International Journal of Heat and Mass Transfer 92 (2016) 55–65

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Experimental investigation on the effect of asymmetrical sealing on tunnel fire behavior

Chen Chang-kun [a,*], Zhu Cong-xiang [a], Liu Xuan-ya [b], Yu Nian-hao [b]

[a] Institute of Disaster Prevention Science and Safety Technology, Central South University, Changsha, Hunan 410075, China
[b] Key Laboratory of Building Fire Protection Engineering and Technology of MPS, Tianjin 300381, China

ARTICLE INFO

Article history:
Received 19 May 2015
Received in revised form 22 August 2015
Accepted 25 August 2015
Available online 8 September 2015

Keywords:
Tunnel fire
Asymmetrical sealing
Sealing ratio
Temperature distribution

ABSTRACT

Sealing the tunnel entrance is a common tactic for tunnel fire fighting, while it is not easy to seal the two entrances synchronously in actual tunnel fire-fighting process. A set of reduced experiments were then conducted to investigate the effect of asymmetrical sealing of tunnel entrances on tunnel fire behavior and temperature distribution. The data of temperature, radiative heat flux and mass loss rate, etc. were acquired. The results demonstrate that hot smoke region shifts to the side not completely sealed, and burning at the side with less sealing ratio is more violent with higher smoke temperature and longer hot smoke plume. Plume temperature at the tunnel entrance could reach to 300 °C as measured in the experiments and jet flame was observed at the end not completely sealed. These would lead to great danger to fire fighters in actual tunnel fire fighting.

1. Introduction

Tunnel fire could lead to great casualties and economic losses [1,2] e.g. the fire happened in the Simplon Railway Tunnel of Switzerland in 2011, in which 10 carriages filled with goods burned violently and the temperature reached 800 °C leading to the roof of tunnel facing the danger to collapse. The fire caused by the crash of two trucks filled with methanol in the tunnel of Jin Ji-Highway in China on March 1, 2014, resulted in a total of 31 dead and 9 missing. Hence fire safety of tunnel has drawn much attention of scholars from various countries and a great number of studies were carried out to investigate the fire characteristics in tunnel [3–5].

Theories and models for tunnel fire behavior have been widely researched during the past few years. Ingason developed a single mathematical expression for tunnel fire with different growth rates, and established a presentation of available design curves as well, which makes the fire design more convenient and reliable [6–8]. Kurioka et al. [9] exploited an empirical formulae for flame tilt, apparent flame height, maximum temperature of the smoke layer and its position based on the results obtained in the 1/10 scale model tunnel. And the above formulae were justified by Hu et al. [10] and Wang et al. [11] further with a series of fire experiments in actual tunnels, respectively. Wang [12] developed a theoretical prediction model for maximum temperature of smoke beneath ceiling using dimensional analysis. Kashef [13] and Yuan et al. [14] developed formulas to predict the temperature distribution and smoke diffusion extent in tunnel fires with natural ventilation. Fire characters in tunnel could be influenced by various factors and the influence factors have been specially investigated by some researchers. E.g. Hansen and Ingason [15,16] studied the influence of fuel type on the heat release rate and put forward simple theoretical calculations of the overall HRR of multiple objects. Ji et al. [17–20] and Fan et al. [21] investigated the impact of fire locations and tunnel inclination slope on the maximum smoke temperature in tunnel. Gao et al. [22] investigated the influence of accumulated upper hot layer on the maximum ceiling gas temperature by a modified virtual source origin concept. Zhong et al. [23,24] studied the fire Smoke flow and natural ventilation with vertical shaft in tunnel at different longitudinal ventilation velocity. Li et al. [25], Li and Ingason [26], Carvel et al. [27] researched the influence of ventilation on the ceiling temperature and heat release rate.

All the studies above on different aspects of tunnel fire provide a lot of significant references for later tunnel fire researches and fighting. However, special study on tunnel fire fighting, especially on sealing is relatively less. Currently, disposal of railway tunnel fire mainly includes water-perfusion, fighting in tunnel and sealing, etc., in which sealing is an important approach to put out the tunnel fire of oil tank train by blocking the tunnel using sandbags, bricks, etc. [28,29] The sealing process mainly includes three stages: plugging suffocation, cooling down and unpacking [30], in

* Corresponding author.

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2015.08.079
0017-9310/

which the plugging suffocation process requires the most humans and material resources and takes the greatest risk. Due to the intense radiant heat and toxic smoke at tunnel entrances, it is difficult for the fighters to seal the tunnel entrances conformably in this complex fire environment. The tunnel entrances are then sealed asymmetrically and this asymmetrical sealing phenomenon may lead to various possible consequences. Therefore, it is necessary to research the effect of asymmetrical sealing on tunnel fire development.

A series of experiments were conducted in a 1/9 reduced railway tunnel with different sealing ratios at the two entrances. Temperature distribution inside tunnel and near the entrances, radiation heat near tunnel entrances, mass loss rate of fuel, etc. were acquired. Comparisons between the symmetrical and asymmetrical sealing are conducted to research fire behavior on the condition of asymmetrical sealing better. The study is expected to provide some references for actual tunnel fire-fighting.

2. Experimental configuration

2.1. Model tunnel system

Experiments were conducted in a 1/9 reduced tunnel. The tunnel was 8 m long and 0.6 m wide. The cross section was an arch with vertical wall of 0.5 m and arc segment of 0.3 m. The view of the tunnel is shown in Fig. 1 and the three-dimensional layout of the tunnel structure is presented in Fig. 2. The vault was constructed from steel frame wrapped with asbestos to ensure the ruggedness and heat insulation. The side walls and bottom of the tunnel were constructed from bricks and concrete. Additionally, the side walls were plastered over with cement mortar to improve the airtightness. Six stone piers were built non-equidistantly near one of the entrances on which thermocouple matrix was placed.

Holes were reserved at the bottom (see Figs. 3 and 4) where electronic balances were placed to measure the mass loss rate of fuel. The electronic balances were closely wrapped around by asbestos and were covered by the fire-proof plates to avoid damage from high temperature. The fuel pans ($0.6\ m \times 0.3\ m \times 0.1\ m$) were mounted on the electronic balance with its 4 legs passing through the holes of fire-proof plate and were laid along the centerline in the middle of the tunnel width with the longitudinal interval of 0.1 m (see Fig. 4). Ignition holes ($0.2\ m \times 0.2\ m$) were mounted in a side wall through which fuel was ignited. Once fuel was ignited the openings could be shut down immediately (see Fig. 5).

Methanol with purity of 99% was used as the fuel in the experiments. The fuel was loaded by steel pans to simulate carriages filled with liquid fuels. Based on the Froude number conservation, the scaling of the heat release rate, smoke temperature and smoke velocity between reduced-scale and full-scale follow the scaling laws,

$$\frac{Q_m}{Q_f} = \left(\frac{L_m}{L_f}\right)^{5/2} \tag{1}$$

$$T_m = T_f \tag{2}$$

$$\frac{V_m}{V_f} = \left(\frac{L_m}{L_f}\right)^{1/2} \tag{3}$$

where, Q is the heat release rate (HRR), T is the temperature, V is the velocity, L denotes the model size and L_m/L_f is the similarity ratio. The subscript 'f' and 'm' represent the full and model scale parameters respectively. Four fire sizes with heat release rates of 201 kW were used in the experiments. For a full scale using the scaling laws, the corresponding fire sizes is 48.8 MW.

2.2. Parameters of the experiments

To acquire the temperature data in the tunnel thoroughly, 13 columns of thermocouple trees were distributed along the tunnel centerline at different distances from the fire source, and k-type stainless steel sheathed thermocouples were utilized. In addition, the temperature of the smoke out of the tunnel entrance was also detected by arranging 6 thermocouple trees with different distances, which were made of 10 thermocouples with a vertical space of 0.25 m and the top one was 2.5 m high from the floor. The detailed arrangement of the thermocouples can be seen in Fig. 6.

Three radiation heat flow meters, Nos. 1, 2, 3, were mounted 1 m away from the tunnel entrance with 0.25 m vertical spacing, as shown in Fig. 6, to measure the radiant heat near the entrance. Mass loss rate of fuel was measured with electronic balances, whose measurement accuracy was 0.1 g and maximum measurement was 30 kg, and the data were recorded every 3 s by computers. The balances were placed in the holes covered with fire-proof plates as shown in Fig. 4.

2.3. Reduced-scale tunnel fire tests

The entrances of tunnel were sealed with sealing plate 300 s after ignition. The sealing plate was made up of asbestos-lined fire-proof plate and the height could be adjusted to simulate different sealing ratios, as illustrated in Fig. 7. The stones and brackets were used to enhance the tightness and stability. 3 different sealing ratios (proportion of the sealing height over the tunnel entrance height), 50%, 75% and 100%, were adopted and 4 tests were conducted in the experiments.

Fig. 8 presents the diagram of the 4 tests labeled as C1, C2, C3 and C4, separately. In case C1 and C2, the entrances of tunnel were sealed symmetrically with ratio of 50% and 75%. While in case C3 and C4, the tunnel were sealed asymmetrically. The sealing ratios at the two entrances were 50% on left and 100% on right in case C3 while for case C4, they were 75% on left and 100% on right. Specific conditions of the tests are tabulated in Table 1.

3. Results and discussion

3.1. Temperature distribution in tunnel

To research the temperature distribution at the fire source, thermocouples B41–47 were amounted over the No.1 fuel pan while thermocouples B27–33 were amounted over the No.2, as shown in Fig. 9. Temperature curves over the two fuel pans were

Fig. 1. General view of the reduced-scale tunnel.