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A study on tilted tunnel fire under natural ventilation

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ABSTRACT

Tilted tunnel fire under natural ventilation has been discussed. Smoke movement in a scale tunnel model of length 8 m, width 1.5 m and height 1 m was studied. Air temperature distribution and velocity components along the longitudinal axis at the tunnel opening were measured. Simulations using Computational Fluid Dynamics on smoke movement in the tilted tunnel fire were then carried out. Buoyancy of smoke layer in the tilted tunnel model was deduced by integrating experimental data with simulations results. Smoke velocity distributions in different tilted tunnels were studied numerically. For a horizontal tunnel, the smoke temperature decay rate along the longitudinal direction can be described by an exponential function. For tunnels tilted from 3° to 9°, smoke temperature decayed with different exponential functions on the two sides of the fire. The smoke velocity along the longitudinal axis was not symmetric about the fire source, but with a maximum value located on the leeward side in tunnels tilted at 3–9°. The neutral plane of flow disappeared at the lower opening of the tunnel when the angle was above 9°. Empirical expressions of smoke temperature and velocity decays along the longitudinal axis for a tilted tunnel were also derived.

1. Introduction

Tunnel fires were studied extensively in the literature with more works focused on observing smoke movement in horizontal tunnels [1,2], formulating empirical equations [3–8], studying the effect of opening location on smoke spread [9,10], studying critical wind speed of longitudinal ventilation system [11–15] and studying the effect of the presence of vehicles or other objects inside the tunnel on smoke spread [16,17].

Experimental data and numerical predictions on near field of a square fire source in horizontal tunnels of five different cross-sections with longitudinal ventilation were combined by Kurioka et al. [17]. The maximum temperature of smoke layer at the tunnel ceiling is expressed as:

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

$$Q^{*2/3}/Fr^{1/3} < 1.35, \quad \gamma = 1.77, \quad \varepsilon = 6/5 \tag{2}$$

$$1.35 \le Q^{*2/3}/Fr^{1/3}, \quad \gamma = 2.54, \quad \varepsilon = 0 \tag{3}$$

The position of maximum smoke layer temperature is given by:

$$\frac{L}{H_d}Fr^{1/2} = \alpha\left[\left(H^{3/2}/b^{1/2}\right)/A_f^{1/2}FrQ^{*(2\eta-1)/5}\right]^{\beta} \tag{4}$$

The parameter $H^{3/2}/b^{1/2}$ was proposed [18] to be used as the reference length for deducing non-dimensional parameters.

The direct and indirect driving forces for smoke movement were divided by Klote [4] into stack effect, buoyancy, thermal expansion, natural wind, heating effect, and mechanical ventilation and air-conditioning. Among these, stack effect, thermal buoyancy and ventilation would give the direct driving forces for smoke movement in tunnels. Pressure difference due to stack effect ΔP_s can be expressed as [4]:

$$\Delta P_s = K_s\left(\frac{1}{T_0} - \frac{1}{T_i}\right)h \tag{5}$$

Pressure difference due to thermal buoyancy ΔP_b is expressed as:

$$\Delta P_b = K_s\left(\frac{1}{T_0} - \frac{1}{T_F}\right)h \tag{6}$$

It can be seen that ΔP_s and ΔP_b are similar in that they are caused by temperature difference with outdoor temperature T_1 or with smoke temperature T_F, but both ΔP_s and ΔP_b are related to the position h above the reference.

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Pressure due to mechanical ventilation P_w is expressed as:

$$P_w = \frac{1}{2} C_w \rho_0 v^2 \tag{7}$$

Experiments on studying smoke counterflow and critical wind speed when the tunnel was blocked by vehicles or other objects were reported by Tang et al. [12]. The vehicles or other objects would change the flow field of ventilation and smoke layer movement in a way different from an empty tunnel by producing different smoke back-layering effect and hence, different critical speed equations. An area factor η was proposed [12]:

$$\eta = \begin{cases} \dfrac{A_1}{A_1 + A_2} \times \left[\dfrac{A_1 - A_2}{A_1} + \dfrac{A_2}{A_1}\left(0.3L/\bar{H}\right) \right] & L/\bar{H} < 3.3 \\ \dfrac{A_1}{A_1 + A_2} & L/\bar{H} \geq 3.3 \end{cases} \tag{8}$$

In this way, changes in the velocity flow field due to changes in tunnel cross-section can be conveniently taken into account in studying back-layering and critical air speed for longitudinal ventilation system when objects were present in the tunnel.

Experimental studies on the relationship between smoke flow pattern and Froude number Fr in a horizontal tunnel were conducted by Yang et al. [18]. When $Fr > 0.9$, a clear interface between the smoke layer and the cool air below was formed, with negligible heat and mass transfer between the two layers. When $0.3 < Fr < 0.9$, turbulence was developed in the smoke layer at the tunnel rear part, and a small amount of heat and mass transfer between the smoke layer and air was observed. When $Fr < 0.3$, the smoke layer was totally turbulent, with significant heat and mass transfer. However, the observations of these three flow patterns are only preliminary results from scale models. When the longitudinal ventilation system was not operating, the flow was entirely State I. When longitudinal ventilation speed was less than 1.8 m/s, region close to the fire source was State I, but being State II for regions far away from the fire source. All these were clearly indicated by the smoke pattern from a small-scale tunnel fire experiment discussed later.

For a horizontal tunnel fire with a ventilation system, the critical velocity v''_{cr} is related to the heat release rate raised to the power of 1/3 for $\dot{Q}'' \leq 0.124$, as concluded from Oka and Atkinson's experiment [11].

$$v''_{cr} = 0.35[0.124]^{-1/3}\left[\dot{Q}''\right]^{1/3}, \quad \text{for } \dot{Q}'' \leq 0.124 \tag{9}$$

However, v''_{cr} is independent of $\dot{Q}''$ for $\dot{Q}'' > 0.124$, and is given by

$$v''_{cr} = 0.35, \quad \text{for } \dot{Q}'' > 0.124 \tag{10}$$

The driving forces for smoke movement are stack effect, buoyancy, thermal expansion, wind, and forces induced by the heating, ventilating, and air conditioning (HVAC) as pointed out by Klote [4]. For horizontal tunnels, driving forces are only due to buoyancy and mechanical ventilation. When a fire occurred in a horizontal tunnel, smoke moved upward due to buoyancy and accumulated under the tunnel ceiling. The smoke density would be increased due to cooling. Smoke moved sideway and mixed with the surrounding low density fresh air. Therefore, for horizontal tunnels, buoyancy along the vertical gravity direction does not drive smoke directly along the longitudinal direction. It was the pressure difference between the hot smoke and the surrounding air that drove smoke along both directions in the tunnel [12]. However, the driving forces for smoke in tilted tunnels are different. The angle between vertical gravity and smoke movement direction will give an acceleration to facilitate smoke spread. Therefore, the critical velocity was greater in tilted tunnels than in horizontal tunnels, as reported by Atkinson and Wu [19]. Smoke movement in tunnel fire was studied numerically by Riess and Bettelini [20]. For tunnels tilted at an angle greater than 1–2%, stack effect should be considered in the ventilation system design. Again, the stack effect is due to the component of hydrostatic pressure difference along the longitudinal tunnel axis.

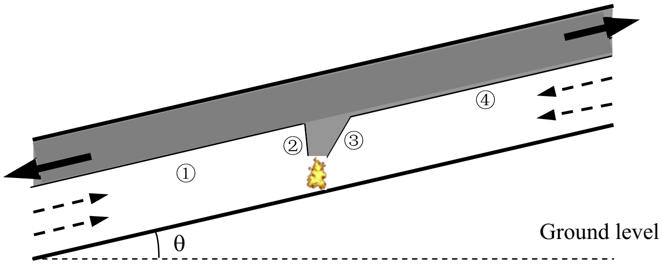

Fig. 1. Smoke movement pattern in a tilted tunnel.

Scale-model experiments on tilted tunnel smoke control were reported by Chow [21]. The tunnel was equipped with longitudinal ventilation system. The tilted angle was adjusted from 0° to 30°. The fire plume deviated from the axis of the burning pool due to the combined effect of gravity and smoke spread along the tunnel ceiling. These results confirmed the discussion about tilted tunnel smoke movement pattern above. The smoke movement pattern in a tilted tunnel inclined with an angle θ to the horizontal can be represented as in Fig. 1. Line ① on smoke interface is almost along the tunnel longitudinal axis. Lines ② and ③ are boundaries of the plume. Line ④ is the smoke front traveling upward due to the acceleration component $g\sin\theta$. Cool air comes in at the lower part of the two tunnel ends, as indicated by the dotted arrows.

Tajadura et al. [22] studied tilted tunnel numerically and pointed out that the tilted angle and its height played a crucial role in smoke spreading. Critical velocity in a tilted tunnel fire was studied experimentally by Atkinson and Wu [19] with tilted angle from 0° to 10°. The critical velocity was greater in tilted tunnels than in horizontal tunnels, and $\dot{Q}'' = 0.12$ was suggested to be a critical value for the relationship between non-dimensional critical velocity and $\dot{Q}''$ to hold. The formula on critical velocity for tilted angles from 0° to 10° was proposed to be:

$$v''_{cr}(\theta)/v''_{cr}(0) = 1 + 0.014{\cdot}\theta, \quad \text{for } \dot{Q}'' < 0.12 \tag{11}$$

Note that Eq. (10) was reported by Oka and Atkinson [11] which focused on horizontal tunnel fire. Eq. (11) was reported by Atkinson and Wu [19] with critical velocity in a tilted tunnel fire studied experimentally. Eq. (10) described the relationship between critical velocity and heat release rate, while Eq. (11) described the relationship between critical velocity and tilted angle.

In studying numerically the smoke movement in tilted tunnels, the formula for effective pressure difference caused by stack effect, as suggested by Riess and Bettelini [23], is:

$$\Delta p_{stack} = \Delta H \rho g \frac{T - T_0}{T} \tag{12}$$

In the above equation, ΔH is the difference in height between the positions studied. It can be seen that the key to accurately calculate pressure difference generated by stack effect is the smoke temperature decay model along the tunnel length. For tilted tunnels, the smoke temperature decay model was quite different from that in horizontal tunnels, and this was discussed in [23].

Experimental studies on smoke temperature decay model for tilted tunnel [24] were conducted by Hu and Chen [24]. The tilted angle θ increased the longitudinal temperature decay when the fire source was set at the lower opening. The modified formula of