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Experimental and numerical studies on ceiling maximum smoke temperature and longitudinal decay in a horseshoe shaped tunnel fire

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ABSTRACT

The present paper investigates the ceiling maximum smoke temperature and longitudinal decay in tunnel fires using a horseshoe shaped 1:3.7 scale-model tunnel constructed by concrete and a full-scale model tunnel established by SIMTEC for the first time. The maximum smoke temperature beneath the ceiling and the longitudinal temperature profiles were obtained and analyzed. The major conclusions are summarized as follows: The ceiling maximum smoke temperature rise right above the fire source is directly proportional to the terms of $Q^{2/3}/H_f^{5/3}$ and the ceiling maximum smoke temperature decreases as a sum function of two exponential equations of horizontal distance. Modified equations are proposed for maximum smoke temperature rise beneath the ceiling and longitudinal temperature decay, and the predictions show a good agreement with the values measured by experiments and numerical simulations. The results obtained by numerical simulations agree well with experimental results, and SIMTEC is reasonable to simulate the tunnel fires to predict the temperature profiles. The results are of important significance for tunnel fire safety and personnel evacuation.

1. Introduction

Tunnel fires have attracted increasing attention in recent years due to its catastrophic consequence, such as the Viamala Tunnel Fire in Switzerland in 2006 with nine people killed, and Korea Daegu Tunnel Fire in 2003 and Austria Mont-Blanc Tunnel Fire killing 198 and 41 people, respectively. Due to the special structure of tunnel, the hot smoke carrying hazardous combustion products can flow a long distance along the tunnel ceiling [1]. In fact, 85% of deaths in fires were caused by the hazardous smoke according to statistics [2]. Simultaneously, the hot smoke, even the fire flame, will directly impinge on the tunnel ceiling and then the temperature of concrete increased, even to the point of collapse. Once the concrete collapse occurred, the steel bars will be directly exposed to the smoke or fire flame, leading to a reduction in steel strength, which eventually result in sinking or collapse of the tunnel structure. Therefore, the maximum smoke temperature profiles beneath the ceiling should be better estimated in order to protect the tunnel surface structure.

In recent years, extensive works have been conducted to study the ceiling maximum smoke temperature and longitudinal decay distribution along the tunnel. Kurioka [3] studied the maximum temperature under the ceiling in tunnel fires with rectangular and horseshoe shaped cross section, and established an empirical equation to predict the maximum smoke temperature under the ceiling. Hu [4] conducted full-scale fire burning tests in horseshoe shaped tunnels to study the maximum smoke temperature under the tunnel

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ceiling, and results showed a good agreement with Kurioka's model. Li [5] provided a theoretical model to predict the maximum smoke temperature beneath the ceiling and carried out two experimental test series in rectangular and horseshoe shaped scale-model tunnels to verify the reliability of the model. Ji [2] investigated the effects of transverse fire locations on the maximum smoke temperature in rectangular cross section scale-model tunnel fires. Gao [6] studied the sidewall effects on the maximum ceiling temperature in scale-model tunnel fires with rectangular cross section. Hu [7] performed experiments in a 1/5 model tunnel with a simulated vehicular blockage (1.3 m × 0.4 m × 0.5 m) to studied the effects of blockage-fire distance on maximum gas temperature and demonstrated that when the blockage was placed downstream, it did not have influence on maximum gas temperature, while as the upstream blockage-fire distance increased, the maximum gas temperature decreased and eventually approached an asymptotic value. Moreover, the effects of slope, ventilation velocity, aspect ratio and blockage ratio on maximum ceiling temperature have been observed in rectangular shaped scale-model tunnel fires [8].

For the longitudinal temperature distribution along the tunnel, Zhong [9] studied the smoke temperature distribution during the whole fire process in a full-scale curved tunnel. Liu [10] investigated the ceiling temperature profiles in node area of a full-scale curved tunnel, and provide a normalized expression of longitudinal decay taking heat release rate and transverse fire locations into account. Hu [11] conducted burning tests in a rectangular shaped scale-model tunnel, and proposed an exponential decay law to estimate the smoke temperature along the longitudinal direction. Gong [12] performed burning test experiments in a 1:10 scale-model tunnel with rectangular cross section, and proposed a new exponential decay formula for longitudinal temperature profile. Chow [13] experimentally discussed the smoke temperature distribution along a titled rectangular tunnel, and described the longitudinal temperature by different exponential functions taking slopes into account. Hu [14] investigated the combined effects of ceiling extraction and longitudinal ventilation on the temperature profiles, and found that the decay factors can be expressed by a function of heat release rate and ventilation velocity. Moreover, the effects of screen height, tunnel aspect ratio, transverse fire location and natural ventilation on temperature profiles in a rectangular scale-model tunnel were also observed [15–18]. However, most of the researches are based on the data obtained in a scale model tunnel with rectangular cross section. Moreover, all the scale model tunnel are constructed by fireproof board, stainless steel or fireproof glass. There is a difference in the thermal properties between these materials and concrete.

Besides, the smoke temperature profiles in a tunnel fire have been studied extensively using computational fluid dynamics method. Khattri [19] performed numerical simulations in a model tunnel using Fire Dynamics Simulator (FDS) to study the longitudinal ventilation effects on tunnel fire dynamics, and obtained the maximum ceiling temperature and the maximum ceiling flux. Hu [4] investigated the maximum smoke temperature under the ceiling using FDS, and the predicted temperatures showed a good agreement with experimental results. Moreover, a series of parallel simulations have been carried out using FDS to study the temperature distribution upstream and downstream from the fire in a road tunnel and found that the predictions were very close to the full-scale measured data within 40–80 m away from the fire, while as distance increased, the deviations between predictions and measured data were not exceeding 4–5 °C [20]. Furthermore, Hu [21] also studied the longitudinal ventilation effects on longitudinal decay profiles of CO concentration and smoke temperature in a tunnel fire, and found that as longitudinal ventilation velocity increased, CO concentration decays relatively slower along the tunnel. Ji [22] focused on observing the maximum temperature in a inclined tunnel fires using FDS method, and developed an empirical correlation for maximum temperature profiles including slope effects. At present, most of the numerical studies are performed by a practical tool FDS developed by NIST, which is widely used in research of fire-induced smoke flow behaviors. However, FDS shows some limitations in the grid processing to simulate a curved structure, such as a horseshoe shaped tunnel. Nevertheless, another fire simulation tool SIMTEC handles mesh non-orthogonality very well, which is more suitable to simulate fire behaviors in a curved structure.

Therefore, a series of burning experiments were conducted in a horseshoe shaped 1:3.7 scale model tunnel, which was constructed by concrete. Correspondingly, a series of full-scale numerical simulations were carried out using SIMTEC. The present paper provides an analysis of the maximum smoke temperature beneath the ceiling and the longitudinal decay distribution in a horseshoe shaped tunnel fire. The comparison between the results measured by experiments and numerical simulations and the predictions by theoretical equations are performed.

2. Theoretical analysis

2.1. Maximum temperature beneath the ceiling

Kurioka developed an empirical expression between maximum ceiling temperature and heat release rate based on a series of burning tests in horizontal tunnel, shown as follows [3]:

$$\frac{\Delta T_{\max}}{T_\infty} = \gamma\left(\frac{Q^{*2/3}}{Fr^{1/3}}\right)^{\varepsilon} \tag{1}$$

where

$$\frac{Q^{*2/3}}{Fr^{1/3}} < 1.35,\ \ \gamma = 1.77,\ \ \varepsilon = 1.2$$

$$\frac{Q^{*2/3}}{Fr^{1/3}} > 1.35,\ \ \gamma = 2.54,\ \ \varepsilon = 0$$