International Journal of Heat and Mass Transfer 53 (2010) 2844–2855

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Longitudinal distributions of CO concentration and difference with temperature field in a tunnel fire smoke flow

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ARTICLE INFO

Article history:
Received 2 July 2007
Received in revised form 1 March 2009
Accepted 18 January 2010
Available online 11 March 2010

Keywords:
Tunnel fire
Smoke temperature
Carbon monoxide concentration
Longitudinal profile
Longitudinal ventilation

ABSTRACT

Longitudinal decay profiles of CO concentration and smoke temperature in a tunnel fire smoke flow are theoretical analyzed and compared, with their difference investigated, under different longitudinal ventilation velocities. Experimental data on longitudinal CO distribution achieved from a set of full scale road tunnel fire tests are presented to compare with the theoretical equation. CFD simulations are also carried out by Fire Dynamics Simulator (FDS). It is found that the longitudinal profile of CO concentration along the tunnel yields a function of $C_x/C_0 = 1/(1 + bx)$, and its difference with that of the smoke temperature increases along the tunnel by a function of $C_x/C_0 - \Delta T_x/\Delta T_0 \approx \lambda(1 - e^{-Kx})$. The smoke temperature decays much faster than the CO concentration along the tunnel. Their longitudinal profile difference decreases as the longitudinal ventilation velocity increases, and increases along with the distance away from the fire asymptotically to a quasi-steady value. The value of b decreases as the longitudinal ventilation velocity increases, which indicates that the CO concentration decays relatively slower along the tunnel under a higher longitudinal ventilation velocity. And its value is shown to be less affected by the longitudinal ventilation velocity for a relative larger fire. The increase in the longitudinal ventilation velocity leads to the enhancement of the air mass entrainment, thus results in the decrease of the longitudinal decay profile difference between the CO concentration and the smoke temperature. The value of λ is found to decrease with the increase of the longitudinal ventilation velocity, following a reciprocal function of $\lambda \sim 1/(\phi + \alpha u)$. Its value at zero longitudinal ventilation velocity is higher for a larger fire, but decreases faster with the increase of the longitudinal ventilation velocity than a smaller fire. The full scale experimental data and the CFD simulation results both agree well with the theoretical analysis and equations.

1. Introduction

Tunnel fire safety attracts increasing attention since the numerous catastrophic tunnel fire accidents occurred in recent years, such as those in Mont-Blanc, Austria [1] in 1999 killing 41 people and Dague, Korea [2] in 2003 killing 198 people, others including Tauern, Austria [3] in 1999; Kitzsteinhorn in 2000; Gotthard in 2001; and Frejus, France/Italy in 2005. Statistics have shown [4] that smoke and toxic gases, such as carbon monoxide, are the most fatal factors in fires, and about 85% of people killed in building fires were killed by toxic smoke. Inhalation of toxic gases can directly harm and kill the people in a fire environment. In a tunnel fire, or other underground fires, more toxic carbon monoxide will be produced because of incomplete combustion due to lack of oxygen supply. Taking appropriate methods to control the dispersion of the smoke and toxic gases in case of a fire is a serious concern for smoke management in tunnels. However, in order to provide appropriate fire safety, the physics of transportation of smoke and toxic gases should be well understood first. In a tunnel fire, the CO gas is transported longitudinally along the tunnel with the aid of buoyancy from temperature gradient above ambient and the inertial force from the longitudinal ventilation. People trapped in the fire also have to evacuate in the longitudinal direction in a tunnel. This makes the study of transportation characteristics of CO in a tunnel fire is more crucial than that in normal enclosures.

As the fire smoke flow is buoyancy driven, smoke temperature distribution is commonly used to characterize or represent the smoke flow distribution, including the smoke layer interface height (e.g., [5,6]) and horizontal smoke flow front position (e.g., [7–9]), as two most important parameters concerning human safety in case of a tunnel fire. However, it should be noted that it is the toxic gases, such as carbon monoxide (CO), rather than the thermal radiation, that is the most fatal factor in a fire, especially at positions some far away from the fire source. The temperature distribution along the tunnel is dominantly affected by the heat loss to the ambient, while the CO volume concentration distribution is controlled by the fresh air mass transportation into the smoke flow, which acts as a dilution effect. The longitudinal distribution of

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0017-9310/$ - see front matter
doi:10.1016/j.ijheatmasstransfer.2010.02.013

Nomenclature

b	decay factor of CO concentration in Eq. (7)
C	CO concentration
c_p	specific heat capacity
H_s	thickness of the smoke layer
$\bar{h}$	heat transfer coefficient
K	decay factor of smoke layer temperature in Eq. (14)
L	characteristic distance
m	mass flow rate of the smoke layer
m'	air entrainment flow rate into the smoke layer at the interface
P	the perimeter of the cross section of the smoke layer
Pr	Prandtl number
$\dot{q}$	heat loss from the smoke flow to the ambient
Re	Reynolds number
T_a	ambient air temperature
T_x	smoke layer temperature at position x
u	longitudinal ventilation air flow velocity
u_s	traveling velocity of the smoke layer
W	width of the tunnel
x	distance away from the reference position of +50 m

Greek symbols

α	coefficient of u in Eq. (21)
β	entrainment coefficient
ϕ	constant in Eq. (21)
ρ_a	density of the ambient air
ρ_s	density of the local smoke layer
λ	longitudinal profile difference constant in Eq. (17)

Subscripts

a	ambient air
s	smoke layer

CO concentration and smoke temperature along the tunnel should have inherent difference, as they have different dominant mechanisms. Numerous studies have been carried out by former researchers, focused on the investigation of the longitudinal smoke flow temperature distribution in a tunnel/channel fire with results indicating that it follows an exponential decay [9–13]. But there are few literatures on the longitudinal decay trend of CO concentration in a tunnel fire smoke flow. And furthermore, how it differs with that of the smoke temperature also needs to be investigated and quantified, in view of that they have different dominant mechanisms. The commonly existed longitudinal ventilation air flow in the tunnel would add complexity into the above problem, as it contributes an influence of inertial force to the buoyancy driven dispersion of the smoke flow and enhances the entrainment of fresh air into it. How their difference in a tunnel fire smoke flow will be influenced by the longitudinal ventilation also needs to be found out.

In this paper, the longitudinal profile of CO concentration and how it differs with that of the smoke temperature are theoretical analyzed, with the influence of longitudinal ventilation considered. Experimental data achieved during a set of full scale road tunnel fire tests and numerical CFD simulations carried out by Fire Dynamics Simulator (FDS), are used to compare with the theoretically analytical equations.

2. Theoretical analysis

The development of buoyancy-driven fire smoke flow in a tunnel/channel can be described into four stages [10,11]: (I) impinging region of rising plume on the ceiling; (II) radial spread of smoke under the ceiling after impingement; (III) interaction with side walls with a transition stage to one-dimensional spread and; (IV) a final one-dimensional spreading stage. The smoke temperatures in the relatively earlier stages I, II and III, which near the impinging region of flame upon ceiling and side walls, are relative high, where the oxidization of CO still occurs considerably. This paper focuses on the consideration of the smoke flow in the one-dimensional spreading stage. In this stage, as the smoke temperature is relatively low, following basic assumptions were taken:

(1) The oxidization of CO in the hot smoke flow leads to a slow decrease in CO concentration along the tunnel. However, as the temperature plays an important role on the oxidation of CO within the smoke flow and is low at this circumstance, this effect is neglected compared with the dilution effect due to entrainment of fresh air into the smoke flow. It was indicated [14] that CO within the upper smoke layers can be almost oxidized to CO_2 if the upper layer temperatures are higher than 900 K (or 627 °C), but could hardly be oxidized to CO_2 if the upper layer temperatures are below about 800 K (or 527 °C).

(2) The radiation loss is strong in the near flame region. However, it should be very much lower in the region far away from the fire. The radiation heat loss from the smoke flow to the ambient is thus ignored compared with the convective heat loss to the tunnel boundaries.

As shown in Fig. 1, the longitudinal decrease in CO concentration and smoke temperature should have different dominant controlling mechanism. The only factor that contributes to the longitudinal decrease in CO concentration is the entrainment of fresh air into the smoke flow due to the recirculation behavior at the smoke–air layer interface, which leads to the dilution of the local CO concentration. The conservation mass equation for the CO species can be taken as

$$C_0 m_0 = (m_0 + m')C_x \tag{1}$$

where C is the local concentration of CO, m is the local mass flow rate of the smoke flow and m' is the air entrainment mass flow rate into the smoke flow during the traveling from initial reference position 0 to position x ($m_x = m_0 + m'$). It was reported that the air entrainment mass flow rate into the smoke layer was proportional to the relative velocity of the smoke flow and the longitudinal ventilation air flow [15]:

$$m' = \rho_a \beta W |u - u_s| x \tag{2}$$

where ρ_a is the ambient air density, x is the longitudinal distance between initial reference position 0 and position x, W is the width of the tunnel, u is the longitudinal ventilation air flow velocity, u_s is the longitudinal traveling speed of the smoke flow and β is entrainment coefficient.

However, the decrease in smoke temperature should attribute to both the entrainment of fresh cool air into the smoke flow and the heat loss from the smoke flow to the ambient by convection. The energy equation can be taken as

$$c_p m_0 T_0 + c_p m' T_a - \dot{q} = c_p (m_0 + m') T_x \tag{3}$$

where c_p is specific heat capacity and $\dot{q}$ is the heat loss from the smoke flow to the ambient during the traveling from initial