Full-scale Experimental study on the suppression effect of water sprinkler system on energy saving building fire

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Abstract. In an energy saving building fire, the high temperature and pressure of the indoor smoke or flame break the window glass, and even forms ejecting fire that the flame spills out of the window. It is extremely dangers that the ejecting fire flame to the upper floor might contribute to the unpredicted hazard of the fire in energy saving building with amounts of insulation material. Therefore, the aim of this paper is proposing a method of protecting external windows based on the water sprinkler system. The system can suppress the spread of fire on the facade of the building, and prevent the formation of three-dimensional combustion of the building. This paper design and carried the two groups full-scale experiments to check the suppression effect of water spray system on the glass of the window under the different heat release rate (HRR) and thermal radiation from the fire. The conclusions describe the thermal radiation attenuation characteristics and temperature attenuation characteristics inside and outside the window. Consequently, we find that the sprinkler system can effectively protect the integrity of the glass and control the outdoor temperature within a safe range under the conditions of fire source power of 0.6 MW, 1.5 MW, and 3 MW. After the sprinkler system was turned on, the outdoor heat flux density rapidly decreased from a peak of 197 W/m² and stabilized at 80 W/m², which was 59% lower than the peak value. The research provides the deep insight into the temperature suppression phenomenon under the spray, and the protection method of ejecting fire for the external window is helpful to reduce the possibility of flashover in the indoor spray coverage. Due to the large range of heat release rates set in this paper, the experimental results provide a data reference for the fire protection design of future energy saving buildings.
1. Introduction

Currently, in order to reduce the loss of energy in buildings and improve the energy efficiency of buildings, many high-rise and energy saving buildings are designed and built. In the event of a fire in a high-rise building, it is often the case that the high temperature and high pressure of the indoor smoke or flame causes the glass to break and the flame to eject from the window. Since the insulation materials used in such buildings are flammable, these flammable materials are quickly ignited. The rapid spread of the flame along the façade caused a fire on the upper floor, causing great casualties and property damage.

For fire spill flame, many researchers [1-11] have carried out experimental research and obtained the law of occurrence and development of fire spill flame. Kawagoe [1] first proposed the concept of opening factor $AH$ to study the relationship between fuel combustion rate and opening in indoor fires, where $A$ represents the area of the opening and $H$ represents the height of the opening. Yokoi [2] was the first to carry out the experiment of small size enclosure opening fire overflow. Taking alcohol as fuel, the radial temperature distribution model of fire spill plume was obtained by studying different opening conditions. Yee-ping Lee [3] proposed that the critical heat release rate of a fire overflow is:

$$Q = \frac{3000}{0.5} \times \frac{1}{1500} \times \frac{1}{A} \times \frac{1}{H} \times \frac{k}{J} \times \frac{g}{kg} \times \frac{0.005}{s} \times \frac{1}{H} \times \frac{1}{kW}$$

(1)

In addition, Lee et al. designed a long enclosure fire overflow test bench that can be assembled using three cubic modules. The size of each cubic module is $0.5m \times 0.5m \times 0.5m$, and the enclosure size and opening size of the bench can be varied. They proposed new length scale $l_1$ and $l_2$, and used these two length scale to express the height of the flame and the heat radiation. They derived a new theoretical calculation formula, which is in good agreement with the experimental data.

However, current research only focuses on the flame morphology, transient characteristics and temperature distribution of the facade of the building after the window is opened. Few studies have been conducted on how to prevent the occurrence of fire spill plume. At the same time, the researchers’ experiments are usually based on small-scale models (1:4 and 1:8, etc.), and the experimental correlations obtained still require verification of full-scale experiments. Therefore, this study is based on a full-scale experiment to study how to prevent fire overflow and protect building exterior insulation materials.

Meanwhile, we are not able to carry out effective fire protection design on the façade of this high-rise building fire. Therefore, it is proposed to use a water sprinkler system to protect the windows of energy saving buildings to prevent the fire from spreading outward. Water sprinkler system is a widely used means of fire prevention. After the fire broke out, the temperature inside the building continued to rise. When the temperature rose to the operating temperature of the sprinkler, the sprinkler system began to move. The sprinkler sprays water onto the protected glass to prevent the temperature of the glass from being too high and broken, causing the fire to spread outward.

The research purpose of this paper is to explore: (a) whether the water spray system can protect the window glass from being damaged by high-temperature smoke or flame under different fire source powers and scenarios, (b) the external temperature attenuation degree of the window, and (c) the external thermal radiation attenuation degree of the window.
2. Experimental setup

Although full-scale experiments have the advantage of being true and reliable, the operation of full-scale experiments is difficult. The manpower and material resources consumed are large, making it difficult to perform repetitive experiments. Therefore, we have designed several experimental conditions to test the protective effect of spray under different fire scenarios. The main scenarios are: (1) As shown in figure 1 (a) and figure 1 (c), whether the glass can be kept intact, the temperature distribution inside and outside the room and the heat radiation distribution when the heat release rate is 0.6 MW. (2) As shown in figure 1 (b) when the heat release rate is 1.5 MW and 3 MW, an experimental chamber with two windows is used to study whether the glass at a different distance from the fire source can be kept intact and the outdoor temperature distribution.

The experimental design has two parts. In the first part (figure 1a), an experimental enclosure (lengths, widths and heights: 5m × 4.5m × 3.6m) and a window (widths and heights: 1.8m × 1.6m) are used. A thermocouple tree is set at every 0.2m from floor in the interior corner, and every 0.2m from the bottom to the outside of the window. Alcohol pool fire is used as the fire source, and the size of oil pan is 1.2m × 1.2m. The experimental model used in the second part includes an experimental enclosure (lengths, widths and heights: 5m × 4.5m × 3.6m) and two windows of the same size, the size of which is 2.4m × 1.8m. The raft was used as a source of fire, facing the window on the right. The thermocouples and nozzles outside the window are arranged in the same form in both sets of experiments. A sprinkler is attached to the inside of each window to protect the glass. The horizontal distance between the window and the sprinkler (pressure: 0.1Mpa, flow characteristic coefficient: 63.5, rated operating temperature: 68°C) is 0.25m. The thermocouples used to measure the temperature in the experiment are all k-type thermocouples (with a diameter of 0.5mm), which are used to measure the temperature curve of indoor and outdoor.

![Figure 1. Experimental setup.](image)

(a) The first part of the experimental arrangement. (b) The second part of the experimental arrangement. (c) Arrangement of sprinklers and thermocouples outside the window.
Figure 2. (a) Sprinkle. (b) Wood crib burner. (c) A picture of the experiment. (d) A picture after the experiment.

Figure 2 shows a complete experimentation. Figure 2(a) shows the sprinkler installed above the window. The arrangement and combustion of wood crib burner are introduced in figures 2(b) and figures 2(c). When the burn was over, the glass of the room was intact as shown in the figures 2(d).

| NO. | Compartment size   | Window size   | Fire source               |
|-----|--------------------|---------------|----------------------------|
| 1   | 5m×4.5m×3.6m       | 1.8m×1.6m     | 1.2m×1.2m Ethyl alcohol pool |
| 2   | 7.8m×5.4m×3.4m     | 2.4m×1.8m     | 3MW Wood crib             |
| 3   | 7.8m×5.4m×3.4m     | 2.4m×1.8m     | 1.5MW Wood crib           |

3. Results and discussion

3.1. Indoor temperature distribution

Steckler K D [7] found that the indoor gas temperature showed stratification with height during the experiment. Figure 3 shows the steady-state average temperature as a function of height at the inner corner of the experimental room. During the experiment, the temperature was about 260°C in the area above 2.5 m. In the region below 2.5 m, the temperature gradually decreases as the height decreases,
eventually dropping to about 30°C. The temperature distribution in the upper region is kept substantially constant, so the distribution of the smoke layer is relatively uniform. In the lower region, as the smoke layer gradually decays, the temperature also gradually decreases.

![Temperature profile](image)

**Figure 3.** The temperature profile of the inner corner of the room

The heat absorbed by the water after entering the compartment through the sprinkler mainly includes the heat absorbed by the water vaporized into the water vapor, and the heat absorbed by the heat convection during the rising of the water vapor:

\[
Q_{abs} = Q_{vap} + Q_{conv}
\]

\[
Q_{vap} = \Delta H
\]

\[
Q_{conv} = n \rho c_p (T_g - T_w)
\]

It can be seen from equations (2) and (3) that the quality of water evaporation \( n \rho \) and the temperature of indoor smoke \( T_g \) are the key factors affecting heat absorption. The higher the indoor flue gas temperature, the faster the water evaporates and the more heat is absorbed by vaporization. At the same time, the temperature difference \( T_g - T_w \) is greater, and the heat absorbed by the heat convection is also more. However, since the quality of water vapor is difficult to measure during the spraying operation, we can only use qualitative methods for analysis.

Peizhong Yang [12] proposed that the indoor temperature history is divided into four development stages in the presence of the sprinkler system. After igniting the fire source, it enters the stage of rapid growth. After the indoor temperature rises, the sprinkler is triggered to enter the fire suppression phase. After the smoke layer is stabilized, the indoor temperature rises again and enters the stage of continuous fire growth. Eventually the combustibles are exhausted and enter the decay phase. Figure 4 contains the first three stages. It can be seen from the indoor temperature history around the window that the change in the temperature history is in line with Peizhong Yang's description in the range of 1.6m to 2.2m.

However, from 1.4m to 1.0m, the temperature has dropped from about 100°C to about 50°C, and it has not increased with time. This shows that the spray can not only protect the integrity of the outer
window, but also can effectively reduce the temperature around the indoor windows. The lower temperature in the lower part of the room can prevent further development of the fire and prevent the occurrence of flashover around the window.

It can be seen from figure 4 that after the sprinkler system is started, the temperature around the window is greatly reduced due to the cooling effect of the water. From 1.6m to 2.2m (upper part of the window), after the sprinkler is turned on, the temperature around the window can be restored to the temperature before the sprinkler is turned on after at least 200s. During the experiment, the sprinkler remained open and the glass remained intact. This also slows down the speed of fire development and spread, and has won valuable time for fire rescue.

During the experiment, in the fire suppression phase, water evaporates and heat conveys throughout the window area, causing a rapid decrease in temperature. The flue gas layer then stabilizes gradually, and the temperature in the upper part of the window (at 1.4 m to 2.2 m) gradually rises above the maximum temperature before the spray starts.

![Figure 4. Temperature history around the indoor window.](image)

(a) The stage of rapid growth. (b) The fire suppression phase. (c) The stage of continuous fire growth.

3.2. The history of outdoor temperature

As can be seen from figure 5, after igniting the source of ignition, the temperature outside the window also begins to rise rapidly, reaching a maximum temperature of 33°C. When the sprinkler system is started, the outdoor temperature returns to around 16°C. It shows that when the fire source is located in the center of the room and the fire source power is 0.6MW, the glass does not rupture. The glass and spray insulation system can suppress the temperature rise outside the window.
In experimental conditions 2 and 3, the heat release rate of the fire source is larger and closer to the window, and the variation law of the outdoor temperature distribution is quite different from the experimental condition 1. Modak [13] proposes that the heat radiation from the fire source to the surrounding environment can be expressed as:

$$\Phi = \frac{\chi_r \Phi_0}{4\pi R_0^2}$$

(5)

Where $R_0$ is the distance from the window to the center of the fire source, $\chi_r$ is the total energy radiation fraction. Since the distance between the left window and the center of the fire source $R_i$ is greater than the distance between the right window and the center of the fire source $R_j$, the heat radiation from the outside of the left window is greater than the outside of the right window. That is, the temperature of the window near the side of the fire source is increased more than the temperature of the window away from the side of the fire source.

Figure 5. Temperature distribution around outdoor windows

(a) Experimental condition 2 left window temperature history
(b) Experimental condition 2 right window temperature history
It can be seen from figure 6 that within 30 min, the temperature outside the left window of the experimental condition 2 (the side away from the fire source) is increased by about 4°C, which is much smaller than the temperature rise of the outside of the right window (the side near the fire source) by about 13°C. In the experimental condition 3, the temperature rise outside the left window is up to about 11°C, and the temperature outside the right side window rises by about 16°C.

3.3. Heat fluxes

As shown in figure 7, the heat flux density inside and outside the room begins to rise after the alcohol pool fire is ignited. The difference is that the indoor heat flux density and the rising speed are much larger than the outside of the window, which means that in the early stage of the fire, the glass can isolate most of the heat without the protection of the sprinkler system.

After igniting the fire source for 60s, the indoor sprinkler system is activated, and the sprinkler sprays water onto the glass for protection. The outdoor heat flux density starts to decrease rapidly after reaching 197W/m², and the indoor heat flux density also decreases. However, after the smoke layer is stabilized, the heat flux density value rises again as the room temperature increases.
Finally, throughout the experiment, the glass remained intact, and the outdoor heat flux density was maintained at around 80 W/m², a 59% reduction from the peak. This shows that the sprinkler system can not only effectively protect the integrity of the outer glazing, but also significantly reduce the outdoor heat radiation value.

4. Conclusions
During the experiment, the glass maintained good integrity under the protection of the sprinkler system in the three experimental conditions. At the same time, the sprinkler system also controls the temperature and heat radiation outside the window to a safer range, effectively reducing the possibility of ignition of the external thermal insulation material of the energy-saving building. From this we can draw the following conclusions:

- Before the sprinkler system is started, the heat radiation from the outside of most indoor fire sources to the outside can be isolated without the glass being destroyed. It can be concluded that the sprinkler system may not be turned on if the power of the fire source is small or the temperature around the window is low.
- Under the conditions of heat release rate of 0.6MW, 1.5MW and 3MW, the sprinkler system can not only effectively protect the integrity of the glass, but also greatly reduce the rise of the outdoor temperature and the thermal radiation from the fire source to the outside.
- In the case that the indoor fire source is 0.6MW alcohol pool fire, the sprinkler system controls the temperature of the area below 1.2m indoors to about 50 °C, and does not increase with time, which effectively protects the bottom of the room. The area reduces the possibility of a flashover.

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References

[1] Kawagoe, K 1958 Fire Behaviour in Rooms-Report No. 27. Tokyo: Building Research Institute

[2] Yokoi S 1960 Study on the prevention of fire-spread caused by hot upward current. BRI Report 34

[3] Lee Y P et al 2009 Heat fluxes on opposite building wall by flames emerging from an enclosure Proceedings of the Combustion Institute 32 2551-8

[4] Delichatsios M A, Lee Y P and Tofilo P 2009 A new correlation for gas temperature inside a burning enclosure Fire Safety Journal 44 1003-9

[5] Sun X et al 2018 Temperature evolution and transition inside fire compartment with an opening subject to external sideward wind Pro. Combustion Institute 37 3869-77

[6] Sun X et al 2018 Experimental study on evolution of compartment fire and facade flame through an opening with the fire source attached to a backwall at different elevations Pro. Combustion Institute 37 3919-26

[7] Steckler K D, Quintiere J G, Rinkinen W J 1982 Flow induced by fire in a compartment. Symposium on Combustion 19 913-20

[8] Quintiere J G, W J Rinkinen, W W Jones 2007 The Effect of Room Openings on Fire Plume Entrainment Combus. Sci. Technol. 26 193-201

[9] Lu K H et al 2014 Heat flux profile upon building facade with side walls due to window ejected fire plume: An experimental investigation and global correlation. Fire Safety Journal 70 14-22

[10] Hu L H et al 2013 A mathematical model on lateral temperature profile of buoyant window spill plume from a compartment fire Int. J. Heat and Mass Transfer 56 447-53

[11] Gao W et al 2016 Fire spill plume from a compartment with dual symmetric openings under cross wind Combustion and Flame 167 409-21

[12] Yang P, Liu T, Qin X 2010 Experimental and numerical study on water mist suppression system on room fire Building and Environment 45 2309-16

[13] Modak A T 1977 Thermal radiation from pool fires Combustion and Flame 29 177-92