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Experimental investigation of pool fire behavior to different tunnel-end ventilation opening areas by sealing

Chang-kun Chen [a,*], Huang Xiao [a], Nan-nan Wang [a], Cong-ling Shi [b], Cong-xiang Zhu [a], Xuan-ya Liu [c]

[a] Institute of Disaster Prevention Science & Safety Technology, Central South University, Changsha 410075, China
[b] Beijing Key Laboratory of Metro Fire and Passenger Transportation Safety, China Academy of Safety Science and Technology, Beijing 100012, China
[c] Key Laboratory of Building Fire Protection Engineering and Technology of MPS, Tianjin 300381, China

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ABSTRACT

A series of experimental tests were conducted in a 1/9 reduced-scale tunnel to investigate the effect of sealing ratio (which is equal to the sealing height divided by the tunnel entrance height) on combustion process and temperature field of liquid pool fires in tunnel using methanol as fuel. The two tunnel entrances were sealed symmetrically with different ratios (such as 0%, 25%, 50%, 75% and 100%) in the tests. In addition, fuel area was also considered. Temperatures inside tunnel and near the entrance were measured together with the mass loss rate of fuel. The results demonstrate that during the sealing process, the ceiling temperature inside tunnel varies versus sealing ratio, which is primarily due to the comprehensive effect between the heat loss by the hot smoke flowing out of tunnel entrance and the heat produced by combustion significantly related to ventilation, and both the above two factors are related to the open area of tunnel entrance. The possible depression effect related to the fuel area of sealing on combustion was observed in the experiment. Moreover, there exists a critical sealing ratio closely related to the fuel area, at which the ceiling temperature inside tunnel would reach the maximum. And the larger the fuel area is, the lower the critical sealing ratio would be. Additionally, the dimension and temperature of the fire plume near tunnel entrance, which is always a serious threat to the firefighters in real tunnel fire, were also obtained and analyzed.

1. Introduction

Nowadays, tunnel fire is a serious issue world-widely, which could lead to catastrophic consequences such as tunnel collapse and enormous casualties. As a typical case, the Gotthard Road Tunnel Fire in Switzerland on October 24, 2001, 11 persons were killed in this incident (Carvel et al., 2004). And the fire occurred in a subway tunnel in Daegu Korea on February 18, 2003, causing 198 deaths and 146 injures (Jeon and Hong, 2009). The above tragedies demonstrate that tunnel fire is still a serious threat and thus how to fight the large-scale fire in the relatively closed tunnel space timely should be paid more attention to.

When there is a fire in a tunnel, emergency measures should be taken to minimize structural damages and losses of human lives. For fires in tunnel, it is hard to be extinguished because of the narrow space, high-density combustibles and complicated environment. For instance, the fire occurred in a tunnel of Jin-Ji Expressway (Jincheng-Jiyuan) in China in March 2014, in which two vehicles with methanol crashed and thus a fire broke out, causing 40 deaths and 12 injuries. Moreover, in Baoji-Chengdu Railway, China, a truck carrying oil in the tunnel derailed and caused a fire in May 2008. The accident actually was extinguished for nine days by sealing the tunnel entrance partly. Thus it can be seen that sealing the two tunnel entrances simultaneously for reducing oxygen concentration during fire is one of the good choices for fire extinguishing, especially for liquid pool fire. However, for many actual circumstances, it is difficult to seal the tunnel entrance completely because of the flame jet and the possible collapse near the tunnel entrance due to the high temperature in the process of sealing. On the other hand, the above sealing process has an important influence on the effectiveness of extinguishing, which could probably bring about major casualties for the firefighters. In order to understand the response behavior of the combustion and the smoke layer inside the tunnel under sealing, investigation on the sealing effect should raise more concern.

During the past few years, a series of theories and models for liquid pool tunnel fires have been developed by experiments and numerical simulations. Kurioka et al. (2003) conducted a series of experimental tests in the use of liquefied methanol or kerosene

* Corresponding author.
E-mail address: cckchen@csu.edu.cn (C.-k. Chen).

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and developed the empirical formulae for flame tilt, apparent flame height, maximum temperature of the smoke layer and its position based on the results to study the fire properties in the near field of a fire source considering the aspect ratio. Lee and Hong (2005) investigated the effect of aspect ratio of a tunnel cross-section on the critical ventilation velocity and proposed a new correlation model for non-dimensional critical ventilation velocity and the HRR using ethanol pool fires. Later, Roh et al. (2007) conducted reduced-scale experiments to examine the difference of backlayering between naturally ventilated HRR and varied HRR by longitudinal ventilation using n-heptane pool fires. Additionally, they found the relationship between the non-dimensional critical ventilation velocity and HRR (Roh et al., 2008).

In the study of tunnel fires, the temperature distribution is often an important aspect of the research. Kashef et al. (2013) and Yuan et al. (2013) carried out a series of reduced-scale experiments to investigate ceiling temperature distribution and smoke propagation in tunnel fire with natural ventilation, and develop a formula to predict the temperature distribution and smoke propagation extent. Ji et al. (2012) investigated the influence of different transverse fire locations on maximum smoke temperature under the tunnel ceiling. And Fan et al. (2013) assessed the impact of smoke on smoke temperature distribution in road tunnel fires, and developed a simplified correlation on transverse temperature distribution. Hu et al. (2006) studied the maximum smoke temperature under the ceiling by full-scale burning tests and simulations. Ji et al. (2015) also studied the upstream maximum temperatures along the tunnel centerline by numerical simulation. In researches on the smoke and the tunnel ventilation, Li et al. (2011), Li and Ingason (2014), Blanchard et al. (2012), Gannouni and Maad (2015) and Tang et al. (2013) studied the temperature of buoyancy-driven smoke and the critical velocity together with the backlayering length in tunnel fires. Tong et al. (2009) conducted a number of full-scale burning tests in a road tunnel with natural ventilation using shafts to study the maximum smoke spreading horizontal lengths. Also in the road tunnel fire tests, Wang et al. (2009) studied the smoke removal efficiency which was rarely reported in the previous references and the Kurioka model together with the built mathematical models are validated by those experiments. Ingason and Li (2010), Ingason et al. (2012, 2015) carried out a series of tests in a model tunnel with longitudinal ventilation under different fire conditions. To study the influence of different fire areas, Tsai et al. (2010) carried out small-scale experiments and numerical simulations to investigate critical ventilation velocity for two tunnel fires occurring simultaneously. Heidarinejad et al. (2016) used Fire Dynamics Simulator (FDS) to study various arrangements of different vehicles at upstream of two fire sources. Zhong et al. (2016) researched the smoke development of a sloped long and large curved tunnel in the natural ventilated underground space under three different fire powers. And Chen et al. (2016a) investigated the temperature distribution and behavior of fires in a model tunnel with different fuel area sizes. Yi et al. (2015) studied the heat exhaust coefficient of transversal smoke extraction system in tunnel under fire in the 1/10 scale model tunnel. Oka and Oka (2016) conducted the experiments in the small-scale tunnel to investigate the values of the coefficients included in the developed correlation for the velocity attenuation. For sealing tests, Chen et al. (2016b) performed a set of experiments in a 1/9 reduced-scale tunnel to investigate the effect of fuel area size and asymmetrical sealing on the temperature distribution and behavior of fires in a tunnel.

All the above studies on different aspects of tunnel fires are helpful to understand the pool fire in the relatively narrow space scientifically and it is valuable for reference in tunnel firefighting system design. So far, handling policies of tunnel fires mainly include water-perfusion, fighting in tunnels and sealing, etc. At present, it is still quite dangerous for firefighters to seal the tunnel portals in that complex fire environment because of intense radiant heat and toxic smoke at tunnel entrances Chen et al. (2016b). The research of sealing approach to putting out tunnel fires is relatively less. And better understanding requires more systemic research and reporting. Therefore, in order to comprehend the tunnel fire scientifically and help with the sealing strategies, it is important to investigate the sealing effect on tunnel fires further.

In this paper, to study the distinct characteristics for liquid pool fires in tunnel with different sealing ratios, a series of experiments were carried out in a 1/9 reduced-scale model tunnel. The temperatures inside the tunnel and near the entrance, the mass loss rate of fuel were measured. Also, the response behavior of the burning in the tunnel, the distribution of smoke layer inside tunnel, and the characteristic of the fire plume near the entrance under different sealing ratios were observed.

2. Reduced-scale experiment

2.1. Model tunnel system

A series of experimental tests were carried out in a 1/9 reduced-scale tunnel. The reduced-scale tunnel is arched, 8 m long, 0.6 m wide and 0.8 m high, as shown in Fig. 1. The side walls and floor are made of brick-concrete structure. To improve the airtight property of the model tunnel, the side walls are coated with cement mortar. The tunnel vault is a steel arch frame, and the inner and outer sides of the steel frame are covered by a layer of asbestos to ensure the vault's sturdiness and heat insulation. Moreover, a thermocouple matrix is installed on one side of the tunnel entrance. Figs. 2 and 3 present the stereogram and sectional view of the tunnel, respectively.

There are several reserve holes with electronic balances on the side wall of the model tunnel to measure the mass loss rate, as shown in Fig. 4a. In the experiment, to prevent the electronic balances from heat, the surroundings of the balances are wrapped with asbestos closely and the top of the balances are laid with fire-proof plate. Also, there are several reserve holes for igniting before the experiment. In the test, once fuel was ignited, the reserve holes were filled up with bricks and then the fire-proof plates were used to seal these reserve holes immediately. Fig. 4b shows the process of holes sealing with fire-proof plates.

Methanol is a typical experimental fuel and there are many of experiments using methanol as fire source done before. (Kurioka et al., 2003; Fan et al., 2013; Yi et al., 2015) In the test, methanol with the purity of 99.9% is used as the burning fuel and one kind of identical rectangular tray (60 cm × 30 cm × 10 cm) is used in the experiments. Each fuel tray is filled with 4 kg methanol and mounted on the electronic balance to measure the mass loss rate of the fuel. In the experiments, fuel trays are located along the tunnel longitudinal centerline, and both sides of the fuel tray are 0.15 m far from the side walls of the model tunnel, as shown in Fig. 5.

2.2. Measurement system

In order to obtain the detailed temperature distribution inside tunnel, series of K-type thermocouples (diameter of 0.3 mm) are mounted along the tunnel longitudinal centerline. Moreover, more concentrated thermocouples are fixed 50 mm below the ceiling to measure the ceiling temperatures in detail. Furthermore, 60 thermocouples are fixed near one side of the tunnel portals to measure the temperature of flame jet. The layout of thermocouples is shown in Fig. 6.