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Effects of ambient pressure on transport characteristics of thermal-driven smoke flow in a tunnel

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ABSTRACT

Thermal-driven smoke flow is the greatest threat to the trapped people in tunnels, and the basic understanding of the smoke transport characteristics is necessary for the engineering applications of smoke control and exhausting system. However, most of the previous studies only focused on the smoke transport at normal pressure. As a matter of fact, the ambient pressure decreases with the increasing of the altitude, and the influence of different ambient pressures on the transport characteristics of thermal-driven smoke has been rarely considered before. This paper presents an investigation on the effect of ambient pressure on the smoke transport characteristics in a tunnel. A series of fire simulations were conducted in a full scale road tunnel with ambient pressure ranged from 100 kPa to 50 kPa and the heat release rate (HRR) varied from 3 MW to 15 MW. The smoke mass transport along the tunnel for different conditions is analyzed, and results show that for a certain HRR, the smoke mass flow rate decreases with reduced ambient pressure due to the decreased air density and the weakening of air entrainment strength. Based on the dimensional analysis, a quantitative model to predict the average smoke mass flow rate in the tunnel is proposed considering both ambient pressure and HRR. Moreover, the credibility of the predictive model is validated by comparing with a wide range of experimental results from both full scale and reduced scale experiments at different pressures.

1. Introduction

Owing to the long-narrow structure of tunnels, the thermal-driven smoke flow is easier to accumulate below the ceiling and spread to a long distance along the tunnel, and consequently has caused many severe casualties [1–3]. Statistics shows that smoke is the greatest threat to the trapped people in fires, and about 85% of the victims are killed by the hot and toxic smoke [4,5]. Therefore, it is necessary to clarify the smoke transport characteristics to further guides the engineering applications of smoke control and exhausting system, and thus the thermal characteristics and mass transport of the smoke in tunnel fires have attracted much more attention recently [6–11].

Mass transport is an important aspect of the transport characteristics of thermal-driven smoke flow, and the related knowledge of smoke mass transport is vital for predicting smoke behavior, determining smoke control strategies and designing smoke extraction system. Extensive researches on mass transport of free smoke plume in open space have been reported and some quantitative models are proposed to estimate the smoke production rate. Mccaffrey [12] indicated that the fire plume in open space can be divided into three regions: the continuous flame region, the intermittent region, and the buoyant plume region. Zukoski et al. [13] carried out experiments to measure the smoke mass flow rate in the buoyant plume region and proposed a classical model to predict the smoke mass flow rate based on the ideal plume theory. The equation is given by

$$\dot{m}_p = 0.21\left(\frac{\rho_0^2 g}{c_P T_0}\right)^{1/3}\dot{Q}^{1/3}Z^{5/3} \tag{1}$$

Further, Heskestad [14] introduced a “virtual origin” and employed the convective heat release rate (HRR) to quantify the smoke mass flow rate.

With respect to smoke mass transport in tunnel fires, there are a certain differences due to the long-narrow structure of the tunnel. Previous studies [7,15,16] have pointed out that the smoke spread in tunnel fires can be divided into four stages: free rising plume stage, radial spread stage, transition stage and one-dimensional spread stage. The one-dimensional spread stage is the longest one of these four stages and the smoke mass flow reaches the maximum value in this stage. Compared with the first three stages, the mass flow rate of the fully developed one-dimensional stage is much larger and it is more referable

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Nomenclature

c_p	specific heat capacity of air (kJ kg^{-1} K^{-1})
D^*	fire characteristic diameter (m)
g	gravitational acceleration (m s^{-2})
H	tunnel height (m)
$\dot{m}_p$	mass flow rate of plume in open space (kg s^{-1})
$\overline{m}$	average mass flow rate of smoke in one-dimensional spread stage (kg s^{-1})
$\overline{m}^*$	dimensionless mass flow rate in one-dimensional spread stage (−)
P_0	ambient pressure (kPa)
$\dot{Q}$	heat release rate (kW)
$\dot{Q}_P^*$	dimensionless heat release rate (−)
T_0	ambient temperature (K)
T_s	smoke temperature (K)
v	smoke flow velocity (m s^{-1})
Z	height from the fire source (m)

Greek

ρ_0	air density (kg m^{-3})
δx	grid size (m)
β	air entrainment coefficient (−)

for the designing of smoke exhausting system. Ji et al. [15] investigated the stage partition of smoke spread and the air entrainment in a small scale tunnel by measuring the temperature and velocity within the smoke layer, and found that the air entrainment rate of smoke in one-dimensional spread stage is significantly smaller than the first three stages which ranges in the near filed of the fire source. Jiang et al. [16] carried out a series of experiments in a model tunnel with exhaust system, and found that the air entrainment of one-dimensional spread stage increased with the smoke extraction rate and HRR. In addition, Haselden and Hinkley [17,18] gave a comprehensive investigation on the smoke spread velocity, and the temperature, the opacity and the depth of the smoke layer in a disused railway tunnel. Yang et al. [19] measured the velocity and the depth of buoyancy-driven smoke in a reduced scale corridor and obtained the volume rate of smoke flow at different HRRs. However, most of the current research on smoke mass transport in tunnel fires were carried out at normal pressure by default.

In recent years, the tunnel constructions at high altitude areas (low ambient pressure) are increasing. For instance, the Changlashan road tunnel on Tibetan Plateau in China is located at the altitude of 4500 m where the ambient pressure is about 58 kPa, almost half of the normal pressure (101 kPa) [20]. The lower ambient pressure implies the smaller air density, and this change of air density will directly affects the smoke mass transport in tunnel fires. Tang et al. [21] carried out fire experiments in a compartment at two ambient pressures (64 kPa and 100 kPa), and found that the air entrainment coefficient of the buoyant spill plume at ambient pressure of 64 kPa is about 0.8 times that of 100 kPa, indicating that the strength of air entrainment process gets weaker at lower ambient pressure. Wang et al. [22] conducted a series of fire tests in a full scale simulated aircraft cargo compartment at four ambient pressures (100 kPa, 90 kPa, 80 kPa and 70 kPa) and also found that the air entrainment coefficient of smoke became smaller at lower pressure.

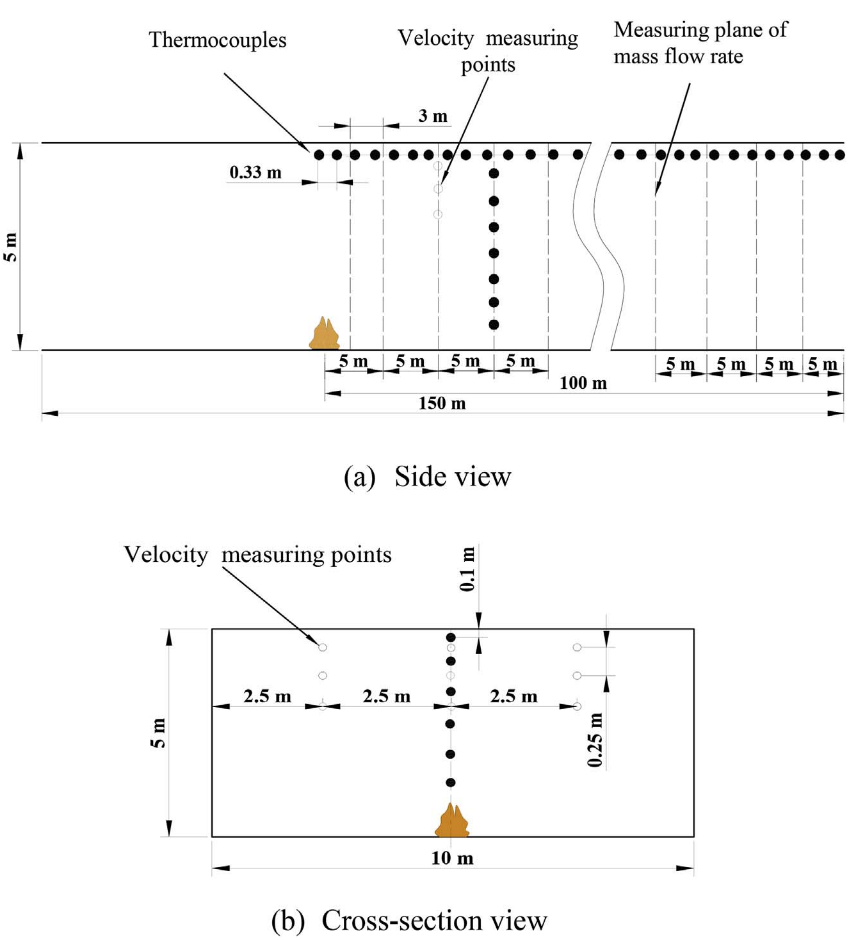

Fig. 1. Arrangements of the measuring points.