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Impacts of Staircase Windows on Pressurized Ventilation System

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Abstract

Chinese fire prevention codes provided that pressurized ventilation system should be used in the staircase which can not exhaust fire smoke naturally. However, the codes only specified the specific parts of pressurized ventilation and ventilation volume, while they did not specify how to make the pressurized ventilation effective in particular cases. As a result, in engineering application, some staircase pressurized ventilation systems can not effectively prevent smoke entering the staircase. For instance, in a staircase where the pressurized ventilation system must be used according to the codes, opened windows were set in the wall of the staircase so as to facilitate lighting and ventilation. Although that conforms to the codes, the effect of preventing smoke invasion is still unknown. This simulation study focused on the influence of opened windows on the pressurized ventilation system. It was found that if there were no open windows in the staircase, the system worked. At the same time, smoke would flow into the staircase in a short time and the high temperature was fatal to the evacuees if there were opened windows on the wall of this space. These results indicated that opened windows in the staircase would lead to uselessness of the pressurized ventilation system. In conclusion, it was suggested there are no windows in the staircase in which a pressurized ventilation system should be used. And if windows are necessary in the pressurized staircase for light, the windows should be fixed casement windows.

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Keywords: opened window, staircase, pressurized ventilation system

Nomenclature

Q	heat release rate (kW)
g	gravitational acceleration （m/s^2）
T	air temperature (℃)
Greek symbols	
ρ	air density (kg/m^3)
δ	grid size (m)

1. Introduction

Fire smoke is the main reason for casualties in building fire [1], so whether smoke control system can effectively control the smoke in fire has become the prerequisite for people to safely evacuate from the fire building. Since a staircase is the only evacuation passageway of the building leading to the floor, the effect of smoke prevention in a staircase determines whether people in the entire building can successfully escape. Therefore, smoke control system in a staircase should prevent the fire smoke from entering the staircase or delay smoke entering the staircase in order to get more time for safe evacuation [2].

According to the current fire protection codes in China, the pressurized ventilation system may be used in the smoke prevention of a staircase [3] [4]. However, the codes only specified the specific parts of pressurized ventilation and the air

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volume, while they did not specify how to make the pressurized ventilation effective in particular cases. As a result, in engineering application, some staircase pressurized ventilation systems can not effectively prevent smoke entering the staircase. For instance, in a staircase where the pressurized ventilation system must be used according to the codes, an opened window was set in the exterior wall of the staircase so as to facilitate lighting and ventilation. Although that conforms to the codes, the effect of preventing smoke invasion is still unknown. At present, there are many researches on the smoke's flow properties in staircase [5] [6], but there are few on the smoke prevention effects of staircase pressurized ventilation system. This simulation study focused on those staircases installed with pressurized ventilation system in opened window and windowless situation. Hopefully it will provide evidence for the proper design of staircase pressurized ventilation system.

2. Model Establishment and Design of Fire Scene

2.1. Building model

In light of calculation speed and simulation time, a seven-floor office building was simulated by using Fire Dynamics Simulator (FDS), a computational fluid dynamics model. And this building mainly consisted of office rooms, corridors, staircases and its chambers. Its three-dimensional model was shown in Figure 1, and detailed size of all parts was listed in Table 1.

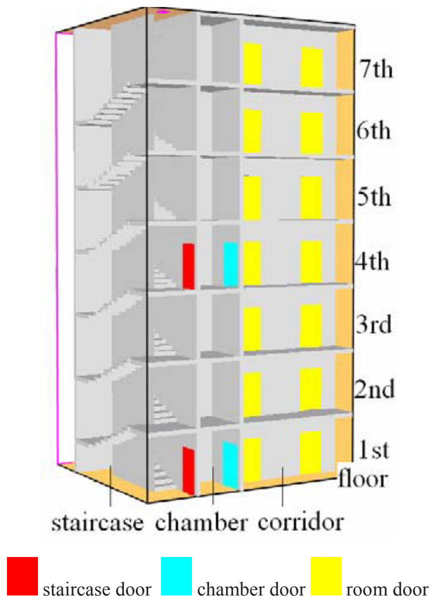

Fig. 1 Building model

Table 1 Size of Building Model

Enclosure	Size (m)/ each floor			Door Size (m)		Window Size (m)	
	Length	Width	Height	Width	Height	Width	Height
Staircase	7.2	2.5	3	1	2		
Chamber	2.5	2.2	3	1	2		
Corridor	6	1.4	3				
Room	8	3	3	1	2	1.2	1.2

2.2. Ventilation Volume and Air Outlet

In order to study the impacts of staircase windows on the pressurized ventilation system, only pressurized ventilation was considered in the staircase without supplying air in the chamber. According to current national codes, air volume of the pressurized ventilation system in the staircase should be 25000 m^3 /h when the staircase door is a set of double doors with width of 1.6m. As a result, ventilation volume of this model is 18750 m^3 /h (25000*0.75) with a 1m-wide door and the coefficient of 0.75 [4].

In general, a pressurized ventilation outlet should be installed at every two floors in staircases [3] [4]. In this paper, four pressurized ventilation outlets were installed in the first, third, fifth and seventh floor, respectively. And the floor plan is shown in Figure 2. According to Eq. (1), air outlet size should be calculated and determined with the air volume, air outlet number and air velocity. Thus, the minimal area of the needed air outlet should be 0.186m^2. Obviously, that is nearly impossible in practical projects. Considering that air outlet size, in our building model was set as 0.5m (width) ×0.4m (height) with air velocity at each air outlet of less than 7m/s. That was suitable for the current national codes.

$$f_i = Q_f \Big/ \left(m \cdot W_f \right) \tag{1}$$

Where f_i is outlet area (m^2), m is air outlet number, Q_f is total ventilation volume of pressurized ventilation system (m^3/s), W_f is air velocity at air outlet and 7m/s is available in calculation.

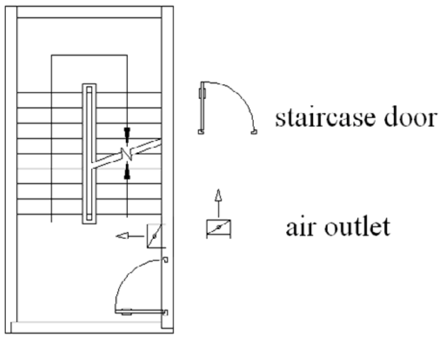

Fig. 2 Floor plan of the staircase

2.3. Fire Source

Fire was set in the office on the first floor adjacent to the chamber so as to study the impacts of staircase windows on the smoke prevention of pressurized ventilation system in this unfavorable condition. Heat release rate (HRR) of the fire referred to Shanghai Local Standard of Heat Release Rate [7] (Table 2). According to HRR of “offices and guest rooms with spray system” in Table 2, HRR should be 1.5 MW. In light of the distinctions between simulation and real fire, HRR of determined fire source should be 2.25 MW with the safety coefficient of 1.5. The t^2 –model (fire increase type) was used in this study ($q = \alpha t^2$) [8]. In that equation, the value of fire increase index (α) referred to the fire category which is defined in America’s National Fire Protection Association [9] (Table 3). Taking into account the inflammable materials are rapidly combusted furniture and light curtains in the office fire, fire increase index should be 0.187 KW/s^2 (Table 3).

Table 2 Heat Release Rate

Place	Heat Release Rate Q (MW)	Place	Heat Release Rate Q (MW)
Shopping mall with spray system	3	Atrium with spray system	1
Supermarket and warehouse with spray system	4	Office and guest room without spray system	6
Public places with spray system	2.5	Garage without spray system	3
Garage with spray system	1.5	Atrium without spray system	4
Office and guest room with spray system	1.5		

Table 3 Fire Increase Index

Fire Category	Typical Inflammable Materials	Fire Increase Index α (kW/s^2)
Low-speed fire	……	0.0029
Medium-speed fire	Cotton/ polyester cushion	0.012
High-speed fire	Full mailed bags, wooden shelves and trays, foamed plastics	0.044
Ultra high-speed fire	Pool fire, inflammable furniture and light curtain	0.187

2.4. Opening Status of Doors and Windows

In the design of pressurized ventilation system, the opening status of a door has an essential role in whether the pressurized ventilation system can work effectively. When the fire breaks out in a building, the door will be opened frequently with a large number of people evacuating in a short time. Thus, the opening status will last for a long time. And the number of floors with simultaneously opening doors increases which is specified as below according to the codes of China [3]:

First of all, in a building ≤ 100m, doors of only 2 floors should be considered to be open simultaneously as for the building lower than 20 floors, whereas those of 3 floors for the building having 20 floors or more.

Secondly, as for a building higher than 100m, it should be divided into a certain number of buildings lower than 100m. And then the number of floors with simultaneously opening doors should be determined according to the above.

Besides the number of floors with simultaneously opening doors, whether the staircase and chamber door in the same floor are opened simultaneously also has a great impact on the pressurized ventilation system. If they are opened simultaneously, that is the most unfavorable condition for the pressurized ventilation system of the staircase [10]. Based on that, the paper assumes that doors in the first floor and the fourth floor are opened simultaneously in the fire, whereas staircase doors and chamber doors in other floors are closed.

In addition, the smoke prevention effect was studied in the two different situations. One is that the staircase was not installed with a window. The other is that the staircase was respectively installed with a window of 1.2m×1.2m from the first floor to the seventh floor (Figure 3).

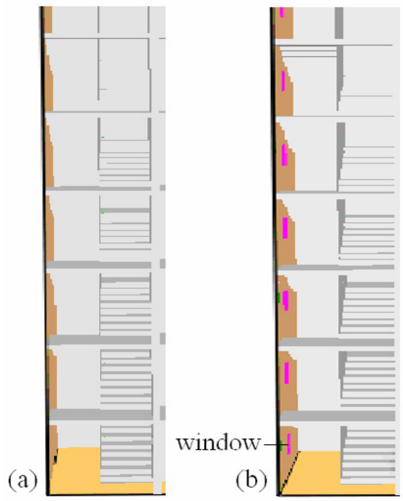

Fig 3 Staircase (a) without windows and (b) with opened windows

2.5. Grid Division

When using FDS, the setting of a grid size has great impacts on the accuracy of simulation results. The more detailed the grid division is, the more accurate the calculation results are. Generally speaking, a grid size can be determined in accordance with Eq. (2) and Eq. (3) [11] [12]. In this way, there will be thousands of millions of grids. Therefore, in light of computer performance and computing time limit, it is rather difficult to put this theoretical approach into practice. As a result, what we can do is to take an equilibrium point between simulation accuracy and time duration, get a proper result within a reasonable period of time. The grid of 0.2m×0.2m×0.2m was used in this paper.

$$D^*/\delta_x = 4 \sim 16 \tag{2}$$

$$D^* = \left(\frac{Q}{\rho_\infty c_p T_\infty \sqrt{g}} \right)^{\frac{2}{5}} \tag{3}$$

where δ_x is grid size (m), D^* is fire radius (m), Q is heat release rate (kW), ρ_∞ is air density (kg/m^3), C_p is air heat capacity (J/kg·℃), T_∞ is air temperature(℃), g is gravitational acceleration（m/s^2）.

3. Results and Analysis

3.1. Smoke Diffusion

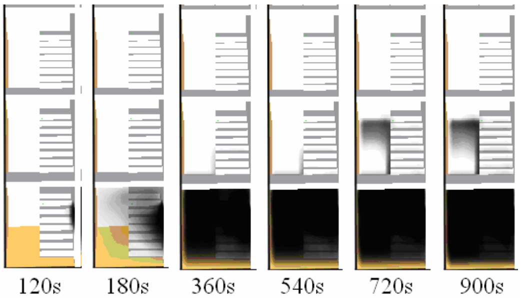

Fig. 4 Smoke diffusion in the windowless staircase

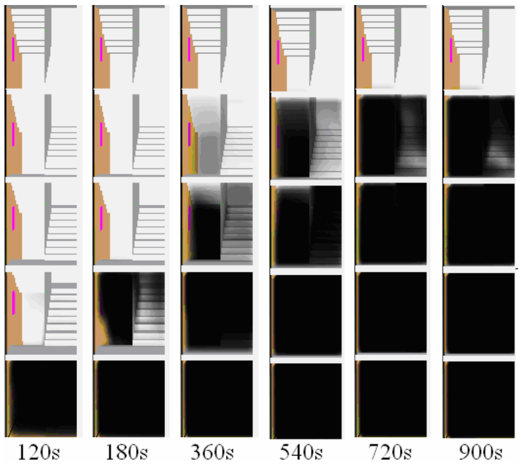

Fig. 5 Smoke diffusion in the staircase with opened windows

In Figure 4, it indicated that it took nearly 120s for the smoke to enter the windowless staircase. At the same time, the smoke filled the first floor and began to diffuse in the second floor of staircase when the staircase had windows (Figure 5). It showed that compared with the staircase with opened windows, it takes more time for the smoke to enter the windowless staircase. Thus, people in danger will have more time to evacuate from the fire building with a windowless staircase.

In the situation of staircase with windows, the smoke diffused into the fourth floor at 360s since the fire broke out. Then, the smoke spread to the rooms of the fourth floor through the staircase, chamber and corridor, and finally flowed to the outside through room windows (Figure 6). In contrast to the former situation, the smoke could be seen on the second floor at 720s in the situation of windowless staircase while there was no smoke above the second floor. And there was not a significant increase in the space invaded by the smoke at 900s. Therefore, it indicated that the smoke invaded wider leading to much more difficulty in evacuation and more loss of life in the situation of staircase with windows.

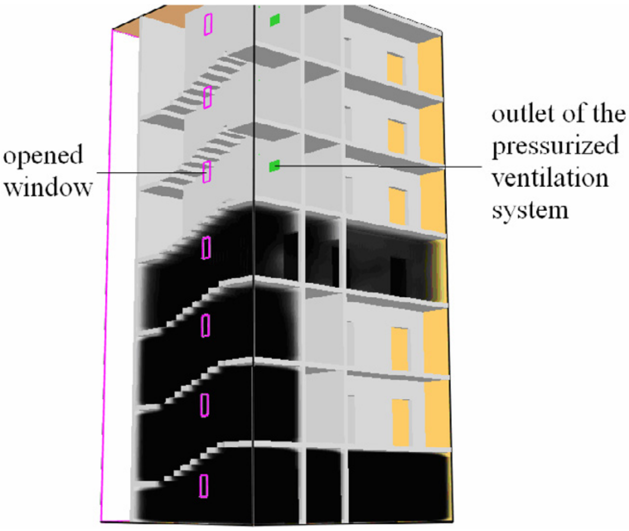

Fig. 6 Smoke diffusion in the building at 900s

There was not enough positive pressure in the staircase with opened windows to prevent smoke, since part of fresh air from pressurized ventilation system ran out through opened windows. When the air pressure increased inside the corridor and chamber with smoke accumulating, it was higher than the air pressure inside the staircase. Then the smoke entered the staircase accordingly. At the same time, there was still part of the smoke flowing to the outdoors through opened windows. And the smoke volume into the staircase was much greater than that running outside. So the smoke in the staircase accumulated more and more, and diffused to the upper space of the staircase. At the beginning, relative pressure in the fourth floor rooms, passage and chamber was zero. As a result, when the smoke reached the staircase of the fourth floor, it flew to the chamber, passage and rooms successively through opened doors, and finally to the outside. However, there was no smoke invading the staircase of the fifth floor to seventh floor, because part of fresh air from the outlets ran outside through opened windows, and the rest flew to the chamber and corridor through opened doors on the fourth floor after being mixed with smoke.

3.2. Changes of Temperature, CO Density and Visibility

When there is a fire, smoke temperature, CO density and visibility is chosen as evacuation indexes in order to assess the impacts of smoke on the evacuation. At present, the limit of those indexes is still not unified for safe evacuation. So the limit should be considered according to the project property, fire probability, risk factor, etc. In this study, the limits of CO density, smoke temperature and visibility were set respectively as 0.25%, 50℃ and 10m [13]. Life safety would be threatened if those indexes were beyond the limit. In addition, detectors were set at the height of 2m, 5m, 8m, 11m in the staircase (respectively represents staircases from the first floor to the fourth floor) in order to compare the effect of smoke prevention in the opened window and windowless staircase in terms of CO density, visibility and temperature. The results were showed as followed:

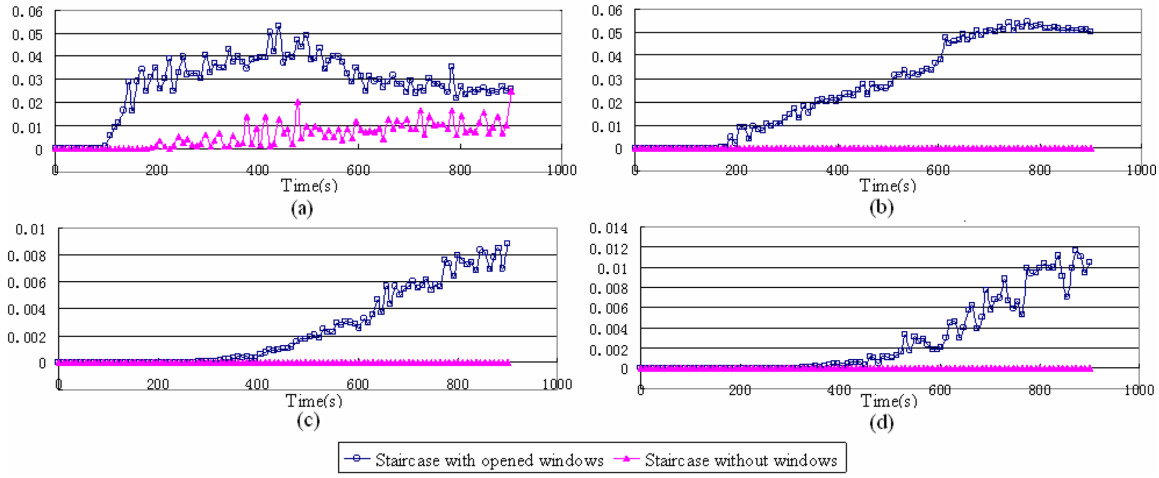

Fig.7 Concentration of CO (%) at the height of (a) 2m (b) 5m (c) 8m (d) 11m

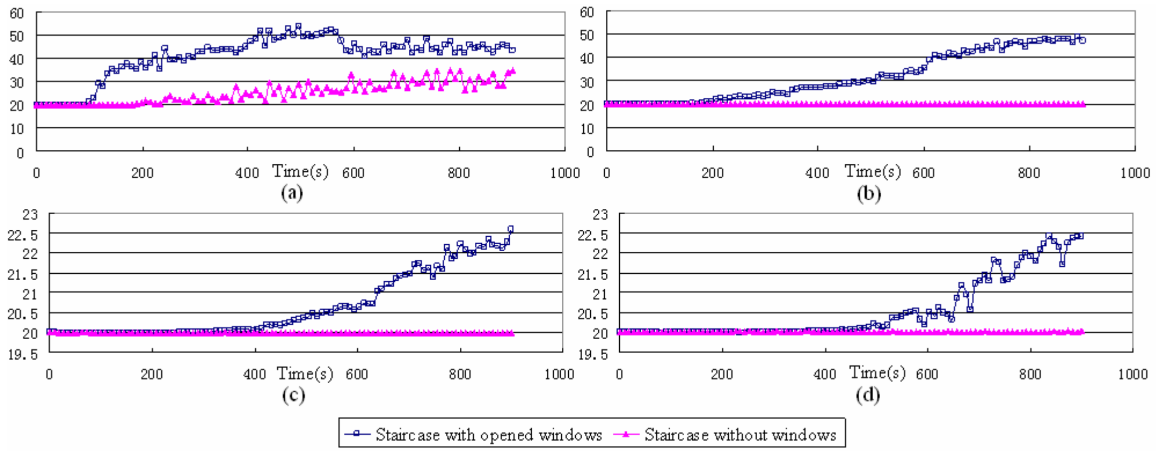

Fig.8 Temperature (℃) at the height of (a) 2m (b) 5m (c) 8m (d) 11m

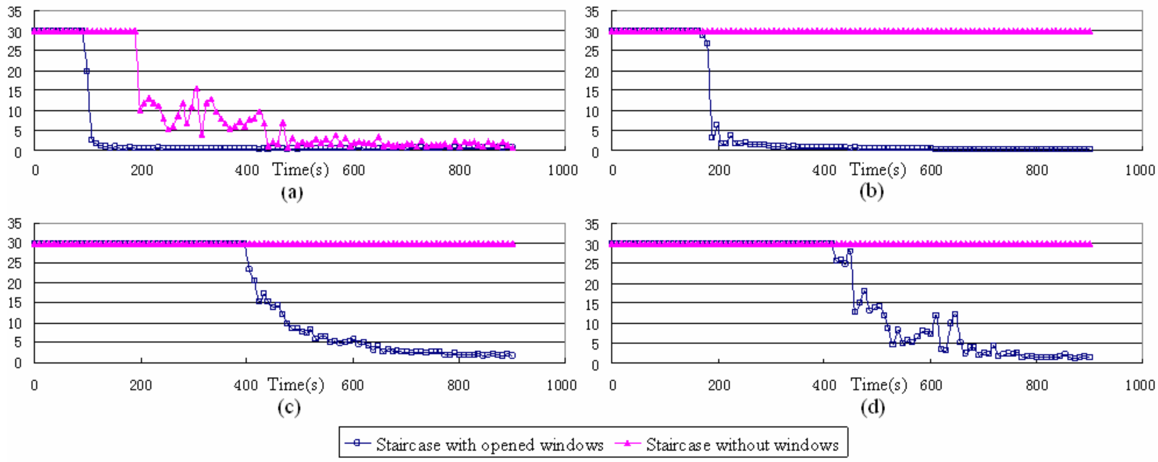

Fig.9 Visibility (m) at the height of (a) 2m (b) 5m (c) 8m (d) 11m

As shown in Figure 7a, Figure 8a and Figure 9a, in the windowless staircase, smoke temperature, CO density increased at the height of 2m while visibility decreased greatly. It showed that the smoke invaded the first floor of staircase. That was because that the air from the pressurized ventilation system could form a relatively low positive pressure. That could only prevent the smoke into the staircase at the beginning of the fire. With the smoke produced, the smoke pressure in the corridor had a gradual increase. The outlets of the pressurized ventilation system beside the door could not form an air flow with enough velocity in the opposite direction of the smoke. Thus, the smoke entered the staircase of the first floor. Even so, smoke temperature and CO density had a relatively smooth increase with a relatively slow decrease in visibility, compared with those in the staircase with opened windows. It suggested that the pressurized ventilation system had a better effect of smoke prevention in the windowless staircase than that in the staircase with opened windows.

And smoke temperature, CO density and visibility were identical to those at the initial time in the second floor (5m) above of the windowless staircase (Fig.7b, 7c, 7d; Fig.8b, 8c, 8d; Fig.9b, 9c, 9d). It indicated that no smoke entered this space and pressurized ventilation system worked well with an effective smoke prevention. When there were opened windows in the staircase, smoke temperature and CO density increased, and visibility decreased greatly. Among these indexes, CO density increased. But it was not a threat to the evacuees. That was because that the smoke was diluted when rapidly mixed with fresh air from the pressurized ventilation system. As smoke gradually entered the staircase, its temperature would exceed 50℃. That led to casualties. Meanwhile, the visible light was shaded by a lot of smoke particles inside the staircase. As a result, it was difficult for evacuation with decreased visibility. Therefore, the pressurized ventilation system could not effectively prevent smoke into the staircase with windows.

4. Conclusion and Suggestions

In conclusion, the pressurized ventilation system could not prevent the smoke effectively from entering the staircase with opened windows. It could result in evacuation difficulty and casualty. The reason may be related to relatively faster and wider smoke invasion with higher temperature and rapid decrease in visibility. In contrast to that, pressurized ventilation system could effectively prevent smoke invasion in the windowless staircase. It is favorable for safe evacuation.

Therefore, the staircase should be installed without opened windows when the pressurized ventilation system is used in the staircase. As for the lighting concerned by the architect, the author suggests that fixed windows, not opened windows, should be adopted for lighting in the staircase. However, natural ventilation can not be used in the windowless staircase or the staircase with fixed windows. In that case, the pressurized ventilation system can be designed as double-stage system. That is to say, lower air volume should be used at ordinary times with larger air volume in fire.

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