CFD Study on the Air Temperature Field inside Fire-Rated Duct of Pressurisation System

Hang Yin and Longfei Tan

Sichuan Fire Research Institute of Ministry of Emergency Management, No. 69 Jinke South Road, Jinniu District, Chengdu, China.
Email: bank2002yinhang@126.com

Abstract. Avoiding overheating of the supply air inside the fire-rated duct of pressurisation system is crucial for the escape and rescue of the building occupants during the development of a fire. The simulation scenarios are established concerning three cross-sectional dimensions of ducts and four inner air velocities. Based on the performance criteria of insulation specified in the international standard of ISO 834-1, the temperature fields of supply air inside different fire-rated ducts and corresponding safety are analysed based on the assumption that the exterior of fire-rated ducts is in a consistent state of being subjected to fire.

1. Introduction
The pressurisation system is a special form of smoke control system that should be maintaining the air supply state for restricting the penetration of smoke into certain critical areas, such as stairways, lobbies and corridors. Generally, the ductwork of pressurisation system shall be capable of resisting the anticipated fire temperatures generated during the development of a fire. Meanwhile, it is noteworthy that the overheating of the supply air inside the fire-rated duct should be avoided as well, because the supply air is directly exported to the escape and rescue area of the building occupants. However, previous studies mainly focused on the technology and strategy of smoke control on the systems level [1-5], the research on the flow field inside the ductwork of smoke containment system are less comparatively. In this study, the inner air temperature fields of fire-rated duct of pressurisation system are numerically simulated using the CFD software of FLUENT.

2. Geometrical Model and Computational Domain
A common height of standard floor of buildings, five meters, is set as the length of study objects. As shown in figure 1, three types of fire-rated ducts of initial section are built in the cross-sectional dimensions of 0.5×0.5 m, 1.0×1.0 m and 1.5×1.5 m, respectively.

![Figure 1. Three types of ducts with different cross-sectional dimensions.](image)

The cross section of ducts is vertical to the gravity direction. Additionally, two kinds of computational domains are constructed based on different inner velocity fields of ducts. For the ducts
in air supply state, the computational domain only contains the volume of geometrical model. For the ducts in off-duty state, the computational domain is extended appropriately for obtaining a better calculation accuracy, as illustrated in Table 1.

Table 1. Dimensions of computational domain for the ducts in off-duty state.

| Cross-sectional dimensions of ducts | Length  | Width  | Height |
|-----------------------------------|---------|--------|--------|
| 0.5x0.5 m                        | 4.5 m   | 4.5 m  | 15 m   |
| 1.0x1.0 m                        | 5.0 m   | 5.0 m  | 15 m   |
| 1.5x1.5 m                        | 5.5 m   | 5.5 m  | 15 m   |

3. Simulation Scenarios and Boundary Conditions
As shown in Table 2, 12 simulation scenarios are designed concerning three cross-sectional dimensions of ducts and four inner air velocities. The direction of inner air velocities is opposite to the gravity direction. According to the provisions specified in the international standard of ISO 834-1, the criterion to confirm the specimen has lost its insulation performance is any of the following: (1) The average temperature increase above the initial average temperature of the surface unexposed to fire is more than 140°C; (2) The temperature increase above the initial temperature at any location of the surface unexposed to fire is more than 180°C. To analyse the most unfavourable condition, four external surfaces of each fire-rated duct mentioned above are assumed to be subjected to fire simultaneously. Therefore, the average temperatures of the corresponding four internal surfaces are set as the critical temperature, 160°C, by assuming the initial average surface temperatures are 20°C. The detailed simulation scenarios and boundary conditions of geometrical model are illustrated in Table 2 and Table 3, respectively.

Table 2. Simulation scenarios with different cross-sectional dimensions and inner air velocities.

| Inner air velocities | 0 m/s | 5 m/s | 10 m/s | 20 m/s |
|----------------------|-------|-------|--------|--------|
| Cross-sectional dimensions: 0.5x0.5 m | Scenario 1 | Scenario 2 | Scenario 3 | Scenario 4 |
| Cross-sectional dimensions: 1.0x1.0 m | Scenario 5 | Scenario 6 | Scenario 7 | Scenario 8 |
| Cross-sectional dimensions: 1.5x1.5 m | Scenario 9 | Scenario 10 | Scenario 11 | Scenario 12 |

Table 3. Boundary conditions of geometrical model.

| Inner air velocities: 0 m/s | Inner air velocities: 5, 10, 20 m/s |
|-----------------------------|------------------------------------|
| Inlet of ducts              | Pressure-in | Velocity-in |
| Outlet of ducts             | Pressure-out | Outflow     |
| Internal surface of ducts   | Wall: 160°C, 871 J/(kg·K), 202.4 W/(m·K) |

4. Sections of Temperature Analysis and Safety Criterion
As shown in Figure 2, the temperature fields of middle longitudinal section A-B-C-D and middle transverse section E-F-G-H are the objects of investigation. According to the research findings described in SFPE (Society of Fire Protection Engineers) Handbook of Fire Protection Engineering, the tolerance time for exposure to hot air of 60°C and 100% relative humidity is only 30 min, and will be shorten to 12 min when the air temperature is 100°C and relative humidity is less than 10%. Therefore, in this study, the criterion to confirm the safety of the supply air inside the fire-rated duct is defined strictly that the average temperatures of above-mentioned sections are no more than 60°C.
5. Changing Process of Temperature Field of Target Sections

Taking Scenario 1 and 4 for example, the changing process of the temperature fields of section A-B-C-D and E-F-G-H are shown in figure 3 and 4.

![Figure 3. Temperature fields of section A-B-C-D for Scenario 1 and 4.](image1)

![Figure 4. Temperature fields of section E-F-G-H for Scenario 1 and 4.](image2)

It can be seen that, for Scenario 1, the static air under normal temperature inside the duct is heated by the high-temperature duct wall and rises under the action of buoyancy. The annular thermal boundary layer thickens gradually along the flow direction of heated air. When the temperature field
of inner air reaches steady state, the temperatures of main zone for the entrance region and fully developed region are 20-30°C and 30-40°C, respectively. For Scenario 4, since the inner air velocity is 20m/s, the heat exported from the duct wall is taken out rapidly along with the air. Therefore, only a thin thermal boundary layer appears near the duct wall. The temperature of main zone always maintains 20-30°C.

6. Temperature Field of Target Sections under Steady State
The temperature fields of section E-F-G-H under steady state are shown in figure 5. For the scenarios without initial air velocity, as the cross-sectional dimension of duct increases, the length of entrance region flow increases and the thickness of thermal boundary layer decreases. For the scenarios with initial air velocity, the thickness of thermal boundary layer decreases with the increase of cross-sectional dimension of duct and inner air velocity.

Figure 5. Temperature fields of section E-F-G-H under steady state.

Figure 6. Average temperature of section A-B-C-D under steady state.

Figure 7. Average temperature of section E-F-G-H under steady state.
The average temperatures of section A-B-C-D and E-F-G-H under steady state are shown in figure 6 and figure 7, respectively. It can be seen that the average temperatures of section A-B-C-D and E-F-G-H both decrease with the increase of cross-sectional dimension of duct and inner air velocity. Moreover, since the heat convection rate in the state of natural convection is smaller than that in the state of forced convection, a large amount of heat still exists in the duct without initial air velocity. Therefore, the average temperatures of the two sections for the scenarios in off-duty state are obviously higher than those for the scenarios in air supply state. However, the maximum average temperatures of section A-B-C-D and E-F-G-H are only 40.4°C and 35.8°C, respectively.

7. Conclusion
The temperature fields of supply air inside different fire-rated ducts of pressurisation system, concerning three cross-sectional dimensions of ducts and four inner air velocities, are simulated in this study. The temperatures inside the ducts in off-duty state are obviously higher than those in air supply state. It can be seen from the simulation results that the average temperature of the middle longitudinal section and middle transverse section of the ducts are less than 40.4°C and 35.8°C, respectively, when the fire-rated ducts are in a state of air supply and being subjected to fire. Based on the performance criteria of insulation specified in existing standard, the supply air is safe enough to be exported from the pressurisation system during the period in which the fire-rated duct maintains its insulation performance.

Acknowledgements
This research was financially supported by Research Program of Fire and Rescue Department of Ministry of Emergency Management (No.2018XFGG18) and Central Public-interest Scientific Institution Basal Research Fund (NO.20218805Z).

References
[1] Lu S, Wang Y H, Zhang R F and Zhang H P. 2011 Procedia Eng 11 369–378.
[2] Merci B, Shipp M. 2013 Fire Safety J 57 3–10.
[3] Węgrzyński W. 2017 Int. J. Heat Mass Tran 114 483–500.
[4] Byrne E, Georgieva K and Carvel R. 2018 Tunn. Undergr. Sp. Tech 81 306–314.
[5] Li J, Prétre H, Suard S, Beji T and Merci B. 2021 Fire Safety J 125 103426.