NRC Publications Archive Archives des publications du CNRC

Ceiling temperature distribution and smoke diffusion in tunnel fires with natural ventilation

Kashef, Ahmed; Yuan, Zhongyuan; Lei, Bo

This publication could be one of several versions: author's original, accepted manuscript or the publisher's version. /
La version de cette publication peut être l'une des suivantes : la version prépublication de l'auteur, la version
acceptée du manuscrit ou la version de l'éditeur.

For the publisher's version, please access the DOI link below. / Pour consulter la version de l'éditeur, utilisez le lien
DOI ci-dessous.

Publisher's version / Version de l'éditeur:

<https://doi.org/10.1016/j.firesaf.2013.09.019>

Fire Safety Journal, 62, Part C, pp. 249-255, 2013-10-15

NRC Publications Record / Notice d'Archives des publications de CNRC:

<https://nrc-publications.canada.ca/eng/view/object/?id=70c3c1c3-b39f-4ece-a82d-27d22eb2cc04>

<https://publications-cnrc.canada.ca/fra/voir/objet/?id=70c3c1c3-b39f-4ece-a82d-27d22eb2cc04>

Access and use of this website and the material on it are subject to the Terms and Conditions set forth at

<https://nrc-publications.canada.ca/eng/copyright>

READ THESE TERMS AND CONDITIONS CAREFULLY BEFORE USING THIS WEBSITE.

L'accès à ce site Web et l'utilisation de son contenu sont assujettis aux conditions présentées dans le site

<https://publications-cnrc.canada.ca/fra/droits>

LISEZ CES CONDITIONS ATTENTIVEMENT AVANT D'UTILISER CE SITE WEB.

Questions? Contact the NRC Publications Archive team at

PublicationsArchive-ArchivesPublications@nrc-cnrc.gc.ca. If you wish to email the authors directly, please see the
first page of the publication for their contact information.

Vous avez des questions? Nous pouvons vous aider. Pour communiquer directement avec un auteur, consultez la
première page de la revue dans laquelle son article a été publié afin de trouver ses coordonnées. Si vous n'arrivez
pas à les repérer, communiquez avec nous à PublicationsArchive-ArchivesPublications@nrc-cnrc.gc.ca.

National Research
Council Canada

Conseil national de
recherches Canada

Canada

Ceiling temperature distribution and smoke diffusion in tunnel fires with natural ventilation

Ahmed Kashef

Corresponding author

Institute for Research in Construction, National Research Council, Canada

Tel.: +1 613 990 0646

Fax: +1 613 954 0483

E-mail address: ahmed.kashef@nrc.ca

Zhongyuan Yuan

School of Mechanical Engineering, Southwest Jiaotong University, China

Bo Lei

School of Mechanical Engineering, Southwest Jiaotong University, China

Ceiling temperature distribution and smoke diffusion in tunnel fires with natural ventilation

Abstract:

A series of experimental tests was carried out in two 1/15 reduced-scale tunnels to investigate ceiling temperature distribution and smoke diffusion in tunnel fires with natural ventilation. Based on experimental results and the one-dimensional theory, formulas to predict the temperature distribution and smoke diffusion extent were developed. As the smoke was extracted through natural ventilation shafts, the tunnel was conceptually divided into two zones or sections: the fire and non-fire sections. In both sections, the smoke temperature can be expressed using the temperature decay formula and reference temperature formula. The temperature decay is an exponential function. The reference temperature in the fire section can be developed from the definition of the dimensionless temperature and a constant value that is different for different tunnels. The reference temperature in the non-fire section represents the relationship between the dimensionless reference temperature in the non-fire section and a constant value that is different for different tunnels. The smoke diffusion area represents the relationship between the dimensionless length of the smoke layer and the temperature decay at the location of smoke.

Keyword: *tunnel fire, Natural ventilation, ceiling temperature distribution, smoke diffusion distance*

Nomenclature

a	constant value
B	tunnel width (m)
b	constant value
D	smoke diffusion distance (m)
Fr	Froude number
g	gravity acceleration (m/s^2)
H	tunnel height (m)
h	shaft height (m)
k	decay coefficient in fire section
k_n	decay coefficient non-fire section
L	shaft distance (m)
l	shaft length (m)
m	mass flow rate (kg/s)
Q	heat release rate (kW)
S	distance from fire source to inner boundary of shaft (m)
T	temperature (K)
V	volume flow rate (m^3/s)
w	shaft width (m)
x	distance from the reference location (m)

Greek letters

Δ	difference property between smoke and ambient
α	ratio of small-scale to full-scale
ρ	density (kg/m^3)

ξ	local resistance factor
<i>superscript/Subscript</i>	
*	dimensionless quantity
0	ambient quantity
<i>b</i>	buoyancy property
<i>i</i>	inertia property
<i>m</i>	small-scale property
<i>nref</i>	reference property in non-fire section
<i>r</i>	full-scale property
<i>ref</i>	reference property in fire section

1. Introduction

Fires in tunnels can lead to catastrophic consequences [1-2]. As a result, fire safety in tunnels has attracted special interest for researchers around the world. During recent years, a great number of studies were carried out to investigate fire characteristics in tunnels or enclosed spaces with forced ventilation systems and a series of established theoretical and empirical models were developed [3-11].

Compared to the traditional forced ventilation system, natural ventilation, by setting openings at the top of the tunnel section, is an alternative way of ventilating tunnels, which not only saves on the energy consumption of ventilation in the tunnel section, but also saves on the investment of the ventilation facility. From the point of engineering application, the most important issue for this ventilation method is how to design the ceiling openings to ensure proper evacuation of fire-induced smoke. Using full-scale experiments and a theoretical method, Wang [12] researched smoke diffusion characteristics in tunnel fires with natural ventilation and developed formulas to predict the maximum temperature and backlayering distance in tunnels. These formulas, however, were derived under the condition that ambient air velocity existed. Kashef et al [13] used reduced-scale experiments to investigate the effect of some parameters on ceiling temperatures and, based on a one-dimensional theory, two formulas to predict the ceiling temperatures were developed. However, Kashef et al did not discuss the effect of tunnel configuration on smoke diffusion characteristics.

In this paper, a series of experimental tests were carried out in two scaled tunnels and a new theoretical method was developed to investigate the ceiling temperature distribution and smoke diffusion extent in tunnel fires with natural ventilation.

2. Reduced-scale Experiments

2.1 Model tunnel system

A series of experimental tests was carried out in two 1/15 reduced-scale tunnels; namely, Tunnel A and Tunnel B. These two tunnels had the same cross-sectional area, 0.7 m wide and 0.32 m high. The length of Tunnel A was 15 m, while the length of Tunnel B was 17 m. Tunnel A was made of different materials such as steel for the ceiling, toughened glasses for both side walls and concrete for the tunnel floor. Tunnel B was made of only one material; cement board. The layout of these two tunnels is shown in Fig. 1.

The four cuboid shafts were mounted at the top of the ceiling in the middle of the tunnel width to simulate a natural ventilation system. In Tunnels A and B, the width of the natural ventilation shaft was a constant value of 0.167 m. In this paper, the effects of shafts intra-distance and shaft size on smoke diffusion characteristics were investigated. Two shaft distances of 2.67 m and 4.0 m were adopted in Tunnel A. From the view of smoke exhaust, the intra spaces between consecutive shafts were more important than shaft distance, so an inner space of 3.33 m was used in Tunnel B. The shaft distance and shaft inner space are shown in Fig. 2. Four different shaft sizes (length $\times$ height) were studied in Tunnel A: 0.533 m $\times$ 0.267 m, 0.667 m $\times$ 0.267 m, 0.800 m $\times$ 0.267 m and 0.667 m $\times$ 0.133 m. These four shaft sizes were also used in Tunnel B and, in addition, one more shaft size of 0.667 m $\times$ 0.4 m was also studied in Tunnel B.

A porous bed propane gas burner was used as the fire source in this paper. A fire source with a diameter of 158 mm was situated on the tunnel floor 170 mm away from the wall of Tunnel A to simulate the fire in the train location. While a fire source with a diameter of 178 mm was set up on the tunnel floor in the middle of the tunnel width of Tunnel B. In each tunnel, the fire source was located in the centre of the longitudinal direction of the tunnel section between the two consecutive shafts. Two different fire sizes approximately 5.74 kW and 11.48 kW in Tunnel A and several different fire sizes in the range of 3.2 kW to 14.5 kW in Tunnel B were used to investigate the effect of fire size on the tunnel fire dynamics.

To simulate the effect of train blockage, the model train was placed above the fire source in Tunnel A. The model train was made of galvanized iron and was 7 m long, 0.187 m wide and 0.18 m high.

(a) Tunnel A

(b) Tunnel B

Fig. 1 A schematic layout of the model tunnel system

2.2 Measurement system

In order to examine the smoke temperature distribution, in each tunnel, a series of k-type thermocouples was mounted 1 cm below the centre line of the ceiling. The layout of thermocouples is shown in Fig. 2. Considering the longitudinal symmetric distribution in the centre of the fire source, the thermocouples were mainly set upon one side from the centre of the fire source, and some thermocouples were situated on the other side to examine the symmetric characteristics. In Tunnel A, the smoke

exhaust through the natural ventilation shaft was measured by a hot wire anemometer. Based on the finite volume method, six points were set up on the cross-section in the vertical centre of the shaft to examine smoke exhaust. The layout of measurement points in the shaft is shown in Fig. 3. In this paper, the six points were situated in the first shaft closest to the fire source.

To simplify descriptions in later sections, the reduced-scale tunnel was virtually divided into two regions: “fire section” and “non-fire section”, as shown in Fig. 2.

Fig. 2 Layout of the thermocouples

Fig. 3 Layout of the measurement points in the shaft

2.3 Scaling law

To relate the model to full-scale in reduced-scale fire experiments, Froude number modeling has been widely used. The Froude number represents the ratio of inertia forces to gravity forces. Using Froude modeling, the scaling of the heat release rate, smoke temperature and smoke velocity between reduced-scale and full-scale could be expressed as follows:

$$Q_m / Q_r = \alpha^{5/2} \quad (1)$$

$$v_m / v_r = \alpha^{1/2} \quad (2)$$

$$T_m = T_r \quad (3)$$

2.4 Experimental conditions

The experimental conditions in Tunnels A and B are summarized in Table 1 and Table 2, respectively.

Table 1 Experiments conducted in Tunnel A

Test No.	Shaft length mm	Shaft height mm	Shaft distance m	Train blockage	HRR kW
1	533	267	4.00	Y	5.74
2	667	133	4.00	Y	5.74
3	667	267	4.00	Y	5.74
4	800	267	4.00	Y	5.74
5	667	133	4.00	N	5.74
6	667	267	4.00	N	5.74
7	800	267	4.00	N	5.74
8	533	267	2.67	Y	5.74
9	667	133	2.67	Y	5.74
10	667	267	2.67	Y	5.74
11	800	267	2.67	Y	5.74
12	667	133	2.67	N	5.74
13	667	267	2.67	N	5.74
14	800	267	2.67	N	5.74
15	533	267	4.00	Y	11.48
16	667	133	4.00	Y	11.48
17	667	267	4.00	Y	11.48
18	800	267	4.00	Y	11.48
19	667	133	4.00	N	11.48
20	667	267	4.00	N	11.48
21	800	267	4.00	N	11.48
22	533	267	2.67	Y	11.48
23	667	133	2.67	Y	11.48
24	667	267	2.67	Y	11.48
25	800	267	2.67	Y	11.48
26	667	133	2.67	N	11.48
27	667	267	2.67	N	11.48
28	800	267	2.67	N	11.48

Table 2 Experiments conducted in Tunnel B

Test No.	Shaft length mm	Shaft height mm	Shaft distance m	Train blockage	HRR kW
1	667	267	4.00	N	3.90
2	667	267	4.00	N	4.76
3	667	267	4.00	N	5.88
4	667	267	4.00	N	7.84
5	667	267	4.00	N	11.90
6	533	267	4.00	N	5.30
7	800	267	4.00	N	4.12
8	800	267	4.00	N	11.05
9	667	133	4.00	N	3.61
10	667	133	4.00	N	12.20
11	667	400	4.00	N	5.96
12	667	400	4.00	N	11.70

3. Theoretical analysis

3.1 Ceiling temperature distribution

To investigate the ceiling temperature distribution, the dimensionless temperature should be defined [14]:

$$\Delta T^* = \Delta T / (Q^{*2/3} T_0) \quad (4)$$

Where Q^* is the dimensionless of heat release rate, which is defined as following:

$$\dot{Q}^* = \dot{Q} / \rho_0 c_p T_0 g^{1/2} H^{5/2}$$

Based on the one-dimensional theory, the ceiling temperature in tunnel fires with natural ventilation can be solved through the ceiling temperature decay combined with the reference temperature formulas [13].

The ceiling temperature decay in fire section and non-fire section can be expressed as, respectively:

$$\frac{\Delta T_x}{\Delta T_{ref}} = e^{-k_x x} \quad (5)$$

$$\frac{\Delta T_x}{\Delta T_{nref}} = e^{-k_n x} \quad (6)$$

From Eq.(4), the reference temperature in fire section can be expressed as:

$$\Delta T_{ref} = \Delta T_{ref}^* Q^{*2/3} T_0 \quad (7)$$

In another paper by the authors [16], the experimental results indicated that the dimensionless ceiling temperature in the fire section, ΔT_{ref}^* , does not depend on fire size, shaft distance, shaft size, or train blockage. Rather, ΔT_{ref}^* only depends on the heat transfer coefficient of ceiling material. So for the same tunnel ceiling material, ΔT_{ref}^* would assume the same value.

On the other hand, the reference temperature in non-fire section depends on the shaft distance and shaft size as the smoke exhaust from shaft, while does not depend on the fire size and train blockage.

As per reference [16], the smoke mass flow rate through the first shaft from fire source can be expressed as:

$$\dot{m}_s \propto \rho_0 g^{1/2} \dot{Q}^{*1/3} \Delta T_{ref}^{*1/3} H^{*-1} H^{5/2} e^{-k(S-x_{ref})^{1/3}} \quad (8)$$

Where:

$$S = (L - l) / 2$$

The dimensionless length H^* can be written as following:

$$H^* = l^{-2/3} w^{-2/3} h^{-1/3} H^{5/3}$$

The smoke mass flow rate m_{nref} , can be written as follows:

$$m_{nref} = f(m_{ref}, m_s) \quad (9)$$

Observing Eq. (8) and Eq.(9), the above formula can be assumed as:

$$m_{nref} = m_{ref} (1 - bH^{*-1} \Delta T_{ref}^{*1/3} e^{-k(S-x_{ref})^{*1/3}}) \quad (10)$$

where b is a constant value which can be determined experimentally.

Based on the free fire plume theory, the relationship between the smoke temperature and the smoke mass flow rate can be expressed as following:

$$\frac{\Delta T}{T_0} \propto \left(\frac{m}{\rho_0 g^{1/2} H^{5/2}} \right)^2 \quad (11)$$

Equation 11 can be used to determine the reference temperature in non-fire section. Finally, the reference temperature in non-fire section can be expressed as:

$$\Delta T_{nref} = \Delta T_{ref}^* Q^{*2/3} T_0 e^{k(x_{ref} - x_{nref})} (1 - bH^{*-1} \Delta T_{ref}^{*1/3} e^{-k(S-x_{ref})^{*1/3}})^2 \quad (12)$$

Equation (12) can be re-written, using the defined advanced dimensionless reference temperature, as follows:

$$1 - \Delta T_{nref}^{**1/2} = bH^{*-1} \Delta T_{ref}^{*1/3} e^{-k(S-x_{ref})^{*1/3}} \quad (13)$$

Where, ΔT_{nref}^{**} is the advanced dimensionless reference temperature in the non-fire section:

$$\Delta T_{nref}^{**} = \Delta T_{nref}^* / (\Delta T_{ref}^* e^{-k(x_{nref} - x_{ref})})$$

Equation (13) represents the relationship between the advanced dimensionless reference temperature in the non-fire section and the smoke mass flow rate through the shaft.

3.2 Smoke diffusion distance

The layout of smoke diffusion distance is shown in Fig. 4. For tunnel fires with natural ventilation, when the smoke propagated to the first shaft from the fire source, most of the smoke was extracted from the shaft, and the remaining smoke could pass through the shaft and continue to propagate in the non-fire section along the ceiling. During this period, fresh air flowed into the tunnel from the tunnel or shaft exits. With an increase in the distance from the fire source in the non-fire section, the smoke

temperature decreased. When the buoyancy force provided by the hot smoke was equal to the inertia force provided by the incoming fresh air, the smoke stopped flowing forward [15]. The distance from the fire source to the location of the end of the smoke layer extent was defined as the smoke diffusion distance in this paper.

Fig. 4 Layout of the smoke diffusion distance

Based on the definition of smoke diffusion distance, the governing forces at the end of smoke layer can be expressed as [15]:

$$P_b = P_i \quad (14)$$

Where P_b is the buoyancy force provided by the hot smoke, and P_i is the inertia force provided by the incoming fresh air. These two forces can be expressed as follows:

$$P_b \propto \Delta\rho gH \quad (15)$$

$$P_i = \frac{\rho_0 u^2}{2} \quad (16)$$

The gas state equation

$$\frac{\Delta\rho}{\rho} = \frac{\Delta T}{T_0} \quad (17)$$

The velocity of the incoming fresh air can be expressed as:

$$u = \frac{\dot{m}}{\rho_0 B H} \quad (18)$$

The flow and temperature fields can be presented as a symmetric distribution on both sides of the fire (Fig. 5) with the fresh air being drawn into the fire section from tunnel ports or ventilation shafts. The drawn fresh air is subsequently heated by fire source, moved upwards due to the buoyancy effect and then flowed out from tunnel through the shafts in the fire section. The mass flow rate of the combustion products were observed to be much less than the mass flow rate of the fire plume, and therefore it can be ignored. As such, it can be concluded that the fresh air flowing into the fire section was mainly exhausted through the first neighboring shafts. Subsequently, the formula of the mass flow rate of the incoming fresh air could be assumed to be the same as the mass flow rate through the first shaft from fire source as expressed by Eq. (8).

Fig. 5 Layout of the smoke flow and incoming fresh air

Combining the above equations:

$$\frac{\Delta T}{T_0} \propto \frac{H^2}{2B^2} \dot{Q}^{*2/3} \Delta T_{ref}^{*2/3} H^{*-2} e^{-k(S-x_{ref}) \cdot (2/3)} \quad (19)$$

Based on Eq. (6), the smoke temperature at the end of smoke layer can be written as:

$$\Delta T = \Delta T_{nref} e^{-k_n(D-x_{nref})} \quad (20)$$

Combining Eqs.(12), (19) and (20):

$$e^{-k_n(D-x_{nref})} \propto \frac{H^2 H^{*-2} \Delta T_{ref}^{*2/3} e^{-k(S-x_{ref}) \cdot (2/3)}}{B^2 \Delta T_{ref}^* e^{-k(x_{nref}-x_{ref})} (1-bH^{*-1} \Delta T_{ref}^{*1/3} e^{-k(S-x_{ref}) \cdot (1/3)})^2} \quad (21)$$

From the above formula, a dimensionless smoke diffusion distance D^* can be defined as follows. The dimensionless smoke diffusion distance represents the ratio of inertia force provided by the incoming fresh air to the buoyancy force provided by the hot smoke.

$$D^* = \frac{H^2 H^{*-2} \Delta T_{ref}^{*2/3} e^{-k(S-x_{ref}) \cdot (2/3)}}{B^2 \Delta T_{ref}^* e^{-k(x_{nref}-x_{ref})} (1-bH^{*-1} \Delta T_{ref}^{*1/3} e^{-k(S-x_{ref}) \cdot (1/3)})^2} \quad (22)$$

From the above analysis, the formula of smoke diffusion distance is:

$$e^{-k_n(D-x_{nref})} = aD^* \quad (23)$$

Where a is a constant value. Variables S , L , l , H , W , h , x , and D were defined in Fig. 6.

Fig. 6 Definition of construction variables

4. Results and discussions

4.1 Temperature decay

The temperature decay in the fire section and the non-fire section can be expressed using Eq. (5) and Eq. (6), respectively.

Fig. 7 shows that the temperature decay varies with the distance from the reference location in the fire section or the non-fire section in Tunnel A. The curve fitting analysis revealed the values of k and k_n to be 0.47 and 0.55, respectively, with correlation coefficient of 0.858 and 0.971, respectively.

Fig. 8 shows that the temperature decay varies with the distance from the reference location in the fire section or the non-fire section in Tunnel B. Values of k and k_n are estimated from the curve fitting analysis to be 0.4 and 0.55 respectively, with the correlation coefficient of 0.903 and 0.987, respectively.

From the above analysis on temperature decay, as the heat transfer coefficient of steel is larger than that of cement board, the value of decay coefficient k in the fire section in Tunnel A is larger than that in Tunnel B. However, because of the smoke exhaust in the shaft, the value of the decay coefficient k_n in the non-fire section is almost the same for both tunnels.

(b) non-fire section
Fig. 7 Ceiling temperature decay in Tunnel A

(a) fire section

(b) non-fire section

Fig. 8 Ceiling temperature decay in Tunnel B

4.2 Reference temperature

For a specific tunnel in this paper, the dimensionless reference temperature ΔT_{ref}^* in the fire section in Eq. (7) is a constant value [13].

According to the experimental data observed in Tunnel A, the ceiling temperature at a distance of 0.9 m from the fire source was selected as the reference temperature in the fire section. In Tunnel B, however, the ceiling temperature at a distance of 0.6 m from the fire source was selected as the reference temperature in the fire section. To determine the value of ΔT_{ref}^* , the experimental data of all tests in Tunnel A and Tunnel B were curve-fitted using Eq. (7) and plotted in Fig. 9 and Fig. 10, respectively. It was found that the reference temperature in the fire section was well represented by Eq. (7). The values of ΔT_{ref}^* were 0.93 and 1.68, respectively for Tunnel A and Tunnel B, for correlation coefficients of 0.981 and 0.984, respectively.

From the above analysis on the reference temperature in the fire section, the value of ΔT_{ref}^* is different for Tunnel A and Tunnel B. This is due to several reasons such as the different transverse fire location, the different reference location, the different materials of tunnel ceiling, etc.

Fig. 9 Reference temperature in the fire section in Tunnel A

Fig. 10 Reference temperature in the fire section in Tunnel B

The value of the constant b in Eq. (13) should be the same for the two Tunnels A and B. From Eqs. (12) and (13):

$$(1 - \Delta T_{nref}^{**1/2})(Q^{*2/3}T_0)^{1/2} = bH^{*-1}\Delta T_{ref}^{*1/3}e^{-k(S-x_{ref})^{*1/3}}(Q^{*2/3}T_0)^{1/2} \quad (24)$$

In order to determine the value of b , the experimental data of all tests in Tunnels A and B were fitted with Eq. (24) and plotted in Fig. 11. The figure shows good agreement between the experimental data and Eq. 24. The value of b was determined to be 0.244 with correlation coefficient of 0.923.

Fig. 11 Reference temperature in the non-fire section

4.3 Smoke diffusion distance

For the formula to determine smoke diffusion distance Eq. (23) represents the relationship between the dimensionless smoke diffusion distance and the temperature decay, so the value of a should be the same for Tunnels A and B.

Fig. 12 shows how the dimensionless smoke diffusion distance varies with the temperature decay. The comparison of experimental data of all tests in both tunnels and the results from Eq. (23) shows a good agreement. The value of a is 1.82, and the correlation coefficient is 0.960.

Fig. 12 Smoke diffusion distance

6. Conclusions

Experimental reduced-scale tests were carried out to investigate the smoke temperature distributions under the tunnel ceiling and the smoke diffusion distance. Combined with the experimental results and one-dimensional theory in tunnel fires, formulas to predict the smoke temperature distribution and smoke diffusion distance were conducted. Finally, based on the scaling law, the smoke parameters for real tunnel were derived from the formulas for model tunnel.

As the smoke exhausted through the natural ventilation shaft, the smoke temperature formulas under the tunnel ceiling should be divided into two portions. In the fire section or the non-fire section of the tunnel, the smoke temperatures under the tunnel ceiling can be expressed as respective temperature decay formula and reference temperature formula. The temperature decay is an exponential function. The reference temperature in the fire section can be derived from the definition of the dimensionless smoke temperature and a constant value that is different for Tunnel A and Tunnel B in this paper. The reference temperature in the non-fire section represents the relationship between the dimensionless reference temperature in the non-fire section and the smoke mass flow rate through the shaft. In this case, the constant value in the formula is the same for these two different tunnels in this paper.

The dimensionless smoke diffusion distance was defined as the ratio of inertia force provided by the incoming fresh air to the buoyancy force provided by the hot smoke. The smoke diffusion distance represents the relationship between the defined dimensionless smoke diffusion distance and the temperature decay and the value of the formula is the same for Tunnels A and B.

References

- [1] R.O. Carvel, G. Marlair, A history of fire incidents in tunnels, in: *The Handbook of Tunnel Fire Safety*, Thomas Telford, London, 2005, pp. 3-41.
- [2] R.O. Carvel, Mitigation of Tunnel Fires, in: *Proceedings from the Fifth International Symposium on Tunnel Safety and Security*, New York, 2012, pp. 27-39.

- [3] Y.Z. Li, B. Lei, H. Ingason, Study of Critical velocity and backlayering length in longitudinally ventilated tunnel fires, *Fire Safety J.* 45 (2010) 361-370.
- [4] L.H. Hu, R. Huo, Full-scale burning tests on studying smoke temperature and velocity along a corridor, *Tunn. Undergr. Sp. Tech.* 20 (2005) 223-229.
- [5] Y.Oka, G.T. Atkinson, Control of smoke flow in tunnel fires, *Fire safety J.* 25 (1995) 305-322.
- [6] Y. Wu, M.Z.A. Baker, Control of smoke flow in tunnel fires using longitudinal ventilation systems—a study of the critical velocity, *Fire Safety J.* 35 (2000) 363-390.
- [7] Q. Zhang, X. Guo, et al., Theoretical analysis on Plane fire plume in a longitudinal ventilated tunnel, *Tunn. Undergr. Sp. Tech.* 30 (2012) 124-131.
- [8] Jae Seong Roh, Seung Shin Yang, et al., An experimental study on the effect of ventilation velocity on burning rate in tunnel fires—heptane pool fire case, *Build. Environ.* 43 (2008) 1225-1231.
- [9] J. P. Kunsch, Critical velocity and range of a fire-gas plume in a ventilated tunnel, *Atmosph. Environ.* 33 (1998) 13-24.
- [10] J. P. Kunsch, Simple model for control of fire gases in a ventilated tunnel, *Fire Safety J.* 37 (2002) 67-81.
- [11] Hitoshi Kurioka, Yasushi Oka, Fire properties in near field of square fire source with longitudinal ventilation in tunnels, *Fire Safety J.* 38 (2003) 319-340.
- [12] Yanfu Wang, Juncheng Jiang, et al., Full-scale experiment research and theoretical study for fires in tunnels with roof openings, *Fire Safety J.* (2009) 339-348.
- [13] A. Kashef, Z. Yuan, B. Lei, Some Effects on Natural Ventilation System for Subway Tunnel Fires, in: *Proceedings from the Fifth International Symposium on Tunnel Safety and Security*, New York, 2012, pp. 309-318.
- [14] B. Karlsson, J.G. Quintiere, *Enclosure Fire Dynamics*. Washington, CRC Press, 2000.
- [15] L.H. Hu, R. Huo, et al., Studies on buoyancy-driven back-layering flow in tunnel fires, *Experi. Thermal and Fluid Sci.* 32 (2008) 1468-1483.
- [16] Z. Yuan, B. Lei, and A. Kashef, Experimental and theoretical study for tunnel fires with natural ventilation. Paper submitted to *Fire Technology Journal*, manuscript # FIRE-D-12-00607R1.

Table 1 Experiments conducted in Tunnel A

Test No.	Shaft length mm	Shaft height mm	Shaft distance m	Train blockage	HRR kW
1	533	267	4.00	Y	5.74
2	667	133	4.00	Y	5.74
3	667	267	4.00	Y	5.74
4	800	267	4.00	Y	5.74
5	667	133	4.00	N	5.74
6	667	267	4.00	N	5.74
7	800	267	4.00	N	5.74
8	533	267	2.67	Y	5.74
9	667	133	2.67	Y	5.74
10	667	267	2.67	Y	5.74
11	800	267	2.67	Y	5.74
12	667	133	2.67	N	5.74
13	667	267	2.67	N	5.74
14	800	267	2.67	N	5.74
15	533	267	4.00	Y	11.48
16	667	133	4.00	Y	11.48
17	667	267	4.00	Y	11.48
18	800	267	4.00	Y	11.48
19	667	133	4.00	N	11.48
20	667	267	4.00	N	11.48
21	800	267	4.00	N	11.48
22	533	267	2.67	Y	11.48
23	667	133	2.67	Y	11.48
24	667	267	2.67	Y	11.48
25	800	267	2.67	Y	11.48
26	667	133	2.67	N	11.48
27	667	267	2.67	N	11.48
28	800	267	2.67	N	11.48

Table 2 Experiments conducted in Tunnel B

Test No.	Shaft length mm	Shaft height mm	Shaft distance m	Train blockage	HRR kW
1	667	267	4.00	N	3.90
2	667	267	4.00	N	4.76
3	667	267	4.00	N	5.88
4	667	267	4.00	N	7.84
5	667	267	4.00	N	11.90
6	533	267	4.00	N	5.30
7	800	267	4.00	N	4.12
8	800	267	4.00	N	11.05
9	667	133	4.00	N	3.61
10	667	133	4.00	N	12.20
11	667	400	4.00	N	5.96
12	667	400	4.00	N	11.70

(a) Tunnel A

(b) Tunnel B

Fig. 1 A schematic layout of the model tunnel system

(a) Tunnel A

(b) Tunnel B

Fig. 2 Layout of the thermocouples

Fig. 3 Layout of the measurement points in the shaft

Fig. 4 Layout of the smoke diffusion distance

Fig. 5 Layout of the smoke flow and incoming fresh air

Fig. 6 Definition of construction variables

Fig. 7 Ceiling temperature decay in Tunnel A

Fig. 8 Ceiling temperature decay in Tunnel B

Fig. 9 Reference temperature in the fire section in Tunnel A

Fig. 10 Reference temperature in the fire section in Tunnel B

Fig. 11 Reference temperature in the non-fire section

Fig. 12 Smoke diffusion distance