Study on Fire Characteristics of Typical Atrium

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Abstract. According to the theory of architecture and fire engineering, U-shaped enclosed atrium and full enclosed atrium are selected as the research objects to understand the fire characteristics of typical atrium. The fire characteristics of the two types of atrium are quantitatively studied and the fire characteristic indexes are compared, which provides more objective data for the building fire safety assessment. Based on the research results, the fire protection design suggestions for typical atrium are proposed.

1. Introduction
The atrium is widely used in various buildings and has become an important part of modern architecture due to the convenient connectivity and the rich visual effects. While there are many fire hazards in the atrium due to its openness and large-scale. According to the theory of fire engineering, the form of building space and the size of openings will directly affect the development of fires. This paper quantitatively studies the fire characteristics of the atrium from the perspective of the architects so that the architects could not only strictly implement the requirements of fire codes, but also solve the fire prevention problems in architectural design according to the fire characteristics of the atrium. U-shaped enclosed atrium and full enclosed atrium are selected as research objects. The fire characteristics of the two types of atrium are respectively compared under the same size, height, and smoke exhaust method.

2. Research method
2.1. Concept definition
U-shaped enclosed atrium is close to the building on three sides, facing the outdoor space on one side which usually adopts a large area of glass curtain wall. Full enclosed atrium is surrounded by the building entities and it can connect and organize the interior.

Fire characteristics refer to the change of smoke temperature, visibility and CO mass fraction in the atrium with time under the same standard fire source. The risk time is determined by the smoke temperature reaching 60 ℃, or visibility less than 10 m, or CO mass fraction reaching 0.25%.

2.2. Fire simulation
PyroSim is used for fire simulation. The standard fire source is set to t² fast fire and the fire growth coefficient α = 0.0469kW/s². The maximum heat release rate of 4MW is reached about at 290s and
then it enters the stable combustion stage. The fire simulation duration is 1800s. The small space model is 20m×15m×12m and adopts natural smoke exhaust. The total area of the openable skylights and high windows is 15m² and 30m² respectively. The large space model is 40m×30m×24m and adopts a combination of natural and mechanical smoke exhaust. The natural exhaust outlet is 15m² and the mechanical exhaust volume is 28.5m³/s and 57m³/s respectively. A horizontal slice tool at a distance of 2m from the ground is set to measure the changes of smoke temperature, visibility and CO mass fraction in the atrium. A vertical slice tool is set to measure the temperature change in the vertical direction of the atrium. The cloud maps of the fire characteristics at the time of 300s and 1800s are selected as comparative objects.

### Table 1. U-shaped enclosed atrium fire model

|                      | small space model | large space model |
|----------------------|-------------------|-------------------|
|                      | G-1               | G-2               |
| skylight is 3m×3m,   | skylight is 2×3m×3m, high window is 2×3m×2m, total area of natural exhaust outlet is 15m² | skylight is 3m×3m, high window is 3m×2m, total area of natural exhaust outlet is 15m², mechanical smoke exhaust volume is 28.5m³/s |
| high window is 3m×2m, total area of natural exhaust outlet is 15m² | skylight is 2×3m×2m, total area of natural exhaust outlet is 30m² |

### Table 2. Full enclosed atrium fire model

|                      | small space model | large space model |
|----------------------|-------------------|-------------------|
|                      | J-1               | J-2               |
| skylight is 2×3m×2.5m, total area of natural exhaust outlet is 15m² | skylight is 4×3m×2.5m, total area of natural exhaust outlet is 15m², mechanical smoke exhaust volume is 28.5m³/s |

### 3. Simulation results and analysis

#### 3.1. Fire cloud maps and characteristic indexes

#### 3.1.1. Fire characteristics of U-shaped enclosed atrium
### Table 3. Fire cloud maps of U-shaped enclosed small space

|          | G-1                  |          | G-2                  |          |
|----------|----------------------|----------|----------------------|----------|
|          | At 300s              | At 1800s | At 300s              | At 1800s |
| Horizontal temperature at 2m | ![Image](image1) | ![Image](image2) | ![Image](image3) | ![Image](image4) |
| Profile temperature          | ![Image](image5) | ![Image](image6) | ![Image](image7) | ![Image](image8) |
| Horizontal CO mass fraction at 2m | ![Image](image9) | ![Image](image10) | ![Image](image11) | ![Image](image12) |

### Table 4. Fire cloud maps of U-shaped enclosed large space

|          | H-1                  |          | H-2                  |          |
|----------|----------------------|----------|----------------------|----------|
|          | At 300s              | At 1800s | At 300s              | At 1800s |
| Horizontal temperature at 2m | ![Image](image13) | ![Image](image14) | ![Image](image15) | ![Image](image16) |
| Profile temperature          | ![Image](image17) | ![Image](image18) | ![Image](image19) | ![Image](image20) |
| Horizontal CO mass fraction at 2m | ![Image](image21) | ![Image](image22) | ![Image](image23) | ![Image](image24) |
Table 5. Fire characteristic indexes of U-shaped enclosed atrium in 4 fire scenes

| Scene | G-1 | G-2 | H-1 | H-2 |
|-------|-----|-----|-----|-----|
| | 300s | 1800s | 300s | 1800s | 300s | 1800s | 300s | 1800s |
| Horizontal temperature at 2m (℃) | | | | | | | | |
| maximum | 170 | 170 | 170 | 170 | 65 | 65 | 65 | 65 |
| minimum | 45 | 100 | 60 | 80 | 25 | 50 | 25 | 45 |
| difference | 125 | 70 | 110 | 90 | 40 | 15 | 40 | 20 |
| Profile temperature (℃) | | | | | | | | |
| upper | 80 | 120 | 120 | 120 | 40 | 60 | 40 | 55 |
| lower | 50 | 80 | 55 | 90 | 30 | 40 | 25 | 40 |
| difference | 30 | 40 | 65 | 30 | 10 | 20 | 15 | 15 |
| Horizontal CO mass fraction at 2m (%) | | | | | | | | |
| maximum | 0.08 | 0.08 | 0.05 | 0.05 | 0.02 | 0.02 | 0.02 | 0.02 |
| minimum | 0.01 | 0.05 | 0.01 | 0.04 | 0 | 0.014 | 0 | 0.01 |
| difference | 0.07 | 0.03 | 0.04 | 0.01 | 0.02 | 0.006 | 0.02 | 0.01 |

Fire scene G-1: At 300s, the maximum horizontal temperature at 2m is 170℃, which is located above the fire source, and the temperature of other parts is mainly 45-60℃. The temperature of the upper part of the profile is mainly 60-80℃ and the temperature of the lower part is mainly 40-50℃. At 1800s, the maximum horizontal temperature is 170℃ and the temperature of other parts is mainly 100-120℃. The upper part is at 140-160℃ and the lower part is at 70-80℃. The smoke temperature at 2m reaches the dangerous state at about 297s, the visibility reaches the dangerous state at about 191s and the CO mass fraction does not reach the dangerous state.

Compared with fire scene G-1, the natural exhaust area of G-2 is doubled and the smoke convection is accelerated. At 300s, the smoke temperature and CO mass fraction in the atrium increased relatively, but the maximum smoke temperature and CO mass fraction at 2m did not change significantly. At 1800s, there is no significant difference in fire characteristics between the two scenes. The time of G-2 for the temperature at 2m to reach the dangerous state has decreased by 8%, while the time for visibility to reach the dangerous state is basically the same as G-1. The results show that the change of natural exhaust area in U-shaped enclosed small space has a weak influence on the fire risk.

Fire scene H-1: The maximum horizontal temperature at 2m is 65℃. At 1800s, the temperature of the upper part of the profile is 50-60℃ and the lower temperature is 40-50℃. The temperature at 2m does not reach the dangerous state, the visibility reaches the dangerous state at about 236s and the CO mass fraction does not reach the dangerous state.

Compared with fire scene H-1, H-2 have the same area of natural exhaust outlet, while the mechanical exhaust volume is doubled. The smoke temperature at 2m does not reach the dangerous state and the time of H-2 for visibility to reach the dangerous state is not different from H-1. The results show that the fire characteristics of U-shaped enclosed large space are not significantly affected by the mechanical exhaust volume.

Compared with fire scene H-1, the smoke temperature and CO mass fraction of G-1 are both higher and the time of G-1 for the visibility to reach the dangerous state is relatively reduced by 19%.
### 3.1.2. Fire characteristics of full enclosed atrium

#### Table 6. Fire cloud maps of full enclosed small space

|         | J-1 At 300s | J-1 At 1800s | J-2 At 300s | J-2 At 1800s |
|---------|-------------|--------------|-------------|--------------|
| **Horizontal temperature at 2m** | ![Image] | ![Image] | ![Image] | ![Image] |
| **Profile temperature** | ![Image] | ![Image] | ![Image] | ![Image] |
| **Horizontal CO mass fraction at 2m** | ![Image] | ![Image] | ![Image] | ![Image] |

#### Table 7. Fire cloud maps of full enclosed large space

|         | K-1 At 300s | K-1 At 1800s | K-2 At 300s | K-2 At 1800s |
|---------|-------------|--------------|-------------|--------------|
| **Horizontal temperature at 2m** | ![Image] | ![Image] | ![Image] | ![Image] |
| **Profile temperature** | ![Image] | ![Image] | ![Image] | ![Image] |
| **Horizontal CO mass fraction at 2m** | ![Image] | ![Image] | ![Image] | ![Image] |
Table 8. Fire characteristic indexes of full enclosed atrium in 4 fire scenes

| Scene   | J-1 | J-2 | K-1 | K-2 |
|---------|-----|-----|-----|-----|
| moment  | 300s | 1800s | 300s | 1800s | 300s | 1800s | 300s | 1800s |
| Horizontal temperature at 2m (℃) | | | | | | | | |
| maximum | 170 | 170 | 170 | 170 | 60 | 60 | 65 | 65 |
| minimum | 60 | 110 | 60 | 110 | 20 | 35 | 25 | 45 |
| difference | 110 | 60 | 110 | 60 | 40 | 25 | 40 | 20 |
| Profile temperature (℃) | | | | | | | | |
| upper | 140 | 180 | 150 | 180 | 40 | 60 | 35 | 50 |
| lower | 80 | 140 | 60 | 120 | 20 | 45 | 20 | 40 |
| difference | 60 | 40 | 90 | 60 | 20 | 15 | 15 | 10 |
| Horizontal CO mass fraction at 2m (%) | | | | | | | | |
| maximum | 0.15 | 0.15 | 0.08 | 0.08 | 0.02 | 0.02 | 0.02 | 0.02 |
| minimum | 0.02 | 0.14 | 0.02 | 0.05 | 0 | 0.01 | 0 | 0.01 |
| difference | 0.13 | 0.01 | 0.06 | 0.03 | 0.02 | 0.01 | 0.02 | 0.01 |

Fire scene J-1: At 300s, the maximum horizontal temperature at 2m is 170℃ and the temperature of other parts is mainly 45-60℃. The temperature of the upper part of the profile is mainly 120-150℃ and the temperature of the lower part is mainly 70-90℃. At 1800s, the maximum horizontal temperature is 170℃ and the temperature of other parts is mainly 100-120℃. The upper part is at 170-200℃ and the lower part is at 120-150℃. Compared to other types of atriums, the temperature of J-1 is higher mainly because there is no high windows. The smoke temperature at 2m reaches the dangerous state at about 270s, the visibility reaches the dangerous state at about 205s and the CO mass fraction does not reach the dangerous state.

Compared with fire scene J-1, the natural exhaust area of J-2 is doubled and the smoke convection is accelerated. At 300s, the smoke temperature and CO mass fraction in the atrium increased relatively. At 1800s, the fire characteristics of the two scenes are not significantly different. The time of J-2 for the temperature and visibility to reach the dangerous state is basically the same as J-1 because there is no high windows. The smoke temperature at 2m reaches the dangerous state at about 270s, the visibility reaches the dangerous state at about 205s and the CO mass fraction does not reach the dangerous state.

Compared with fire scene J-1, the natural exhaust area of J-2 is doubled and the smoke convection is accelerated. At 300s, the smoke temperature and CO mass fraction in the atrium increased relatively. At 1800s, the fire characteristics of the two scenes are not significantly different. The time of J-2 for the temperature and visibility to reach the dangerous state is basically the same as J-1 because there is no high windows. The smoke temperature at 2m reaches the dangerous state at about 270s, the visibility reaches the dangerous state at about 205s and the CO mass fraction does not reach the dangerous state.

Fire scene K-1: The maximum horizontal temperature at 2m is 60℃. At 1800s, the temperature of the upper part of the profile is 50-60℃ and the lower temperature is 40-50℃. The temperature at 2m does not reach the dangerous state, the visibility reached the dangerous state at about 187s and the CO mass fraction does not reach the dangerous state.

Compared with fire scene K-1, K-2 have the same area of natural exhaust outlet, while the mechanical exhaust volume is doubled. The smoke temperature at 2m does not reach the dangerous state. The time of K-2 for visibility to reach the dangerous state is 349s, nearly double that of K-1, indicating that the fire characteristics of full enclosed large space are significantly affected by the mechanical exhaust volume.

Compared with fire scene K-1, the smoke temperature and CO mass fraction of J-1 are both higher and the time of J-1 for visibility to reach the dangerous state is relatively reduced by 10%.
3.1.3. Atrium fire dangerous time

Figure 1 shows the time when visibility at 2m reaches the dangerous state. The time of K-2 is significantly higher than that of other fire scenes, indicating that mechanical smoke exhaust plays a significant role in reducing the harm of fire smoke.

4. Conclusion and suggestion

Based on the fire simulation results and analysis, the following basic conclusions can be drawn. ① When there is no mechanical smoke exhaust in the atrium and the area of the natural exhaust outlet doubles, the maximum smoke temperature and CO mass fraction of the U-shaped enclosed atrium and the full enclosed atrium do not change significantly. ② When there is no mechanical smoke exhaust in the atrium and the area of the natural exhaust outlet doubles, the time of the U-shaped enclosed atrium for the temperature and visibility at 2m to reach the dangerous state will decrease by 8% -13% and the changes of the full enclosed atrium are not significant. ③ Under the same space condition and fire scale, the increase of the natural exhaust outlet area leads to the acceleration of smoke convection and fire risk. ④ When the area of natural exhaust outlet is the same and the mechanical exhaust volume is doubled, the time for the visibility at 2m to reach the dangerous state will be relatively extended by 25% -40%, indicating that the better the mechanical exhaust effect is, the higher the fire safety of the atrium will be. ⑤ For the natural exhaust atrium, it should be ensured that the outlet can be opened in time when a fire occurs.

According to the conclusions of the study, the architects can adopt the following strategies for the fire protection design of the atrium. ① The interior decoration of the atrium should use non-combustible materials as far as possible to reduce the fire load and the possibility of fire in the atrium. ② The atrium should be separated from the main building by fire shutter or fire water curtain, making the atrium an independent fire partition. ③ The atrium shall be designed with the combination of natural exhaust and mechanical exhaust. The effective opening area of the atrium shall not be less than 40% of the ground area and the effective opening area of the top shall not be less than 25% of the ground area. ④ The top skylight should be able to open automatically and set an emergency manual opening function. ⑤ A smoke storage pool can be designed at the top of the atrium to enhance the smoke exhaust effect. ⑥ The glass curtain wall should adopt the fireproof glass with fire resistance limit not less than 1 hour to prevent the glass from bursting under the action of high temperature stress. ⑦ Non-combustible materials shall be used to fill the horizontal gap between the curtain wall and each floor to prevent the spread of fire smoke.
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