AN EXPERIMENTAL INVESTIGATION ON VEHICULAR BLOCKAGE EFFECT ON THE MAXIMUM SMOKE TEMPERATURE IN TUNNEL

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ABSTRACT

Researchers are motivated to study tunnel fires because of the increasing number of large-scale incidents in urban tunnels. When a fire occurs, most likely there are vehicles which get stuck in the tunnel. The stuck vehicles act as additional barriers against the flow of smokes. The effect of blockages on the maximum temperature of smoke which has not received considerable attentions in most of the previous investigations, is studied in this research. A set of scaled-down experiments was performed in a model tunnel [3 m (length) × 0.6 m (width × 0.96 m (height)]. The variables in this section are ventilation velocity, heat release rate (HRR) and blockage percentages. Gasoline was used as fuels in rectangular pools to generate a heat source. The influence of blockage percentages on the maximum smoke temperature beneath the ceiling has been investigated by improving the model of maximum smoke temperature published earlier by Li using local velocity near the fire source. This analysis reveals that the modified model of maximum temperature, which considers the effect of vehicular obstacles, could estimate experimental results with greater accuracy.

1.0 INTRODUCTION

One of the most effective ways to alleviate the ever-increasing traffic volume and congestion is constructing urban tunnels where automobiles, vans, buses, motorcycles, and trucks could travel pass congested urban areas or hills. In recent years, the significant increase in the number and the total length of tunnels contributed to several catastrophic fire incidents in tunnels and tremendous damage to properties and lost of lives around the world. Therefore, many researchers and fire safety engineers have studied fire characteristics in tunnels usually equipped with a ventilation system to understand the risks involved. Maximum smoke temperature beneath the ceiling is an important issue for fire safety engineering because of its influence on the tunnel structure which could be damaged when exposed to the relatively high temperature. In addition, the activation of sprinkler and ventilation systems installed in tunnels is related to this parameter. Consequently, it is worthy to study the maximum smoke temperature under the tunnel ceiling to improve the safety level in the tunnels. There are different factors, including the tunnel geometry, longitudinal ventilation velocity, and the heat release rate (HRR) of the fire source. Such knowledge has been studied by researchers widely and several empirical equations have been proposed to estimate the maximum temperature of hot gases under the ceiling. The first researcher who proposed a model for the maximum temperature in tunnel fires was Kurioka [1]. He carried out experimental tests to study fire characteristics including the maximum temperature and flame tilt angle in a tunnel. The various cross-sectional shapes under longitudinal ventilation were utilized. The following dimensionless empirical model of the maximum temperature rise based on the dimensionless heat release rate and the Froude number was derived:

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

where

$$\begin{cases} \gamma = 1.77, \varepsilon = 1.2 \quad \text{for} \left(\frac{Q^{*\frac{2}{3}}}{Fr^{\frac{1}{3}}}\right) < 1.35, \\ \gamma = 2.54, \varepsilon = 0 \quad \text{for} \left(\frac{Q^{*\frac{2}{3}}}{Fr^{\frac{1}{3}}}\right) \geq 1.35, \end{cases} \qquad (2)$$

$$Q^* = \frac{Q}{\rho_a T_a C_p g^{1/2} H^{5/2}}, \qquad (3)$$

and

$$Fr = \frac{V^2}{gL}. \qquad (4)$$

According to this formula, when the fire is relatively small, the maximum temperature increases with the 2/3 power of the fire HRR, while it decreases with the 2/3 power of the longitudinal ventilation velocity. On the other hand, when the fire is relatively large, the maximum temperature does not vary with these two parameters.

Hu *et al.* [2] compared Kurioka's model by full-scale tunnel fire tests. Although they only confirmed the first part of Kurioka's model, good agreement was observed with the latter. They carried out twelve experiments in total, two experiments in a large-scale tunnel and ten experiments in full scale tunnels. Variations of this study were the fire size, tunnel section geometry, and ventilation velocity. They concluded that:

1. The maximum smoke temperature beneath the ceiling was higher for larger fire sizes, but it decayed faster while traveling down the tunnel.
2. The smoke temperature of upstream backlayering flow decreased with increasing longitudinal ventilation velocity.
3. A comparison between the upstream and backstream smoke temperature revealed that although the smoke temperature for the upstream backlayering was higher near fire source; it decreased much faster while traveling away from the fire than that of the downstream flow.

Smoke diffusion characteristics were analyzed by Wang [3] experimentally and theoretically. A formula developed for maximum smoke temperature under the condition that ambient air velocity existed. Li [4] presented a theoretical analysis to correct the Kurioka's model as it gives an infinite estimation of the maximum smoke temperature when the longitudinal ventilation approaches zero. An axisymmetric fire plume theory was used, and the dimensionless ventilation velocity was the basis of dividing the maximum excess gas temperature into two regions. According to their theoretical analysis and experimental data, which the necessary empirical coefficients are obtained from them, the following equation was presented:

$$\Delta T_{max} = \begin{cases} \dfrac{Q}{u r^{\frac{1}{3}} H_d^{\frac{5}{3}}} & \text{for } u' > 0.19 \\[2ex] \dfrac{17.5Q}{H_d^{5/3}} & \text{for } u' \leq 0.19 \end{cases} \tag{5}$$

where

$$u' = {}^{u}\!/_{u^*}, \tag{6}$$

and

$$u^* = \left(\frac{Q_c g}{r \rho_a C_p T_a}\right)^{1/3}. \tag{7}$$

Li *et al.* [4] also evaluated the experimental results by comparing data from one model-scale test and two full-scale tests. Li *et al.* found a good agreement between the model-scale tests and the other tests. Since Equation 1 is useful for only small fires where the flame does not impinge the ceiling, Li and Ingason [5] continued their experiments and improved their model (Equation 5) to obtain a new model. They concluded that the maximum temperature is dependent on the combination of relevant parameters to an upper limit and then remains constant.

Kashef *et al.* [6] carried out reduced-scale experiments and derived two formulas to predict the ceiling temperature. However, Kashef *et al.* [6] did not discuss the effect of tunnel configuration on smoke diffusion characteristics.

Recently, ceiling maximum temperature and its longitudinal decay in case of tunnel fire were obtained and studied in [7] where the tunnel has a horseshoe shape. The major result of this study proves the results of previous investigations where the maximum smoke temperature beneath the ceiling is proportional to the terms of ${}^{Q^{2/3}}\!/_{H_d^{5/3}}.$ Gao *et al.* [7] proposed modified equations for maximum smoke temperature rise beneath the ceiling and longitudinal temperature decay. Their experimental data had a good agreement with numerical simulations, the differences between experimental and numerical results were less than 7.5%. It should be notified that the present results need to be verified with more full-scale simulations.

The previously discussed models for measuring the maximum smoke temperature considered tunnel fires without blockage effect. However, in most actual tunnel fires, vehicles are usually stuck in the tunnel. A vehicle plays the role of an obstacle in the longitudinally ventilated tunnel, which will impact on local velocity around the fire source remarkably. Consequently, the tunnel fire characteristics such as the burning rate, the smoke flow pattern, and the temperature will be affected.

To examine the effect of blockages as well as their distance to the fire source on the maximum smoke temperature, Hu *et al.* [8] carried out an experiment in a longitudinally ventilated tunnel [8]. A modification coefficient considering the impact of blockage-fire distance was added and then, a global model including both the blockage ratio and blockage-fire distance was developed as in Equation 8. The maximum temperature decreased and then approached a constant value (similar to that with no blockage) with an increase in blockage-fire distance.

$$\Delta T_{max} = \begin{cases} \dfrac{Q}{\left[\dfrac{A - A_{blkg}}{A} + \dfrac{A_{blkg}}{A}\left(0.3\, {}^{d_b}\!/_{\overline{H}}\right)\right] V r^{\frac{1}{3}} H_d^{\frac{5}{3}}} & \text{for } u' > 0.19, d_b < 3.3\overline{H} \\[3ex] \dfrac{Q}{V r^{\frac{1}{3}} H_d^{\frac{5}{3}}} & \text{for } u' > 0.19, d_b \geq 3.3\overline{H} \\[3ex] 7.5\dfrac{Q^{2/3}}{H_d^{5/3}} & \text{for } u' \leq 0.19. \end{cases} \tag{8}$$

Ceiling temperature distribution and smoke diffusion distance in a tunnel equipped with natural ventilation and with a train blockage have also been investigated [9]. This is very important as many times, urban tunnel are congested; researching in such an arrangement is more meaningful. The dimensionless smoke temperature and a constant value, which was different for investigated different tunnels in this article [9], were used to derive the reference temperature in the fire section. Shafee and Yozgatligil [10] studied the effect of blockage ratio and found out that blockages caused the temperature along the tunnel ceiling to increase significantly.

However, few studies have considered the effect of tunnel blockage ratio on the maximum temperature under the ceiling in tunnel fires. Motivated by past studies, this study focuses on the effect of tunnel blockage ratio on the maximum temperature of hot gases under the ceiling in tunnel fires. Data from experimental fire tests in tunnels with considerable blockage ratios are used. By analyzing these experimental data, previous models will be modified by introducing a factor that accounts for the blockage effect.

2.0 EXPERIMENTAL STUDY

2.1 Experimental Set-Ups

The first step in the experimental setup to obtain reliable and qualify results is constructing the right model which can provide the acceptable similarities between the scaled model and the full-scale tunnel. However, the thermal inertia of the involved material, turbulence intensity, and radiation are not explicitly scaled, and the uncertainty due to the scaling is difficult to estimate, the general nature of the buoyancy-driven flows generated by a fire is not dependent on the scale [11]. The dynamic similarity between the scaled model and real model is related to preserving non-dimensional parameters such as the Froude, the Reynolds, and the Richardson numbers. Since it is not possible to preserve all mentioned numbers in most cases, the main goal is the preservation of the Froude number as the latter is the ratio between inertia and buoyancy forces and the Froude scaling model is used to build this scaled model [12]. The Froude number in this analysis in the same as in Equation 4. The scaling relationships for key parameters, velocity, and HRR, based on the preservation of the Froude number are as follows:

$$V_m = V_F \sqrt{\frac{L_m}{L_F}}, \tag{9}$$

$$Q_m = Q_F \left(\frac{L_m}{L_F}\right)^{5/2}. \tag{10}$$

In equations 9 and 10, subscript *m* is allocated for the model and *F* is for the full-scale tunnel. A review on a variety of approaches on similarity analyses, backlayering conditions including the effect of blockages, inclination, and the location of the fire source can be found in an earlier literature survey [13].

In this study, the Froude scaling method was used to build the model tunnel 1:50 scale of the Resalat Tunnel, Iran. The Resalat Tunnel is 150 m long and a diameter of 5.13 m. This expressway connects east to the west of Tehran, Iran. Based on the scaling ratio and method, the length of the tunnel, *L*, was scaled geometrically. The investigated model was 3 m long (*x* coordinate), 0.6 m width (*y* coordinate), and 0.95 m high (*z* coordinate). Fig. 1 shows the drawing of the model tunnel. Tunnel origin located 164 cm away from the right end of the model. The tunnel cross-section area was rectangular. All surrounding walls except half of one sidewall, the ceiling, and the floor of the tunnel were constructed by 25 mm - thick fireproof boards. Ten mm thick tempered glass in half of one sidewall of the tunnel provides the capability of smoke movement observation.

A ventilation fan with 1 kW power and an airflow capacity of 8400 cfm was installed at the left end of the tunnel (upstream section) to generates the longitudinal ventilation. Ventilation velocity was controlled and calibrated by varying the voltage by Toshiba frequency inverter VF-S11. One honeycomb mesh and two metal mesh screens made of wire were installed within a galvanized steel box and connect the three-phase fan and the main tunnel to provide a uniform and straighten flow.

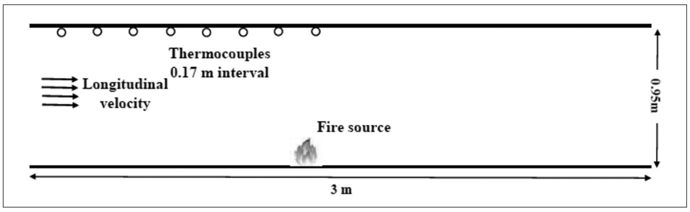

Figure 1: Schematic side view of the model tunnel

A detailed description of the experimental set up can be found in an earlier article [14].

2.2 Heat Release Rate

Real tunnel fires were simulated by pool fires in this study. The fuel was gasoline and square vessels were used as fuel containers and later as burners during fire. There were three different vessel dimensions i.e. 8, 10, and 13 cm square. Each pool was 2 cm deep and filled with a fuel height of 1 cm. The mass burning rate is used to calculate the heat release rate. Since gasoline needs a lot of oxygen in case of complete combustion, the mass burning rate increases with the ventilation velocity for fuel-controlled fires and the rate approaches a constant value for well-ventilated fires. There is no blockage between the fuel source and the fan which explains the easy access of oxygen into the core of the fuel and well-ventilated fire. However, $\dot{m}_f$ and Q are varied with time and ventilation velocity, based on the empirical relationship presented by Burgess [15], the burning rate with constant value is predicted in the function of pool diameter:

$$\dot{m}_f = \dot{m}_\infty \left(1 - e^{-k\theta D}\right), \tag{11}$$

where $\dot{m}_\infty$ is the burning rate of an infinite diameter pool fire. In Equation 11, k is the coefficient of radiative emission, and θ is the mean beam-length corrector. The HRR was determined by the burning rate [16] and can be calculated using Equation 12;

$$Q = \dot{m}_f a H_T, \tag{12}$$

where H_T is the heat of combustion of the gaseous combustibles when it is oxidized completely at ambient condition and *a* is burner area.

These sizes of pools produce simulated fires with heat release rates of 2.21 MW, 4.22 MW, and 8.98 MW in a typical tunnel. These fire sizes correspond to fires of approximately 39-160 MW in a tunnel with a diameter of 5.13 m when the Froude scaling model is used.

2.3 Measuring Instruments

The temperature of hot gases beneath the tunnel ceiling was detected by using one array of eight K-type stainless-steel sheathed thermocouples of 0.3 mm diameter. A K-type thermocouple is a precise and reliable instrument for continuous measurements providing the temperature range of -250 °C to 1260 °C. Thermocouples were placed 1 cm below the tunnel ceiling with 17 cm intervals in the centerline of the ceiling. The first thermocouple, T1, was fixed above the fire source and the other seven thermocouples, T2 - T8, were installed after T1 between the origin and the fan section (Fig. 1).

The main part of the data collection system was the Arduino Mega 2560 microcontroller. The signal from a K-type thermocouple should be digitized before sending it to a microcontroller. Therefore, the MAX6675 amplifier was used to measure the output of a K-type thermocouple, to perform cold-junction compensation, and to provide the result to the Arduino via an SPI interface.

2.4 Vehicular Blockages

Experimental tests with different sizes of blockages were carried out to simulate the influence of vehicles. The vehicle models consisted of three sizes, representing a sedan, a bus, and a truck. The dimensions of the sedan were 0.38 m (L) × 0.15 m (W) × 0.12 m (H), for the bus: 0.54 m × 0.17 m × 0.21 m, and for the truck: 0.61 m × 0.19 m × 0.20 m (Table 1). This represents a 1:12 model of typical vehicles. The purpose of this dimension (1:12 scale) was to examine the effect of different cross-sectional occupancy percentages of the tunnel cross-sectional area rather than to simulate conditions close to actual conditions. Nevertheless, further investigations are needed to explore the behavior of the smoke flow in conditions close to real scenarios for safe and efficient design of tunnel fire. The vehicular blockages were placed on one, two, and three lineups to simulate a tunnel with various lanes of vehicles. Typically, 3 to 15% of the tunnel cross-sectional area was occupied by the model vehicles. Table 1 summarizes the blockage ratio of all scenarios.

Table 1: Blockage ratio of various scenarios in this study

Scenario	Vehicles	Lanes occupy	Blockage ratio
1	Sedan	1	3.4%
2	2 Sedans	1-3	6.8%
3	Sedan-Bus	1-3	9.6%
4	Bus-Truck-Sedan	1-3	12%
5	Bus-Truck-Sedan	1-2-3	15%

3.0 RESULTS AND DISCUSSION

Before studying the effect of blockages on the maximum smoke temperature, the influence of blockages on smoke flow behaviors and values which are used in different parts of this study needs to be determined first. When the blocking area percentage increases, the cross-section area of the tunnel decreases leading to the rise of local velocity at the vicinity of the fire source. As a result, the inertial force with respect to buoyant force enhances and then the Froude number rises. This phenomenon and less entrained air because of it causes more heat convection and radiation and the acceleration of the discharge rate of fire smoke. This also affects smoke characteristics, i.e. the maximum smoke temperature to decrease.

When there is no obstacle in the tunnel, the ventilated air diffuses to the entire tunnel and the concentration of the ventilation flow does not change along the tunnel. However, with the existence of blockages in the tunnel, the tunnel cross-sectional area becomes smaller. When the fire source is located at the centerline and the blockage is positioned at the side lanes, local velocity will be larger when the ventilation air reaches the fire source to preserve continuity (Equation 14). In other words, velocity is inversely proportional with the cross-sectional area. Parameters below are defined to estimate the local velocity:

$$\text{Tunnel blockage ratio } (\alpha\%) = \frac{A - A_{blkg}}{A}, \tag{13}$$

where A is the tunnel cross-sectional area and A_{blkg} is the blockages cross-sectional area. The blocking percentage is defined as:

$$\text{Blockage percentage } (\varphi\%) = \frac{A_{blkg}}{A}. \tag{14}$$

The existence of blockages causes that local ventilation velocity in the vicinity of the fire source V_{local} to change through the changes of the cross-sectional area as the following equation:

$$V_{local} = {}^{V}\!/_{\varphi} = {}^{V}\!/_{(1-\alpha)}. \tag{15}$$

3.1 Influence of Vehicular Blockages on Maximum Smoke Temperature

The behavior of fire-induced flow changes when blockages occupy part of the tunnel cross-sectional area because of the effect obstacles on the longitudinal velocity in the vicinity of the fire and downstream section. The bigger blockage causes higher local velocity which in turn, the discharge rate of smoke is increased and the capability of ventilation to release the heat produced by the fire accelerates [4].

In other words, the maximum smoke temperature, which depends on ventilation velocity, changes with the latter. Table 3 illustrates the effect of blockage ratio on example cases with the same HRR and ventilation velocity.

Table 2: Three examples of the influence of blockages on maximum smoke temperature

Ventilation velocity (m/s)	HRR (kW)	φ%	Maximum smoke temperature (°C)
0.1	2.21	0% 6.8% 9.6%	45.8 45.0 43.0
0.8	2.21	0% 6.8% 12%	36.8 36.0 34.5
2.9	4.22	0% 6.8% 12%	37.8 37.0 35.5

In this section, first, the model presented by Li *et al.* [4], who studied the maximum temperature in a tunnel without blockages, is evaluated by the experimental results of this study in the presence of blockages (Fig. 2). As shown in Fig. 2, Li's model cannot estimate the maximum temperature rise within acceptable errors. Therefore, Equations 5 are amended by using V_{local} (ventilation velocity in the vicinity of the fire source) instead of V and are now represented in Equations 16. Fig. 3 compares the experimental results of the maximum smoke temperature with predictions by modified Li's model considering the blockage ratio (Equation 16). The black line presents modified Li's model considering the blockage ratio. It is shown that there is a good agreement between the model predictions and experimental results (Fig. 3) and they are close enough to the measured values which means that the amended Li's model could estimate the maximum smoke temperature in the presence of obstacles. In addition, at low ${}^{Q}\!/_{V_{local} r^{1/3} H_d^{5/3}}$, ΔT_{max} is below the black line and at high ${}^{Q}\!/_{V_{local} r^{1/3} H_d^{5/3}}$ is above the black line.

$$\Delta T_{\max} = \begin{cases} \dfrac{Q}{V_{local} r^{\frac{1}{3}} H_d^{\frac{5}{3}}} & \text{for } V' > 0.19 \text{ and} \\[2ex] \dfrac{17.5Q}{H_d^{5/3}} & \text{for } V' \le 0.19, \end{cases} \tag{16}$$

where

$$V' = {}^{V_{local}}/_{u^*}, \tag{17}$$

and

$$u^* = \left(\frac{Q_c g}{r\rho_0 C_P T_a}\right)^{1/3}. \tag{18}$$

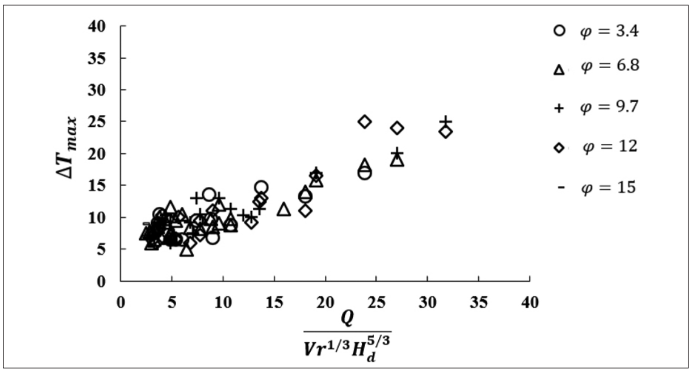

Figure 2: Comparison of Li's model (Equations 5) predictions with experimental results for different tunnel blockage ratio

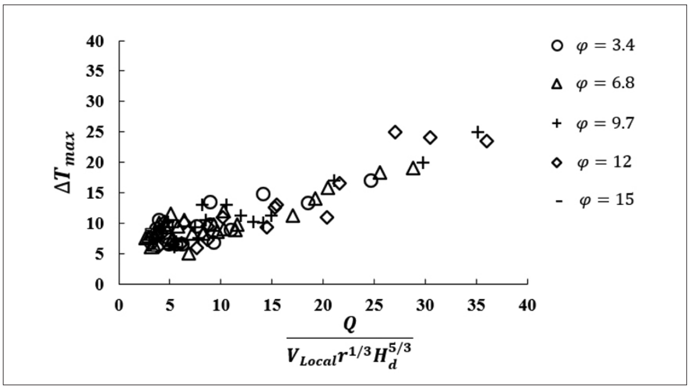

Figure 3: Comparison of modified Li's model (Equations 16) predictions with experimental results for different tunnel blockage ratio

4.0 CONCLUSION

This work investigates the influence of blockages on the maximum temperature of hot gases beneath the ceiling in case of a tunnel fire. A 1:50 reduced scale tunnel with 3 m × 0.6 m × 0.95 m (length × width × height) dimensions was employed to carry out a series of experiments with different fire heat release rates, longitudinal ventilation velocities and blockage percentages. Real tunnel fires were simulated by gasoline pool fires in this study. Temperatures were detected by using one array of eight K-type stainless-steel sheathed thermocouples. The vehicle models consisted of three sizes, representing sedan, bus, and truck. 3 to 15% of the tunnel cross-sectional area was approximately occupied by the model vehicles. Experimental results of this study show that the maximum smoke temperature decreases in the presence of blockages due to the effect of them on local velocity. Moreover, the measured values were compared with previous model proposed by Li which do not consider the blockage influence. When the blockage is placed upstream from the fire source, due to its hinder of the local ventilation flow from directly reaching the fire source region, the maximum gas temperature beneath the ceiling cannot estimate Li's model correctly. Therefore, a modification model with V_{local} instead of V was developed, which is shown to collapse maximum temperature predicted and measured values. Still, further thermal experiments are recommended in order to find the most appropriate and suitable correlations for both low and high ${}^{Q}/_{V_{local}r^{1/3}H_d^{5/3}}$. Moreover, the scaled tunnel model can be further improved to study a wide range of several scenarios.

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