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Performance-based Evaluation on the Natural Smoke Exhausts System of Theatre

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Abstract

Analyze the characteristic of smoke movement in the building, study on the rationality and validity of fire control system of the theatre. Study on the use characteristic of theatre, and fire develops as the fast t^2 fire in the theatre and FDS software was used to simulate fire development according to the fire performance-based design. The result shows that the smoke temperature, CO concentration and visibility is safe for human for 1 200 s. It also proves floor 1 of theatre is safe by using the automatic smoke barrier combine with mechanical smoke exhaust system .The natural smoke exhaust system in the second floor can play an effective smoke control function.

Keywords: theatre; fire protection; smoke control system; performance-based design;

The fire protection of theatre is different from general building because of the special character of structure and the requirement of using function. With the development of economy, various special structures of building are emerge include the theatre. By forms a rich space level and architectural form, it makes an external image with effective in order, elegant environment, fresh style and modern construction aesthetic perception. The using function of theatre tends to diversification and the building area is also increase.

The domestic and international research of theatre is focus on the auditorium, and lounge fire is neglected. The lounge is the necessary pathway which connects the auditorium and external exits. It is also the resting place for the audience, in the case of smaller area the fire risk is relatively lower. But for large theatre there are a lot of audience, it needs lounge with large area, while dining hall, cafe and other shops are generally arranged in the lounge and increase the fire load. When the area is beyond the requirement of code, exhaust system of the lounge will be difficult for fire safety design. Base on performance-based fire protection, exhaust system is designed and the lounge fire is modeled with fire simulate software FDS. It is of great theoretical and realistic significance to correct understood the objective of fire protection and the method of exhaust system design.

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1. Smoke flow regularity of building fire

When the fire occurred, rising fire plume with high temperature above the fire source will be formed as the heat release rate rises. The relatively static air continuously entrains into the plume and mix with the smoke. Therefore, the entrainment of air will be mixed with the gas in plume with the height increase. The structure of plume is shown in figure 1.

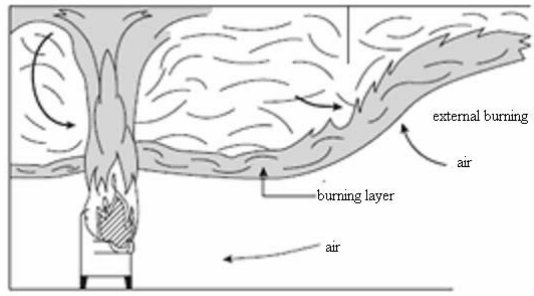
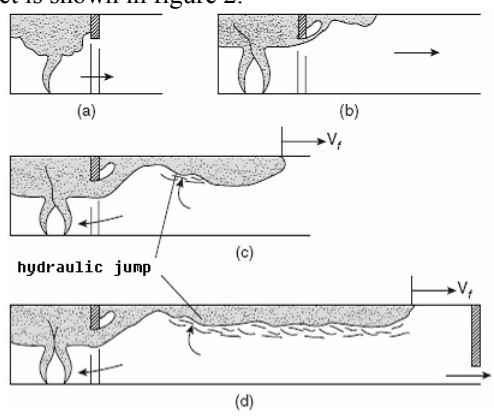


Fig.1.The schematic diagram of fire plumes and smoke layer

After plume reaches the ceiling, it will crash the ceiling and diffuse in all side to form a hot smoke layer that parallel with the surface of ceiling, that is ceiling jet. It also will entrain the air that below ceiling jet in the process of the expansion of ceiling jet. It will begin to flow down when ceiling jet arrive at walls and was blocked. As the temperature of smoke is still high, the smoke will start floating after flowing down a short distance, which is anti-buoyant wall jet. Hot smoke is continuously accumulated around walls and then spread to reaches centre of room when hot smoke layer reach a certain thickness. With the development of fire, the hot smoke layer remained at the same horizontal plane and began to sink stability. If there are doors and windows in the fire region or exist holes that connect the non-fire region, the smoke will be discharged to the outside or spread to other locations in the building. A development process of ceiling jet is shown in figure 2.



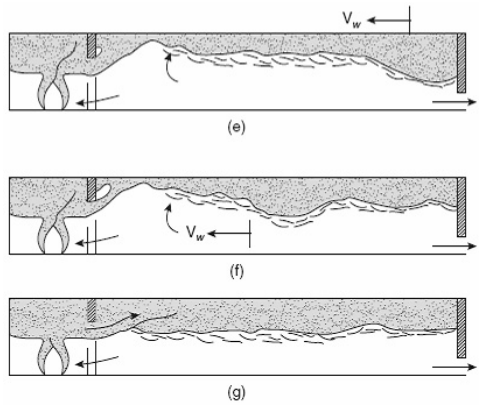
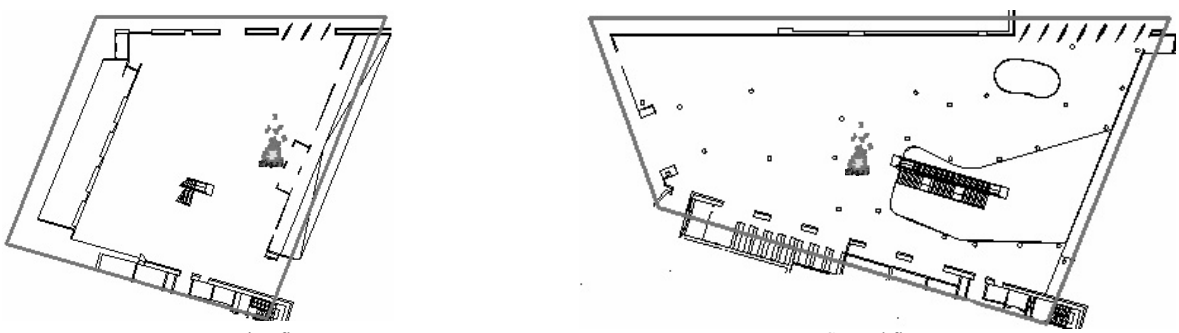


Fig.2.Development processes of ceiling jet

2. Design for smoke control system of lounge

2.1. Basic condition of the lounge



First floor Second floor

Fig.3.Plane graph of the lobby of theatre and locations of fire

The lounge includes two floors with a total construction area of 3 832 m^2 and building height of about 11.2 m. Area of first floor is 1 520 m^2 and height is 6 m; the area of second floor is 2 312 m^2, and height of it is 5.2 m. There is a hole between two floors, and an escalator and stair for the audience are setting in it. The lounge connects with an opera house with capacity of 1 680 seats and a multifunctional hall with 600 ~ 800 seats. The opera house is also a symphony hall, can be used for opera, drama, dance, ballet, symphony etc; multifunction hall can be used for chamber music, chamber opera, experimental drama, popular music, fashion shows and other functions. Lounge as a semi-security region which no other function decorates with non-combustion materials. Cloakrooms, toilets, shops, etc. in the lounge are separated by grade-a fire door.

2.2. Design for smoke exhaust system of first floor 1 in lounge

Automatic smoke barriers are set along the hole between two floors and 2 m above the ground. It initially able to prevent the smoke spread to other floor. The exhaust smoke level for the theater lounge can be calculated according to the Shanghai Engineering building codes DGJ 08-88-2006, which is calculated as follows:

1) Minimum clear height

$$H_q = 1.6 + 0.1 \cdot H$$

where H_q is minimum clear height, m; H is the height of zone where the smoke exhaust system is equipped, m.

2) Mass flow of smoke

when $Z \le Z_1$:

$$M_\rho = 0.032 Q_c^{3/5} Z$$

where Q_c is the convective component of heat transfer and is always determined as $0.7Q$, kw; Z is the height between fuel surface and bottom of smoke layer, m (always greater than or equal to minimum clear height); Z_1 is the limit height of fire, $Z_1 = 0.166 Q_c^{2/5}$; M_ρ is mass flow of smoke, kg/s.

3) Average smoke temperature and different between ambient temperature

$$\Delta T_p = Q_c / M_\rho C_p$$

where ΔT_p is different value between average smoke temperature and ambient temperature, K, $\Delta T_p = T_p - T_0$; C_p is specific heat and is always equal to 1.02, kJ/(kg·K).

4) Exhaust smoke level

$$V = M_\rho T_p / \rho_0 T_0$$

where V is exhaust smoke level, m^3/s; ρ_0 is density of air in ambient temperature, kg/m^3, t_0=20℃, ρ_0=1.2 kg/m^3; T_0 is ambient temperature, K; T_p is average absolute temperature of smoke, K, $T_P = T_0 + \Delta T_P$.

5) Results

The exhaust smoke level of theatre lounge can be obtained according to the steps mentioned above, and the results is shown in figure 1.

Table 1 calculation result of mechanical exhaust smoke volume for floor 1

Q_c /kW	M_ρ /(kg/s)	Z_1 /m	ΔT_p /K	T_p /K	V /(m^3/s)
1750	6.2	3.3	276.0	574.0	10.9

2.3. Design for Natural smoke exhaust system of the second floor

It will be difficult to layout ports and pipes for mechanical smoke system because the glass roof is used in the theatre lounge. Therefore, the natural smoke exhaust system is needed. According to features of structure, the windows can be set along the north and south façades of theatre lounge and the total areas of the windows is about 2% of the area of second floor, while using the hole and exports in the building to supple air. Locations of the Windows in second floor are shown in Figure 4.

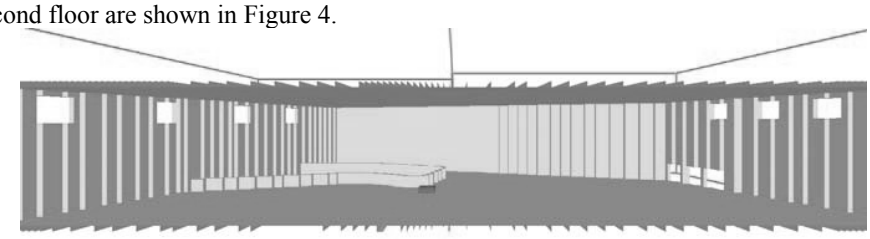


Fig.4.The schematic diagram of windows in floor 2

Since the uncertainty for fire safety that the smoke exhaust design brings, so the smoke exhaust system design need to be evaluated with performance-based fire design to ensure that the safety of building, while provide the basic for optimizing the design.

3. Simulation parameters design

3.1. The fire model and heat release rate of fuel

The building fire can be divided into four phrases: ignition phrase, growth phrase (flashover), full-developed phrase and extinguish phrase. The heat release rate is the important parameter for fire hazard evaluate and basic parameter for fire simulation research, it will change with time in whole fire process. The most extensive research

have been performed, that for most material fire from ignite to full-developed phrase, the heat release rate increases in power exponent and there is a liner relation between heat release rate and time.

$$\dot{Q} = \alpha t^2$$

where $\dot{Q}$ is heat release rate of fire, kW; α is index of fire, kW/s2; $\alpha = \dot{Q} / t_0^2$, kW/s^2; t is duration of fire, s; t_0 is the time required until heat release rate of fire $\dot{Q}_0 = 1$ MW, s.

The different combustions have different fire growth index, and the fire can be divided into four types according to α : ultra-fast growth, fast growth, medium growth and slow growth.

The main fuels in the theatre lounge are sofas and seats for the audience. National Institute of Standards and Technology (NIST) has conducted a set of tests for double smoke movement of sofa fire. It can be found initially the sofa fire is similar to α =0.0469 kW/s^2 fast fire by comparing to the t^2 fire. The Curve of heat release rate change with time for sofa is shown in figure 5.

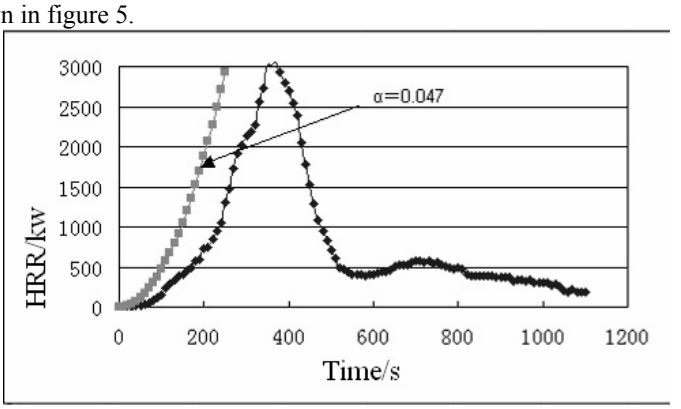


Fig.5.Curve of heat release rate change with time for sofa

The development model for fuels in the lounge can be expressed as:

$$Q = 0.0469t^2$$

The heat release rate for the fuels in the theatre lounge can be defined according to the Shanghai Engineering building codes DGJ 08-88-2006

Table 2 Maximum heat release rate of typical site

Location of fire	Maximum heat release rate Q /MW
Market with sprinkler	3
Office and hotel room with sprinkler	1.5
Public place with sprinkler	2.5
Supermarket and warehouse with sprinkler	4
Office and hotel room without sprinkler	6

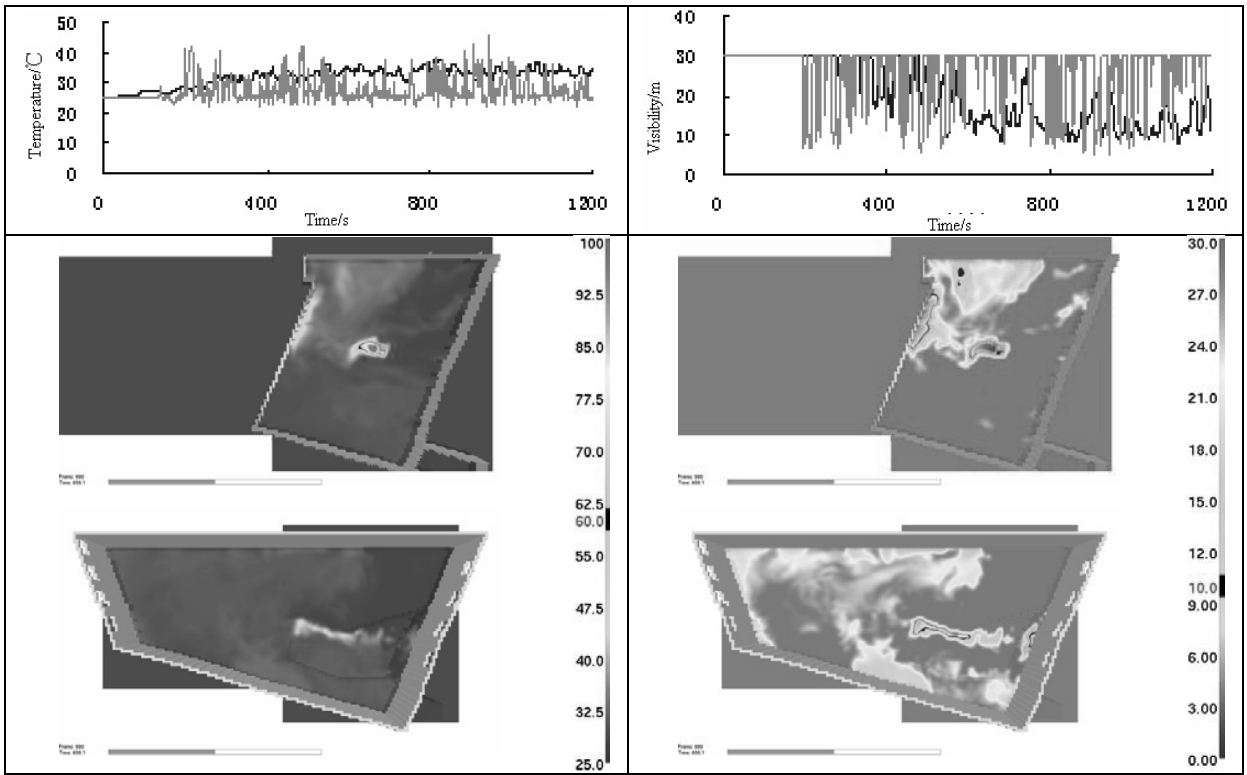
3.2. Performance objectives and indexes

The performance objectives of fire safety design for theatre lounge are: to protect the safety of people and to prevent fire from spreading to other regions. To achieve this goal, the performance indicators to quantify

1) The gas temperature should not exceed 60 ℃ from ground to the height of 2 m;
2) The visibility should not less than 10.0 m from ground to the height of 2 m;
3) The concentration of CO should not larger than 500 ppm from ground to the height of 2 m.

3.3. Fire simulation results

Textile market is modeled with FDS that developed by National Institute of Standards and Technology (NIST) and the results is shown in figure 6 and 7.



Temperature (600 s)	Visibility (600 s)

Fig.6.imulation result of fire source A

Simulation results of fire source A show that ambient air will be absorbed along the rising of smoke. Smoke will rapidly spread along the roof and sink after reaching the ceiling. Because automatic smoke barriers are set along the hole between two floors it initially able to prevent the smoke spread to other floor and discharge the smoke out of the building. But with the development of fire, smoke flooded automatic smoke barrier and flow to the second floor. Then the smoke reaches the roof of second floor because of the upward trend. Smoke will be discharged into the environment via the windows set along the north and south facades.

The temperature and concentration of CO are found below the criteria during the simulation in 1 200 s by analyzing the slices and curves. The visibility was serious reduced near the fire source and walls. Although the visibility near the walls will be lower than 10 m at 276 s, in most areas of first floor and the whole second floor it is always above 10 m. Therefore, the evacuation for the people in this scenario will not affect.

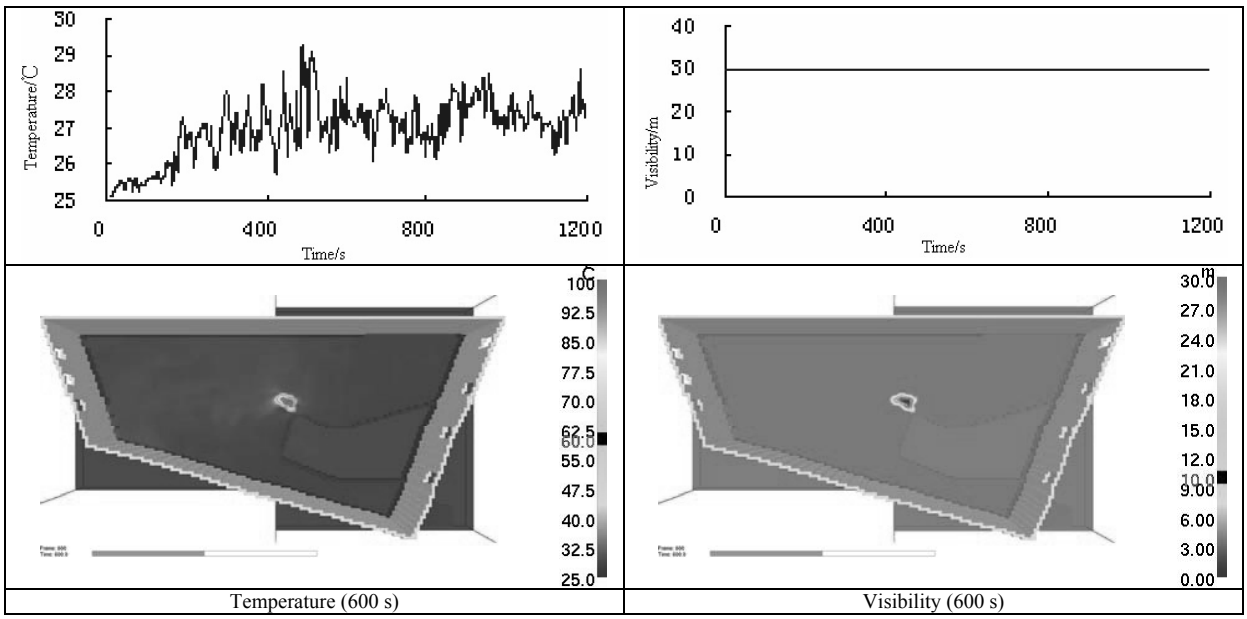


Fig.7.Simulation result of fire source B

According to the Simulation for fire source B, it can be found the smoke will rapidly spread along the roof and form anti-buoyant wall jet when it reaches the walls around. Smoke will be discharged into the environment via the windows and form a steady smoke layer.

The maximum temperature is 29.3 ℃ and concentration of CO is lower than 500 ppm by analyzing the slices and curves. The visibility is always above 10 m and the smoke layer is controlled at the same height of windows.

4. Conclusion

1) The theatre lounge fire can be expressed as fast t^2 fire, the temperature, concentration of CO and visibility are keeping below the criteria 2 m above the ground during the simulation. It can protect the safe of people because the REST is lower than ASET if the smoke exhaust system is effective.

2) Automatic smoke barriers are able to prevent the smoke spread to other floor. The natural smoke exhaust system is effective Rely on windows in the north and south facades of the lounge. The smoke can flow into environment and it does not accumulate, thus ensure the safe of evacuation passageway of the second floor.

3) Mechanical smoke exhaust system is effective by using the exhaust smoke level calculated according to the code, the smoke living in first floor can be discharged, as a result it can provide better evacuation environment.

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