outlet increase to 1.4-2.0 m, the smoke prevention effect in vestibule are improved. The temperature of the area below the air outlet is about 400 K, and the area above the air outlet is about 470 K. It indicates that the smoke spread in vestibule in Scenario 2 is less than it in Scenario 1. But there is still smoke spreading into the room in the area below and above the air flow. In cold state simulation without fire, the 1.4-2.0 m height is the best set height for smoke prevention, which is different from the result of Scenario 2. The main reason for this difference is that the existence of high temperature smoke in the corridor near the vestibule causes the temperature difference inside and outside the vestibule. The air outlet flow temperature is the same as the temperature of air in vestibule, which is lower than the temperature of smoke. The low temperature air outlet flow will move down under the effect of temperature difference in vestibule. As a result, the flow velocity near the upper door space is low, which leads to the spread of smoke from the upper space into vestibule. In the cold state simulation without fire, the air outlet flow is almost horizontal flow to fire door, and completely covering the upper part of the door opening. The streamline diagram in the fire door central section for air outlet set at the height of 1.4m-2.0m in the Scenario 2 with room fire and cold state without fire are shown in Fig 4.

Fig. 3. Contour map of temperature distribution in the fire door central section for air outlet set at the height of (a) 0.2m-0.8m, (b) 1.4m-2.0m and (c) 2.3m-2.9m respectively (scenario 1-3).

Fig. 4. Streamline diagram in the fire door central section for air outlet set at the height of 1.4m-2.0m in the condition (a) with room fire and (b) cold state without fire (Scenario 2).

It can be seen from Fig 3 that when air outlet set at the height of 2.3m-2.9m (the projection of the air outlet vent is above the opening of fire door), the temperature of vestibule remained at about 310 K. The temperature rise is only about 10 degrees. Most of the high temperature smoke is blocked outside the vestibule. In case of fire, high temperature smoke near the door will move upward, thus slowing the downward movement of air outlet flow in vestibule. Therefore, the airflow will be concentrated in the upper part of the door opening of vestibule. As a result of a large air outlet flow, the high temperature smoke is blocked outside the vestibule, so the temperature in vestibule is not rising obviously. To summarize, according to the temperature distribution in the vestibule, it is suggested that the vent of air outlet should be set above the height of fire door opening when the air outlet directly opposite to fire door opening.

3.2. Diagonally opposite

The contour map of temperature distribution in the fire door central section for air outlet set at different heights is shown in Fig 6. It can be seen from the Fig 5 that: 1) when the air outlet is set too low, the temperature rise of the upper part of vestibule is high. A large number of smoke flows into the vestibule endangering the evacuation; 2) when the air outlet is arranged on the upper region, smoke control effect are improved. When the air outlet is set to 1.4 - 2.0m, the overall temperature in the vestibule is in the range of 330 - 350K. When the air outlet is set to 2.3 - 2.9m, the overall temperature in the vestibule is in the range of 330 - 360K. There is not much difference in temperature distribution between the two settings. This is consistent with the results of the cold state simulation, as well as the result of temperature rise obtained from the 1/3 scale experiment. Therefore, in order to get better smoke control effect, it is suggested that the vent of air outlet should be set at the upper part of vestibule when the air outlet diagonally opposite to the fire door opening.

Fig. 5. Contour map of temperature distribution in the fire door central section for air outlet set at the height of (a) 0.2m-0.8m, (b) 1.4m-2.0m and (c) 2.3m-2.9m respectively (Scenario 4-6).

In order to investigate the temperature near vestibule fire door opening and analyze the effect of installation height, the 29 temperature measurement points with intervals of 0.05 m are arranged in a vertical arrangement in the door at the 0.6 m distance from the door opening central line. Fig 6 shows the temperature comparison between the directly opposite position

and the diagonally opposite position for different air outlet installation height. It can be seen that: 1) when the height is 0.2-0.8m, the temperature rise of diagonally opposite position is less than it of directly opposite position; 2) when the height is 2.3-2.9m, the temperature rise of diagonally opposite position is more than it of directly opposite position, which is consistent with the experimental results; 3) when the height is 1.4-2.0m, the fire control effect of diagonally opposite position is better than it of directly opposite position, which is opposite with the experimental results. According to analysis, the main reason of this difference is because that the angle of air egress velocity is not horizontal but there is an upward gradient angle in the 1/3 scale experiment. This factor is not obviously effect the smoke control for the other installation height of air outlet, but it has a greater impact on the air outlet when it is set at the middle height. Without upward gradient angle, air will move downward leaving the air outlet vent, thus lead to the airflow velocity in the upper part of vestibule is small. When there is an upward gradient angle, although air will move downward, due to the vertical upward motion of the airflow itself, it can form a larger airflow velocity in the upper area of vestibule. The numerical simulations ignore the effect of upward gradient angle. The reason for this upward gradient angle is that in the experimental research, the form of the air outlet vent is simplified to a simple rectangular opening, so it is difficult to determine the angle of air egress velocity. While louver outlet are common-used form of outlet vent in the actual building, in this form the angle of air egress velocity can be adjusted in a certain range, it is not difficult to understand the air egress velocity angle has a certain impact on the indoor air movement, but its research is relatively complex, therefore this paper carries on the simplification, only considering the air flow horizontally flows in the vestibule.

Fig. 6. Temperature comparison between the directly opposite position and the diagonally opposite position for air outlet set at the height of (a) 0.2m-0.8m, (b) 1.4m-2.0m and (c) 2.3m-2.9m respectively.

3.3. Perpendicular

This section mainly discusses the effect of air outlet installation height on the smoke control when the air outlet perpendicular to the fire door of vestibule. Fig 7 shows the temperature of the perpendicular relative position for different air outlet installation height. It can be seen that the temperature rise of vestibule increases with the increase of air outlet installation height. When the air inlet is set at 0.2-0.8 m, the temperature rise of the measuring point is only 40 K, and when it is set at 2.3-2.9, the temperature rise is more than 100 K, which is consistent with the rule obtained in the 1/3 scale experiment.

In the cold state numerical simulation without fire, according to the simulation results of air flow distribution, the optimal installation position of air outlet is 0.8-1.4 m when the outlet perpendicular to the fire door of vestibule. Therefore, the height of 0.8-1.4 m is added in the simulation study of relative position 3 - perpendicular relative position. The temperature comparison between different installation heights is shown in Fig 7. It can be seen from the Fig 7 that the temperature of measuring points above 2.2 m in the Scenario 8 (0.8-1.4m) is much higher than this temperature in the Scenario 7 (0.2-0.8 m). This is not consistent with the conclusions obtained from the cold state experiment.

Fig. 7. Temperature of the perpendicular relative position for different air outlet installation height (Scenario 7-10).

In order to analyze the reasons for the difference between the hot-smoke simulation and cold state simulation without fire, airflow velocity distribution on the horizontal section are explored. The horizontal section distribution of air flow velocity in the height of horizontal centerline of 0.2m-0.8m, 0.8m-1.4m and 2.3m-2.9m are shown in Fig 8. When the air outlet is set at 0.2-0.8 m, the air outlet flow gradually shifts to the fire door side in vestibule. When the air outlet is set at 0.8-1.4 m, the effect of hot smoke near door opening on the air outlet flow is weak, so the air outlet flow can still maintain the original direction. When the air outlet is set at 2.3-2.9 m, the outlet is higher than the height of the door opening. In this height the airflow gradually shifts away the fire door side. However, in the cold state, the effect of high temperature smoke is ignored. No airflow shifting is occurred at any air outlet installation height in the cold state simulation. It can be seen that the shift of the supply air flow caused by the high temperature smoke has great influence on the smoke control when the air outlet set at the upper part of the vestibule, and has little influence when the air outlet set at the middle height. When the air outlet set at the lower part of the vestibule, the shift of the supply air flow can enhance the effect of smoke control. Although there are some differences in the optimum setting height of the air outlet, the results of the hot-smoke simulation and the cold state simulation without fire are basically the same. When the air outlet is perpendicular to the door, the outlet should be located near the ground.

Fig. 8. Horizontal section distribution of air flow velocity in the height of horizontal centerline of (a) 0.2m-0.8m, (b) 0.8m-1.4m and (c) 2.3m-2.9m.

3.4. Effect of the relative position on smoke control

In order to explore the optimal setting of the air supply system in the vestibule, the optimal setting in each installation height of air outlet and relative position of air outlet and door opening are selected to comparatively analyzed based on the above research.

Fig. 9. Temperature comparison of different relative positions between air outlet opening and fire door.

According to the result of above three sections, the best effect of smoke control in the three different relative positions of air outlet and fire door opening, namely directly opposite, diagonally opposite and perpendicular, are the Scenario 3, Scenario 6 and Scenario 7 respectively. Therefore, these three scenarios are compared and analyzed. The temperature comparison of different relative positions between air outlet and fire door opening of these three scenarios is shown in Fig 9. The optimal position of air outlet is the position where directly opposite to the door and the height is greater than the height of fire door opening. The second best position is the lower part of the wall perpendicular to the fire door. The worst of the three positions is the upper region which diagonally opposite to the fire door.

4. Conclusions

The effect of air outlet setting of the mechanical pressurization system in a vestibule of high-rise building is investigated in our research. Three relative position between air outlet and fire door opening, namely directly opposite, diagonally opposite and perpendicular position, and three installation height of air outlet are numerically simulated by Computational Fluid Dynamics method, in which fire and smoke effect are considered. The results of the numerical simulation are analyzed and compared with the results of 1/3 small scale experiment, as well as the numerical simulation results of velocity distribution in cold state without fire. In view of the current situation that the location of the air outlet in the actual building is not uniform, and the specific requirements of technical codes and standards are lacking, the influence of different relative position and installation height of air outlet on smoke control are explored in our research. According to the research it is concluded that: In order to get good smoke control effect, 1) when the air outlet directly opposite to fire door opening, it should be set above the height of fire door opening; 2) when the air outlet diagonally opposite to the fire door opening, the outlet should be set at the upper part of vestibule in this case; 3) when the air outlet is perpendicular to the fire door opening, the outlet should be located near the ground. 4) The optimal position of air outlet is the position where directly opposite to the door and the height is greater than the height of fire door opening. The second best position is the lower part of the wall perpendicular to the fire door. The worst of the three positions is the upper region which diagonally opposite to the fire door.

Acknowledgements

This work was supported by Hebei Provincial Natural Science Foundation under Grant No. E2017507004.

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