Studies on Smoke Temperature Distribution in a Building Corridor Based on Reduced-scale Experiments

Jin Zhou*, Jinfeng Mao2, Yuliang Huang3 and Zheli Xing1

1Ph.D. Candidate, College of Defense Engineering, PLA University of Science and Technology, China
2Professor, College of Defense Engineering, PLA University of Science and Technology, China
3Teacher, College of Defense Engineering, PLA University of Science and Technology, China

Abstract
A reduced-scale (1:4) building corridor model was prepared to investigate the heat release rate (HRR) and smoke diffusion in a building corridor. Trays with heptane as fuel were used as fire sources. Three different sizes of trays were involved in this study to investigate the different HRRs. The results revealed that fire associated with larger trays exhibited a steeper power-law growth and decay. The temperature distributions in the corridor for the three cases showed similar tendencies. The temperature in the upper part of the corridor was relatively high, which decayed sharply along the corridor. However, the temperature in the lower part of the corridor was approximately the ambient temperature. Numerical simulation was also introduced to obtain more details regarding the temperature. The ceiling temperature was studied by using dimensionless parameters. The correlation between the ceiling temperature and the distance was fitted by using an exponential equation, and significant fitting results were obtained. Moreover, the vertical average temperatures in the corridor were also studied. The result indicated that greater HRRs led to higher vertical average temperatures with steeper growths and decreases.

Keywords: fire; building corridor; heat release rate; smoke temperature distribution

1. Introduction
Corridors are common in modern buildings, and during fires smoke propagates rapidly through corridors because of their generally narrow and long shape, which can lead to catastrophic results. Numerous studies have been conducted on smoke diffusion through such spaces with significantly large length-width ratios.

Three methods, namely full-scale experimentation, reduced-scale experimentation and numerical simulation, exist to investigate smoke characteristics. Full-scale experimentation is considered to be the most reliable among the three methods. Hu et al. (2005) conducted full-scale experiments in an 88 m long corridor to study the variation in smoke temperature and velocity under the ceiling. The smoke temperature and velocity showed an exponential decay along the corridor. Later, Hu et al. (2006) carried out full-scale burning tests in two vehicular tunnels with and without operating the longitudinal ventilation system to study the smoke temperature below the ceiling under different longitudinal velocities. Additionally, the distribution of smoke temperature along the tunnel ceiling, with variation of the fire size and the tunnel geometry, was also investigated by Hu et al. (2007). In a full-scale tunnel, Tong et al. (2009) studied the smoke flow due to fires in a naturally ventilated road tunnel with shafts. Results showed that large amounts of smoke and heat were released through shafts. However, although the data obtained from full-scale experiments are trustworthy, full-scale experimentation is not used widely owing to its high cost and risk.

Reduced-scale experimentation is a common method of investigating the fire smoke characteristics ascribed to its balance between cost and reliability. It is based on the similitude criterion that is described in detail in the following sections. Many reduced-scale experiments have been conducted to investigate the fire-induced smoke in a corridor under different conditions. To study the maximum temperature under the ceiling in subway station fires, Ji et al. (2011) conducted reduced-scale experiments and developed a simplified calculation of predicting the maximum temperature under the ceiling based on theoretical analysis and small-scale experiments. Li et al. (2014) studied smoke characteristics of a bus bar corridor fire in the underground hydraulic machinery plant in a reduced-scale corridor model, and obtained the smoke temperature distribution and smoke height. Yang et
al. (2012) conducted reduced-scale experiments to test the CO stratification and thermal stratification in a tunnel. Ukleja et al. (2013) investigated the smoke concentration inside and outside of a reduced-scale model of a corridor-like enclosure. Based on theoretical analysis, Chen et al. (2013) developed a model to predict the buoyancy-driven smoke flow layering length beneath the ceiling with a combination of point extraction and longitudinal ventilation in tunnel fires, and confirmed the effectiveness of the model by reduced-scale experiments. Li et al. (2011) established a simplified calculation to predict the velocity, temperature, and thickness of the smoke layer in a long corridor, and the model was validated by reduced-scale experiments. Kashef et al. (2013) studied the distribution of smoke temperature and extent of diffusion in a reduced-scale tunnel with natural ventilation, and developed formulas to predict the temperature distribution and smoke diffusion extent based on experimental results and the one-dimensional theory.

Another method of investigating the fire smoke characteristics is numerical simulation. The process of combustion and smoke movement is complicated; therefore, several simplifications are highly desirable. Thus, the accuracy is limited under many circumstances. Although there are many problems in using computational fluid dynamics CFD, it can be applied to predict macroscopic flow parameters (Qu and Chow, 2012). By using CFD, research has been conducted on the density jump (Qu and Chow, 2012), smoke control (Weng et al., 2014), critical ventilation velocity (Hwang and Edwards, 2015), stack effects on natural ventilation (Ji et al., 2013), and slope influence (Ballesteros-Tajadura et al., 2006) in a tunnel fire.

However, most of the above-mentioned studies focused on the smoke diffusion when fire occurred in the corridor, and, actually, most focused on the tunnel fires. The characteristics of smoke diffusion in a building corridor, when fire occurs in a room and the smoke propagates into a corridor through the door, have rarely been investigated. In this study, reduced-scale experiments were performed to investigate the heat release rate (HRR) of fire, smoke temperature field, ceiling temperature distribution and the vertical average temperature evolution in a building corridor. The authors focused on the circumstance when fire occurred in the room and the smoke propagated into the corridor through the door. Three different HRRs were involved. Numerical simulations were also introduced to analyze the temperature field.

2. Experiments
2.1 Scaling Laws

According to the similitude criterion, all the nondimensional parameters between the reduced- and full-scale models should be made equal. However, under the practical experimental conditions, this is extremely difficult to achieve. Therefore, in this study, the critical nondimensional parameters were equated. According to the similitude criterion with respect to fire, the Froude number is the critical nondimensional parameter for smoke propagation caused by buoyant force. The Froude number provides the ratio of inertial forces to gravitational forces and the formula is expressed as

\[ \text{Fr} = \frac{V^2}{gL} \]  

where \( V \) is the characteristic velocity, \( g \) is the gravity acceleration, and \( L \) is the characteristic length.

The scale laws associated with HRR, temperature, and time between the reduced- and full-scale models are as follows:

\[ \frac{Q_m}{Q_f} = \left( \frac{L_m}{L_f} \right)^{5/2} \]  

\[ \frac{\tau_m}{\tau_f} = \left( \frac{L_m}{L_f} \right)^{1/2} \]  

\[ \frac{T_m}{T_f} = 1 \]

where \( Q \) is the HRR, \( \tau \) is the time, and \( T \) is the temperature. The subscript \( m \) is related to model (reduced) scale, and the subscript \( f \) is related to full scale.

2.2 Reduced-scale Model

A 1:4 reduced-scale model was prepared to study the smoke diffusion in a corridor. Fig.1. shows the layout of the model, which consists of two parts, a corridor and a compartment. The corridor is 15 m long, 0.5 m wide, and 0.75 m high, and the compartment is 1.2 m long, 0.75 m wide, and 0.6 m high. They are connected by a door. One end of the corridor near the compartment is closed; however, the other end is open. The entire model, except the ceiling of the compartment was made of toughened glass in order to observe the flame and smoke. The ceiling of the compartment was made of galvanized iron.

An iron tray containing heptane as fuel was used as the fire source. The tray was located in the center of the room floor. To study the effect of variant HRR on the smoke distribution in the corridor, three different sizes of trays with varying volume of fuel, as listed in Table 1., were used.

| Case | Diameter (mm) | Volume (mL) |
|------|--------------|-------------|
| Case A | 100 | 100 |
| Case B | 140 | 200 |
| Case C | 200 | 300 |
2.3 Measurements

The temperature distribution in the corridor was measured by a series of thermocouple trees. Each thermocouple tree consisted of six K-type thermocouples with a bead bare size of 0.5 mm. The top thermocouple is 20 mm beneath the corridor ceiling and the others are placed at intervals of 140 mm, as shown in Fig. 2(a). The trees are located along the corridor. The layout of the location is shown in Fig.2.(b).
The HRR was calculated using the following formula (5):

\[ Q = \lambda m \rho h_c \]

where \( \dot{m} \) is the mass loss rate of the fuel, \( \lambda \) is the combustion efficiency, and \( h_c \) is the heat of combustion of the fuel. The mass loss rate (\( \dot{m} \)) of the fuel was measured by an electronic scale with extra precision. The scale was connected to a computer, which automatically recorded the mass of the fuel at intervals of 10 s.

3. Heat Release Rate of Fire and Smoke Temperature Distribution in the Corridor

3.1 Heat Release Rate of Fire

In general, the fire experiences three stages: the growth, steady, and decay stages. In this study, the authors mainly focused on the growth and decay stages. The HRR was calculated by using Eq. (5), where \( \lambda \) is approximately 0.6-0.8 (Karlsson and Quintiere, 2000). Li et al. (2011) reported that for the fuel yielding a low amount of soot, the recommended value of \( \lambda \) was 0.8. Fig.3. shows the plot of the HRRs versus time, for three tray sizes. Based on the results, the data were also fitted. The results indicate that the fire exhibits a power-law increase with time. The power values are 2.33, 2.80, and 4.82, respectively for tray sizes of 100, 141 and 200 mm, which means that the fire associated with a larger tray has a steeper growth.

Furthermore, the HRRs in their decay period are also plotted against time as shown in Fig.4., for three tray sizes. The result shows a power-law decay for all cases, and the fire associated with a larger tray exhibited a steeper decay.

3.2 Temperature Distribution Along the Corridor

The temperature distributions along the corridor for the three cases showed similar tendencies. Therefore, Case B was selected to be a representative one to study the temperature distribution along the corridor. Two typical moments were selected to show the distributions. First, when the fire was in the growth stage, and, second, when the fire was in the steady stage and also in its maximum HRR period. Fig.5. shows the temperatures at various heights along the corridor, associated with the above-mentioned two moments, indicating that the temperature immediately below the ceiling, at a height of 730 mm, is significantly higher compared to other locations and decays sharply along the corridor, particularly somewhere near the fire room. The temperature at a height of 590 mm shows a similar tendency to that at 730 mm. However, a small increase in the temperature along the corridor at the interval between 3.5 and 6 m was observed. This small increase might be the consequence of the descent of the smoke layer. The temperatures at the other four heights exhibited a similar tendency; and are slightly higher than the ambient temperature and decay slightly along the corridor.
To obtain more details of the temperature distribution in the corridor, numerical simulation was performed using Fire Dynamics Simulator (McGrattan et al. 2010a and McGrattan et al. 2010b). A full-scale model for numerical simulation was prepared. The material of the surface of the room and the corridor, including walls, ceilings and floors was assumed as concrete. The conjugate heat transfer between the surface and the gas flow was utilized in the smoke flows. The temperature fields of the corridor section along the longitudinal direction were obtained by numerical simulation for four given times, as shown in Fig.6. It is observed that the upper part of the corridor had relatively high temperature, and it decayed sharply along the corridor. However, the lower part of the corridor had relatively low temperature, which was approximate to the ambient temperature. This is in good agreement with the results obtained from the small-scale experiment.

When comparing the temperature data obtained from the numerical simulation with that obtained from the reduced-scale experiment, even with a similar trend, these temperature distributions were not completely identical. Several reasons exist for this disparity, including scales, boundary conditions, algorithm of the numerical simulation, etc.

### 3.3 Ceiling Temperature Distribution Along the Corridor

A dimensionless temperature parameter, $\Delta T / \Delta T_0$ was introduced to normalize the temperature, and it is defined as

$$\Delta T_c / \Delta T_0 = \frac{T_c - T_0}{T_0 - T_a}\quad (6)$$

where $T_c$ is the ceiling temperature at $x$ m distance from the reference location, $T_0$ is the ambient temperature, and $T_a$ is the reference temperature. The position $s_1$ [Fig.2.(b)] is taken as the reference position. Fig.7. is a plot of the dimensionless temperature $\Delta T_c / \Delta T_0$ against dimensionless distance $d/L$ ($d$ is the distance from the reference position and $L$ is the length of the corridor) for the three experimental cases in order to
investigate the ceiling temperature decay along the corridor. The plots in Fig.7. indicate that all three cases exhibit similar ceiling temperature decay trends. Decay of ceiling temperature in tunnels has been extensively investigated, and the results show that \( \Delta T_c / \Delta T_0 \) is an exponential equation of \( d/L \),

\[
\Delta T_c / \Delta T_0 = A \cdot e^{-Bd/L} + C
\]

where \( A, B, \) and \( C \) are constants. Assuming that the corridor has the same characteristics as the tunnel, Eq. (7) is selected to fit the experimental data. The following three fitting equations are obtained for different cases:

Case A:
\[
\Delta T_c / \Delta T_0 = 0.98 \cdot e^{-4.46d/L} + 0.021
\]

Case B:
\[
\Delta T_c / \Delta T_0 = 0.97 \cdot e^{-4.36d/L} + 0.028
\]

Case C:
\[
\Delta T_c / \Delta T_0 = 0.97 \cdot e^{-4.36d/L} + 0.027
\]

Fig.7. shows the fitting curves. The adjusted-R square of three fittings are 0.987, 0.991, and 0.991, respectively, indicating significantly important and relevant fitting results.

3.4 Vertical Average Temperature Evolution in the Corridor

To study the vertical average temperature, \( \Delta T \) is introduced and is defined as follows (Cooper et al., 1982):

\[
\Delta T(\tau) = \frac{1}{H} \int_0^H \left[ T(z, \tau) - T_a(a) \right] dz
\]

\[
\approx \frac{1}{H} \sum_{n=1}^8 \left[ T(z_n, \tau) - T_a(z_n) \right] \Delta z_n
\]

where \( z_n \) is the height of the nth thermocouple and \( \Delta z_n \) is the length associated with the thermocouple. In this study, \( \Delta z_1 = 0.10 \) m, \( \Delta z_2 \) to \( \Delta z_5 \) = 0.14 m, and \( \Delta z_6 = 0.09 \) m.

The vertical average temperature increases of four locations in the corridor are plotted against time as shown in Fig.8. All of the vertical average temperatures have two stages: the growth and the decline stages. The vertical average temperatures in the corridor associated with a larger tray are higher and have sharper growths, caused by stronger HRR. The vertical average temperatures in the corridor associated with the 200-mm-diam tray acquire their maximum and start declining earlier than the other two cases attributed to the HRR trend. When it comes to the decline stage, vertical average temperatures associated with 200-mm-diam decline sharply, particularly somewhere near the
compartment. This phenomenon is caused by more convective heat transfer flux from fire smoke to the corridor envelope as a result of a greater temperature difference.

4. Conclusion

Based on fire scale law, a reduced-scale (1:4) building corridor was prepared to investigate the HRRs and smoke diffusion. The model consisted of a room and a corridor. The fire occurred in the room and the smoke propagated into the corridor through a door. Three HRRs were studied in this study by using different sizes of trays.

The HRR of a fire exhibited a power-law growth and decay, and the fire associated with a larger area presented a steeper growth and decay.

The temperature distributions along the corridor were obtained using thermocouples. The temperature of the upper part of the corridor was relatively high, and it decayed sharply along the corridor. A very small increase in temperature along the corridor occurred in its middle and upper parts as a consequence of the descent of the smoke layer. The lower part of the corridor had relatively low temperature, which is insignificantly higher than the ambient temperature. Numerical simulation was also performed, and the data from the numerical simulation exhibits similarity with that from the reduced-scale experiment.

The ceiling temperature was fitted using an exponential equation. Significantly important fitting results were obtained, with adjusted-R squares of 0.987, 0.991, and 0.991, respectively, for Cases A, B, and C listed in Table 1.

The vertical average temperatures versus time along the corridor were analyzed for all three cases. The results indicated that greater heat release led to sharper growths of vertical average temperatures and higher vertical average temperatures, which decreased sharply in their decline stages.

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Nomenclature

- \(d\) distance from the reference (m)
- \(Fr\) Froude number
- \(g\) gravitational acceleration (m/s\(^2\))
- \(h_c\) heat rate of fuel (J/kg)
- \(L\) length of the corridor (m)
- \(m\) mass loss rate (kg/s)
- \(Q\) heat release rate (W)
- \(T\) temperature (°C)
- \(T_a\) ambient temperature (°C)
- \(T_c\) ceiling temperature (°C)
- \(T_0\) reference temperature (°C)
- \(\Delta T\) temperature difference between the ceiling temperature and that of the ambient air (°C)
- \(\Delta T_0\) temperature difference between the reference temperature and that of the ambient air (°C)
- \(\Delta T_v\) vertical average temperature increase (°C)
- \(V\) smoke velocity (m/s)
- \(z\) height (mm)

Greek symbols

- \(\tau\) time (s)
- \(\lambda\) combustion efficiency

Subscripts

- \(a\) ambient
- \(f\) full-scale
- \(m\) model-scale

References

1) Ballesteros-Tajadura, R., Santolaria-Morros, C., and Blanco-Marigorta, E. (2006). Influence of the slope in the ventilation semi-transversal system of an urban tunnel. Tunnelling & Underground Space Technology, 21(1), pp.21-28.
2) Chen, L. F., Hu, L. H., Tang, W., and Yi, L., (2013). Studies on buoyancy driven two-directional smoke flow layering length with combination of point extraction and longitudinal ventilation in tunnel fires. Fire Safety Journal, 59(7), pp.94-101.
3) Cooper, L. Y., Harkleroad, M., Quintiere, J. G., & Rinkinen, W. J. (1982). An experimental study of upper hot layer stratification in full-scale multiroom fire scenarios. Journal of Heat Transfer, 104(4), pp.741-749.
4) Hu, L. H., Huo, R., Li, Y. Z., Wang, H. B., and Chow, W. K. (2005). Full-scale burning tests on studying smoke temperature and velocity along a corridor. Tunnelling & Underground Space Technology, 20(3), pp.223-229.
5) Hu, L. H., Huo, R., Peng, W., Chow, W. K., & Yang, R. X. (2006). On the maximum smoke temperature under the ceiling in tunnel fires. Tunnelling & Underground Space Technology, 21(6), pp.650-655.
6) Hu, L. H., Huo, R., Wang, H. B., Li, Y. Z., & Yang, R. X. (2007). Experimental studies on fire-induced buoyant smoke temperature distribution along tunnel ceiling. Building & Environment, 42(11), pp.3905-3915.
7) Hwang, C. C., & Edwards, J. C. (2005). The critical ventilation velocity in tunnel fires—a computer simulation. Fire Safety Journal, 40(3), pp.213–244.
8) Ji, J., Zhong, W., Li, K. Y., Shen, X. B., Zhang, Y., and Huo, R. (2011). A simplified calculation method on maximum smoke temperature under the ceiling in subway station fires. Tunnelling & Underground Space Technology, 26(3), pp.490-496.
9) Ji, J., Gao, Z. H., Fan, C. G., and Sun, J. H. (2013). Large eddy simulation of stack effect on natural smoke exhausting effect in urban road tunnel fires. International Journal of Heat & Mass Transfer, 66(6), pp.531-542.

10) Kashef, A., Yuan, Z., and Lei, B. (2013). Ceiling temperature distribution and smoke diffusion in tunnel fires with natural ventilation. Fire Safety Journal, 62(4), pp.249-255.

11) Karlsson, B., and Quintiere J. G. (2000) Energy Release Rate. Enclosure Fire Dynamics. Washington DC: CRC Press.

12) Li, A., Zhang, Y., Hu, J., & Gao, R. (2014). Reduced-scale experimental study of the temperature field and smoke development of the bus bar corridor fire in the underground hydraulic machinery plant. Tunnelling & Underground Space Technology, 955-959(1), pp.2813-2817.

13) Li, S., Zong, R., Zhao, W., Yan, Z., and Liao, G. (2011). Theoretical and experimental analysis of ceiling-jet flow in corridor fires. Tunnelling & Underground Space Technology, 26(6), pp.651-658.

14) McGrattan, K., McDermott, R., Hostikka, S., and Floyd, J. Fire Dynamics Simulator (Version 5) User’s Guide, NIST Special Publication 1019-5, National Institute of Standards and Technology.

15) McGrattan, K., Hostikka, S., Floyd, J., Baum, H., Rehm, R., Mell, W., and McDermott, R. (2010) Fire Dynamics Simulator (Version 5) Technical Reference Guide, NIST Special Publication 1018-5, National Institute of Standards and Technology.

16) Qu, L., & Chow, W. K. (2012). Numerical studies on density jump in a long corridor fire. Tunnelling & Underground Space Technology, 32(11), pp.113-126.

17) Tong, Y., Shi, M. H., Gong, Y. F., & He, J. P. (2009). Full-scale experimental study on smoke flow in natural ventilation road tunnel fires with shafts. Tunnelling and Underground Space Technology, 24(6), pp.627-633.

18) Ukleja, S., Delichatsios, M. A., Delichatsios, M. M., & Zhang, J. (2013). Smoke concentrations inside and outside of a corridor-like enclosure. Fire Safety Journal, 60(8), pp.37-45.

19) Weng, M. C., Yu, L. X., Liu, F., & Nielsen, P. V. (2014). Full-scale experiment and cfd simulation on smoke movement and smoke control in a metro tunnel with one opening portal. Tunnelling & Underground Space Technology, 42(5), pp.96-104.

20) Yang, D., Huo, R., Zhang, X. L., Zhu, S., & Zhao, X. Y. (2012). Comparative study on carbon monoxide stratification and thermal stratification in a horizontal channel fire. Building & Environment, 49(1), pp.1-8.