Experimental study on the smoke temperature distribution alongside the lining in tunnel fires

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Abstract: Tunnel fire temperature is a key factor for tunnel structural safety and evacuation. This study aimed to investigate the smoke temperature distribution alongside the lining across the section and effects of pool sizes and fuels on it through a series of small-scale experiments. The results showed the heat release rates (HRRs) of diesel were significantly lower than gasoline's when they had the same pool size and volume. Nevertheless, the duration of diesel combustion increased obviously. As a result, the maximum smoke temperature under the ceiling for gasoline was significantly higher than diesel's. The results were subsequently adopted to compare with other test results and illustrated a similar result. The initial temperature-rising rates for gasoline pool fires were shown to agree well with the standardized temperature curves, but they were significantly lower for diesel pool fires. Two exponential correlations on vertical temperature distribution were provided respectively for gasoline and diesel fires. These findings are expected to be useful for the design of the thermal boundary on the lining in tunnel fires.

Keywords: tunnel fire, smoke temperature distribution, lining, fuel, experiments

1 Introduction

Tunnel fires and thermal effect on environment and structure have already been an important issue in tunnel[1-2]. Several occurred tunnel fires over the past two decades resulted in severe destruction to tunnel lining structure. For instance, Mont Blanc tunnel fire between France and Italy in 1999, causing the tunnel closed for 3 years. Tauern tunnel fire in Austria in 1999, causing the tunnel closed for 3 months, Yanhou tunnel fire in China in 2014 burned for 2 days, causing serious damage to the tunnel lining of 400 m, and it was closed for 7 months[3-4].The tunnel lining structure safety accordingly attracted much attention when exposed to fire. Typically, the impact of thermal exposure on the tunnel lining structure is believed to be strongly dependent of the maximum temperature and its duration in tunnel fires. Nevertheless, our current concern is the smoke temperature distribution alongside the lining across the section. Because tunnel lining is essentially exposed to an inconsistent fire temperature load, causing the thermal and mechanical behaviours of tunnel lining to be different.

So far, the thermal exposure in tunnel fires was widely evaluated by the use of standardized fire temperature curves, such as ISO 834, the hydrocarbon curve (HC), and RWS curve [5-13]. However, it should be noted that these standardized temperature-time curves were usually based on extreme fire loads. For instance, RWS curve was proposed according to a tanker with 50 m^3 gasoline on fire in a road tunnel. As a result, the maximum temperatures of these curves were mostly higher than 1000 ℃. Tunnel engineers usually adopted these standardized temperature-time curves as temperature load to assess the safety of the tunnel lining. In practice, the use of these fire loads would generally overshoot the tunnel fire load[14]. Due to this fact, PIARC reported the maximum temperature based on the heat release rate in tunnel fires[5]. Some improved models predicting the maximum temperature beneath the tunnel ceiling were subsequently proposed with consideration of heat release rate, ventilation speed and tunnel size as well. Initially, Kurioka et al. suggested an empirical equation to predict the maximum excess temperature which showed a good agreement with the full-scale test result conducted by Hu et al.[15-16]. Li et al. found this model only valid for the prediction of a forced ventilation case in tunnel fires. Because the maximum excess temperature beneath the ceiling reached infinity in his model, when the ventilation speed approached zero. He accordingly proposed an improved model, as equation (1) [17]. Afterwards, Li and Ingason made further job on this model which shows two regions. Each was divided into two sub-regions again[18].

$$\Delta T_{\max} = \begin{cases} \dfrac{Q}{Vr^{1/3} H_{ef}^{5/3}}, & V' > 0.19 \\[2ex] 17.5\dfrac{Q^{2/3}}{H_{ef}^{5/3}}, & V' \le 0.19 \end{cases} \tag{1}$$

where

$$V' = \frac{V}{\left(\dfrac{Q_c g}{r\rho_0 c_p T_0}\right)^{1/3}}$$

where $\Delta T_{\max}$ is the maximum excess temperature beneath the ceiling, Q is the total heat release rate, V is the ventilation velocity, r is the radius of the fire source, H_{ef} is the effective tunnel height, Q_c is the convective heat release rate, g is the gravitational acceleration, ρ_0 is the ambient density, c_p is the thermal capacity of air, T_0 is the ambient temperature.

In addition, there are a lot of studies to focus on sensitivity analysis of the maximum temperature and its spread in tunnel fires, including the influence of tunnel curvature, sloping, blockage, cross-section, ventilation velocity, natural smoke exhaust shaft and fire suppression[19-31]. Recently, extensive studies on transverse fires in a tunnel have further been reported through full-scale tests, model-scale experiments and numerical simulation. Much concern concentrated on effects of transverse fires on the maximum temperature, smoke movement, flame characteristics, air entrainment, and burning rate[32-39].

The above studies allow a better understanding of fire behaviour in tunnels. However, it should be noted that there has never been reported on the smoke temperature distribution alongside the lining across the section in tunnel fires. This is of particularly importance for the thermal analysis of tunnel lining structure. Accordingly, there is a clearly need to understand the maximum smoke temperature distribution on the tunnel lining across the section in tunnel fires. In the light of this, the objective of this paper is to present a detailed small-scale experimental results on HRRs, temperature histories and the maximum temperature distribution on the tunnel lining across the section in tunnel fires. Pool sizes and fuel categories would be fully investigated and discussed. These findings are expected to be useful for the design of the thermal boundary on the lining in tunnel fires.

2 Experimental arrangement

The experiments were undertaken in a small-scale tunnel model with a scale ratio of 1:16. The model was 8.5 m long, 0.6 m wide and 0.44 m high, as shown in Fig.1. A arched ceiling, along with straight walls was imposed upon the cross-section. The model was made of stainless steel of 2 mm thickness, covered by 30 mm thick felt and sheet iron, as seen in Fig.2. The test section was within a middle section of 4.5 m length, where the fireproof glass was installed on one side straight wall instead of stainless steel.

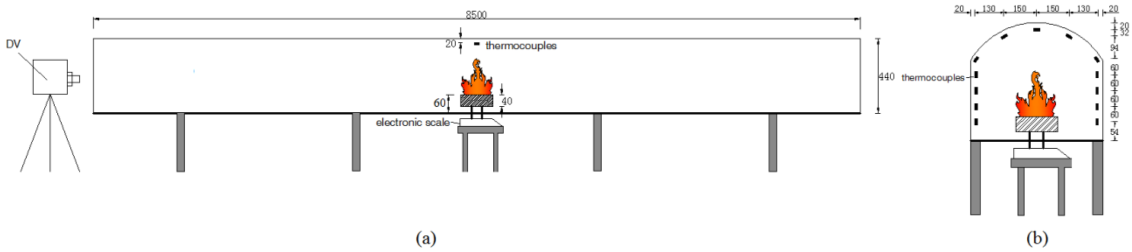


Fig.1 The model tunnel, unit:mm

Fig.2 Schematic of experiment apparatus

The tests were conducted using pool fires. Gasoline and diesel were chosen as the fuels in the present study, because they were the most popular fuels in vehicles. The pool was located in the middle of the cross-section with a height of 20 mm from the ground. Two pool sizes were employed to assess the effect of pool sizes, as shown in table 1. The heat release rates were evaluated both according to the study of Hu et al.[16] and by the use of fuel burning rate in experiments. The Froude modeling was subsequently applied into the physical scale analysis. Through meeting the Froude number conservation, the relationships between model and full-scale can be simplified to obtain the required scaling laws, as shown in Eq.(2) and (3). L denotes the size, and the subscript 'm' represents the model tunnel and 'f" is the full-scale.

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

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

Measurements of smoke temperature were arranged on the fire source section using K type thermocouples. Each thermocouple was positioned 20 mm away from the tunnel lining. The fuel mass was measured by an electronic scale. Flame and smoke layering behaviors were recorded from the front view using a digital cameras (DV), as shown in Fig.1.

3 Results and discussion

3.1 Heat release rate

Heat release rate is usually used to understand the fire intensity and speculate the maximum temperature. Accordingly, the heat release rate is firstly analyzed in this study. It is widely evaluated by the fuel mass loss rate using Eq.(4) [33], where the mass loss rate $\dot{m}$ is adopted by measuring the fuel mass loss per second. The effective heat of combustion is expressed by $\triangle H_{c,eff}$. The combustion efficiency η of pool fires is suggested 0.75 by Hu et al.[40]. In their study, they found the combustion efficiency of pool fires in a tunnel was typically 0.75 by the oxygen consumption and the mass loss rate experimentally. In this study, $\triangle H_{c,eff}$ is taken as 43700 KJ/kg for gasoline and 44400 KJ/kg for diesel, as given in SFPE handbook[41].

$$Q = \eta \dot{m} \Delta H_{c,eff} \tag{4}$$

Fig. 3 gives the typical HRR histories for both fuels. It can be seen that all the HRR histories have a relatively steady stage following a rapid rise. The averaged steady HRRs are listed in Table.1. The HRR of the gasoline fire is observed to be significantly higher than diesel's, being almost three times higher when they have the same volume. From Eq.(4), it is easy to understand that the main cause is the difference in the burning rate of both fuels. As is well-known that the burning rate of the gasoline is normally greater due to its strong volatility. The difference in the duration of combustion can also explain it. The combustion duration of the diesel is significantly longer than gasoline's. In addition, It can also be found that the HRR in the case of pool size B is more than twice of that in pool size A, where the area increases by 69% compared to size A.

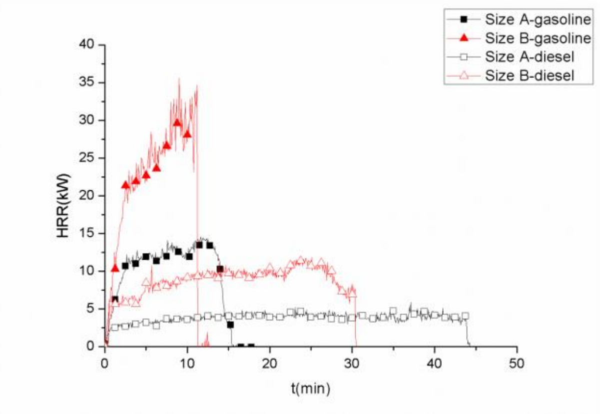


Fig.3 Typical HRRs for both fuels

Table 1 Experimental condition and HRR

Test category	Pool size(mm×mm)	Fuel height(mm)	Duration of combustion(s)	Range of HRR in model(kW)	Averaged HRR (kW)
gasoline	A:100×100	40	925	10.69-14.25	12.47
	B:130×130		675	25.43-35.47	30.45
diesel	A:100×100	40	2655	2.77-5.15	3.96
	B:130×130		1830	8.79-11.2	10.20

3.2 Temperature history and maximum smoke temperature under ceiling

Temperature history is usually designed for the thermal boundary condition on the lining. There are several standardized temperature curves widely used for the safety assessment of tunnel lining. But it is noted that these standardized temperature curves mostly overestimate the thermal load in tunnel fires. As a consequence, there is a clear need to understand the real temperature history.

Figs.4 and 5 show the temperature histories from the middle thermocouple under the ceiling, as well as two standardized temperature curves, namely HC and RABT-ZTV curves. It can be found all of the maximum temperatures from this test are significantly lower than the standardized temperature curves. This is easily understood. From PIARC report, the temperature over 1000 ℃ means the HRR would be greater than 100 MW in tunnel fires[5]. Clearly, the HRRs are far less than this value in this study. In the other hand, the temperature rises at different rates. For gasoline pool fires, the initial temperatures rise at the same rate for size A and size B, and the temperature-rising rates agree well with the standardized temperature curves. In the case of diesel pool fires, the temperature-rising rates are significantly lower than the standardized temperature curves. Furthermore, there is a gentler temperature-rising for size A.

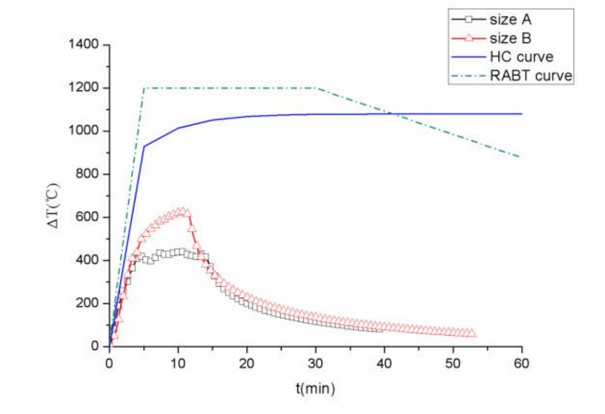


Fig.4 Temperature histories in gasoline pool fires

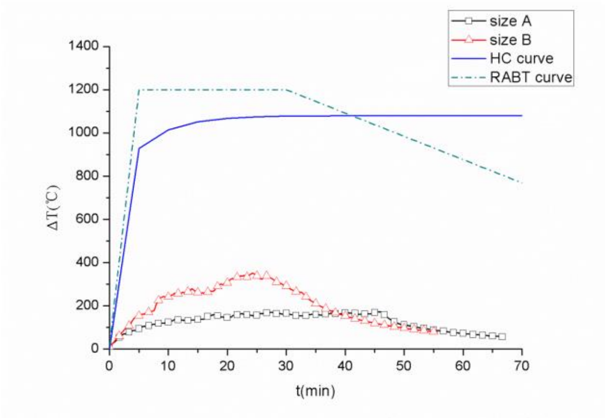


Fig.5 Temperature histories in diesel pool fires

Fig.6 gives the maximum temperatures from this test and other test results, together with Li et al. 's model[17-18,42]. The comparison of the maximum temperatures are shown an acceptable agreement with Li's model. However, it also needs to be noted that our test results are slightly lower than Li's model. The possible reason is that Li's model is mainly derived from the light-weight fuel. This could avoid large amount of soot in fires. As a result, the maximum temperature under ceiling is completely affected by the flame behavior. Conversely, smoke behavior could be the main cause for gasoline or diesel pool fires in this test. Smoke temperature is essentially slightly lower than the flame temperature.

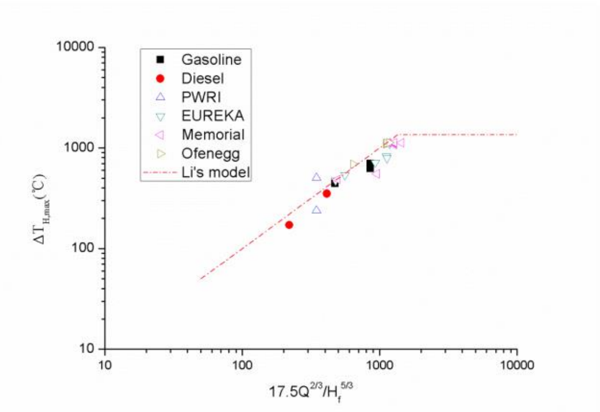


Fig.6. The maximum excess temperature beneath the ceiling[17-18,42]

Figs.7 and 8 show the typical smoke layering and flame behavior in gasoline and diesel pool fires. A heavy smoke layer with a large amount of soot is found under the tunnel ceiling and it gets thicker with the increase of pool size. The substantial soot is assumed to prevent the flame reaching the ceiling, and the flame is submerged in the smoke layer. Actually, the flame doesn't get fully-developed vertically, and is constrained to spread transversely. The flame width become wider with the increase of pool size. As a consequence, the maximum temperature under the ceiling is strongly dependent of the smoke temperature. Additionally, the flame width for the gasoline pool fire is significantly greater than the corresponding diesel pool fire due to its increasing HRR.

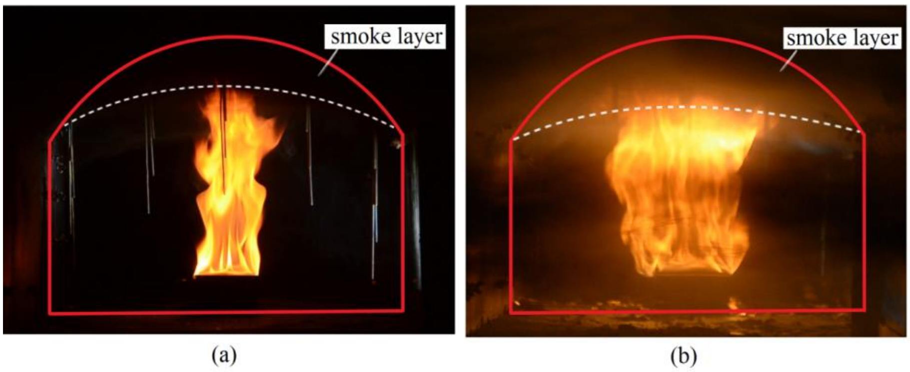


Fig. 7 Smoke layer and flame in gasoline pool fires: (a) size A; (b) size B

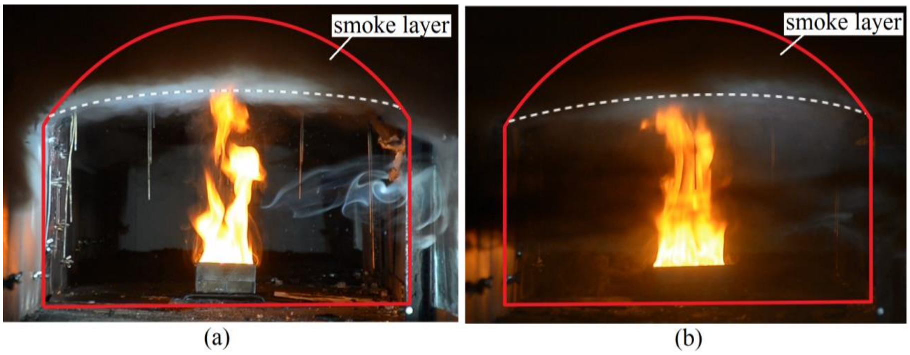
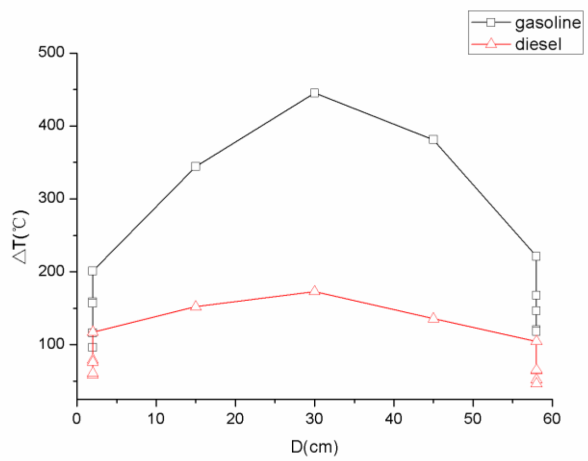


Fig. 8 Smoke layer and flame in diesel pool fires: (a) size A; (b) size B

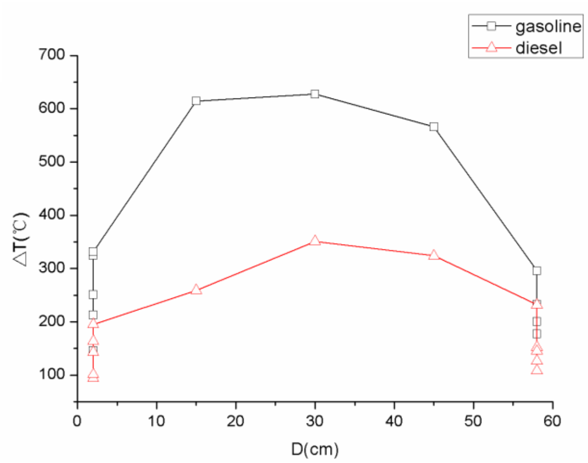
3.3 Smoke temperature distribution alongside the lining

The maximum smoke temperature in this study has been shown a not bad result through comparing with Li's model above. Nevertheless, it is necessary to understand the smoke temperature distribution in order to assess the thermal boundary condition on the lining, rather than the top ceiling. The smoke temperature distributions alongside the lining across the section for various pool sizes are given in Fig. 9. Clearly, the temperature upon the fire is normally larger than the others, producing a hump-shaped profile. The hump of temperature become flat gradually in a larger size pool. It means the high-temperature range extends transversely. It also needs to be noted that the detailed temperatures closed to the both sidewalls cannot be observed very well. In addition, from the point of temperature values, the smoke temperature for gasoline is significantly higher than diesel's. This phenomena is a consequence of the HRR behaviors.

All results presented so far can already help to understand effects of fuel categories and pool sizes on the temperature and its distribution in tunnel fires. Before attempting to provide a simple and useful expression on the smoke temperature distribution, it would clearly be advantageous and necessary to establish a non-dimensional parameter to characterize the temperature.



(a)



(b)

Fig. 9 Transverse temperature distributions: (a) size A; (b) size B

In fact, Alpert previously proposed an empirical equation on the correlations between the maximum temperature and the radial distance under an unconfined ceiling[43].

$$\Delta T_{r,max} = 5.38\frac{(Q/r)^{2/3}}{H}, \qquad r > 0.18H \tag{5}$$

Obviously, this is not applicable to a confined ceiling. An exponential expression was subsequently presented by Delichatsios based on a fully developed 1D channeled ceiling flow[44].

$$\frac{\Delta T_r}{\Delta T_{0,max}}\left(\frac{l}{H}\right)^{1/3} = \beta \exp\left\{-6.67St\frac{r}{H}\left(\frac{l}{H}\right)^{\frac{1}{3}}\right\}, \quad r > H \tag{6}$$

It is noted that this correlation is only used for r>H. In other words, this fits the longitudinal temperature distribution. Even though, this exponential function is found to be still suitable for transverse temperature distributions. Ji et al. proposed an empirical correlation through a series of experiments in a model subway station, which can be expressed as[45]:

$$\frac{\Delta T_{r,max}}{\Delta T_{\infty,max}} = 0.299\exp\left(-0.793\frac{r}{H}\right) + 1 \qquad (7)$$

Note they adopted the maximum temperature rise without the impact of the sidewall to normalize the maximum temperature. As a consequence, this ratio should be greater than 1.

However, it needs to be noted these above radial maximum temperature expressions cannot predict the smoke temperature distribution alongside the lining. And the smoke temperature distribution is necessary to analyze the thermal load on the lining. To do this, constructing such a parameter and normalizing the vertical temperature with the maximum temperature under ceiling gives $\Delta T_{h,max}/\Delta T_{H,max}$. The ratio of vertical height and tunnel height h/H is employed instead of radial position.

Based on the radial maximum temperature distribution correlations proposed previously, We suppose this exponential correlation can still be extended to the vertical smoke temperature distribution and impose it, as follows:

$$\frac{\Delta T_{h,max}}{\Delta T_{H,max}} = \alpha\exp\left(\beta\frac{h}{H}\right) \qquad (8)$$

Figs.10 (a) and (b) show the vertical maximum temperature distributions for gasoline and diesel pool fires, respectively. The vertical temperature distribution can be found to be correlated by an exponential function of Eq. (8), but with different values in these coefficients for gasoline and diesel.

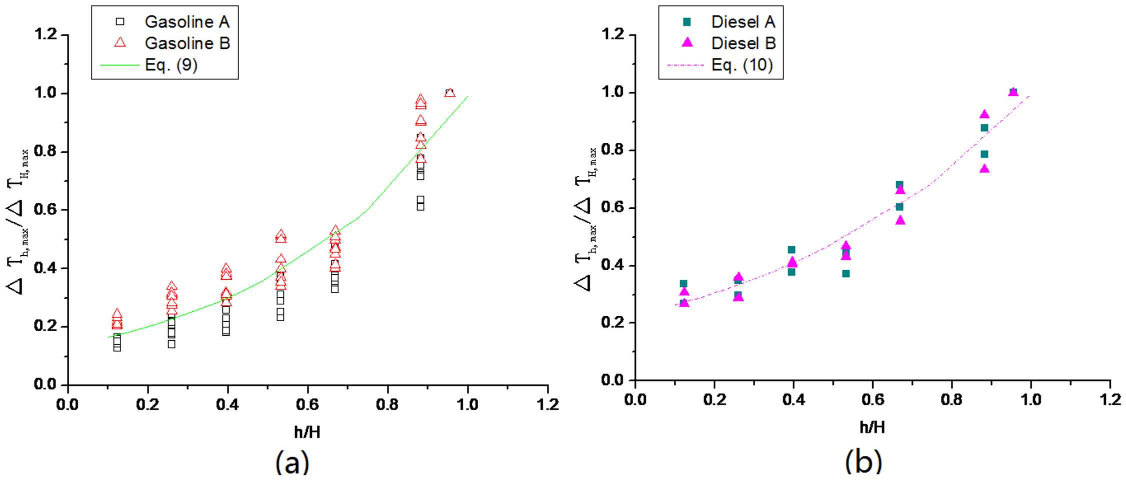


Fig. 10 Vertical temperature distributions for pool fires of size A and B: (a) Gasoline; (b) Diesel

Typically, the correlation can be expressed for gasoline, as follows:

$$\frac{\Delta T_{h,max}}{\Delta T_{H,max}} = 0.136\exp(1.99\frac{h}{H}) \qquad (9)$$

The corresponding for diesel can be expressed as:

$$\frac{\Delta T_{h,max}}{\Delta T_{H,max}} = 0.227\exp(1.48\frac{h}{H}) \qquad (10)$$

The maximum temperature ratio for diesel is shown to be obviously higher than that for gasoline. For instance, the ratio is nearly 0.26 at h/H=0.1 for diesel, being significantly higher than the corresponding values of 0.16 for gasoline. It means the thermal diffusion alongside the lining in diesel fires is stronger than that in gasoline fires.

4 Conclusions

An experimental study was developed to investigate the smoke temperature distribution alongside the lining across the section with gasoline and diesel pool fires in a tunnel. Firstly, the HRR behaviors are shown to be significantly different for gasoline and diesel. The duration of diesel combustion is almost three times than gasoline when they have the same volume. However, the HRR values of diesel are obviously lower than gasoline's. Correspondingly, the maximum smoke temperature for gasoline is significantly higher than diesel's. Additionally, the temperature history is illustrated, the temperature-rising rate of gasoline fire agrees well with the standardized temperature curves and significantly higher than the diesel fire. Furthermore, two correlations on the vertical temperature distribution are provided, respectively, for gasoline and diesel according to these experimental results. These findings are helpful for designing the smoke temperature distribution on the lining in tunnel fires.

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