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Effects of scale ratio and aspect ratio in predicting the longitudinal smoke-temperature distribution during a fire in a road tunnel with vertical shafts

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ABSTRACT

A series of fire experiments using 1:10 and 1:20 scale model tunnels with a number of vertical shafts was conducted to investigate the effects of the scale ratio and the aspect ratio of the model tunnels on the longitudinal smoke-temperature distribution and the performance of a natural ventilation system. These model tunnels had different aspect ratios of the tunnel cross section: the aspect ratios of the 1:10 and 1:20 scale model tunnels were unity and two, respectively. Furthermore, a new model for predicting the longitudinal smoke-temperature distribution during the one-dimensional smoke spreading stage was developed. Then, the temperature distribution predicted by the model was compared with that obtained by the fire experiments to evaluate the model. In this model, the heat transfer from the smoke to the tunnel walls was considered, but the thermal radiation exchange between the smoke and surroundings was not considered, because the temperature difference between the smoke and surroundings was small and the influence of the radiation could be neglected. The key findings obtained were: (1) Two forms of the smoke exhausted from shafts (plug-holing and boundary layer separation) can be classified by the Richardson number, and the critical Richardson number 1.4 (for transitioning from one form to other) was confirmed in this study as proposed by Ji et al (Int. J. Heat Mass Transf., 55, 6032–6041). (2) The efficiency of exhausting heat of the smoke could be estimated from the tunnel geometry, shaft height, and Richardson number. It was shown that the value of the efficiency depends on the aspect ratio of the model tunnel. (3) The developed model was able to predict the longitudinal smoke-temperature distribution under the conditions with and without shafts regardless of the scale ratio of the model tunnel and the aspect ratio of the tunnel cross section.

1. Introduction

A fire occurrence in a tunnel can be turned into a major incident. For example, the Mont Blanc tunnel fire between France and Italy in 1999 killed 39 people, and the Yanhou tunnel fire in China in 2014 killed 31 people (Ingason et al., 2015a). Therefore, ventilation systems to control and exhaust smoke produced by tunnel fires are important for the safety of tunnel users. Ventilation systems are classified into two types: mechanical ventilation systems (MVS) and natural ventilation systems (NVS). MVS drives ventilation using mechanical equipment such as a jet fan, whereas NVS induces ventilation using natural forces such as the stack effect and piston effect. Compared with MVS, NVS has some advantages: electric power for operation is not necessary, maintenance is easy, and the cost is low. In urban areas, most road tunnels are rectangular in shape and are constructed within shallow underground spaces. Hence, NVS with vertical shafts can be used as the ventilation system of road tunnels, such as the Toranomon Tunnel in Japan and the Xianmen Road Tunnel in China. However, there has not been enough research on the performance of NVS during a fire in a road tunnel.

Several studies on the performance of NVS have been conducted in recent years. Ji et al. (2012) conducted fire experiments using a 1:6 scale model tunnel with a vertical shaft and found that the form of the exhaust smoke can be classified by the Richardson number, *Ri*. They concluded that the plug-holing phenomenon occurred when *Ri* was greater than 1.4. Fan et al. (2013) also conducted fire experiments using a 1:6 scale model tunnel with a vertical shaft. They showed that the plug-holing phenomenon reduces the exhaust performance because of the strong effect on the mixing of hot smoke and cold fresh air. Therefore, it is important for NVS to avoid the plug-holing phenomenon. Ura et al. (2014) conducted fire experiments using a 1:12 scale model tunnel with roof openings and found that the smoke spreading

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Nomenclature

A	cross-sectional area (m^2)
C_p	specific heat of air at 300 K = 1007 (J/kgK)
d	thickness, diameter (m)
E	efficiency of exhausting heat of the smoke (–)
g	gravitational acceleration = 9.81 (m/s^2)
h	heat transfer coefficient (W/m^{2}K)
H	height (m)
k	thermal conductivity (W/mK)
L	length (m)
$\dot{m}$	mass flow rate (kg/s)
$\overline{Nu}$	average Nusselt number (–)
P	atmospheric pressure at sea level = 101.3 (kPa)
Pr	Prandtl number (–)
Q	convective heat flow rate (W)
R	gas constant for air = 287 (J/kgK)
Re	Reynolds number (–)
Ri	Richardson number (–)
Ri_{cr}	critical Richardson number = 1.4 (–)
t	time (s)
T	temperature (K)
ΔT	rise in temperature (K)
u	velocity (m/s)
W	width (m)
x	distance from fire source (m)

Greek

α	correction factor (–)
γ	scale ratio (–)
ρ	density (kg/m^3)
$\Delta\rho$	difference in density between smoke and ambient air (kg/m^3)

Subscripts

amb	ambient
cs	smoke flowing under the ceiling
es	smoke exhausted from shafts
s	smoke
sh	shaft
t	tunnel

distance was constant regardless of the fire scale. Tanaka et al. (2016) examined the effect of a transverse external wind on NVS with roof openings using a 1:12 scale model tunnel and concluded that the smoke spreading distance was shorter with a transverse external wind than without such a wind. Furthermore, Tanaka et al. (2017) examined the effect of a longitudinal external wind on NVS with roof openings using a 1:12 scale model tunnel, and found that when a longitudinal external wind blew over the tunnel roof openings, the smoke spreading distance on the upstream side was longer than that without the external wind due to the diffusion of smoke. On the other hand, the smoke spreading distance on the downstream side of the fire was shorter than that without the external wind due to the Venturi effect of the longitudinal external wind. Cong et al. (2017) introduced a new concept (board-coupled shaft) to avoid the plug-holing phenomenon and investigated its effect on the performance of NVS by a CFD-based fire model Fire Dynamics Simulator (FDS), (McGrattan et al., 2017). The simulation results showed that the new concept can avoid the occurrence of the plug-holing phenomenon. Jin et al. (2017) conducted fire experiments using a 1:36 scale model tunnel with roof openings and investigated the respiratory phenomenon caused by vehicle motion. They concluded that the number of roof openings did not affect the inlet velocity at the openings and the respiratory phenomenon was not observed when the vehicle velocity was constant.

Smoke movement and longitudinal smoke-temperature distribution under the ceiling of a tunnel during fire are of intense research interests, and there have been many such studies. Gao et al. (2016) examined smoke-layer thickness, which is an important parameter affecting smoke movement. They showed that the predicted smoke-layer thickness calculated by the buoyancy frequency method agreed well with visual observations. Oka et al. (2016) developed a new equation for estimating the smoke-layer thickness through a theoretical analysis. They compared the calculated results with experimental results obtained using a 1:15 scale model tunnel and verified the validity of the new equation. Jiang et al. (2016) focused on an air entrainment coefficient in the one-dimensional smoke spreading stage and calculated the air entrainment coefficient based on the experimental results obtained by a 1:20 scale model tunnel. They showed that the air entrainment coefficient in the central exhausting was greater than that in the natural exhausting. Gong et al. (2016) studied the longitudinal smoke-temperature distribution and found that the factors affecting smoke-temperature attenuation are thermal convection between the smoke and tunnel walls, thermal radiation exchange between the smoke and surroundings, and heat loss due to air entrainment. Ji et al. (2017) investigated the effect of ambient pressure on longitudinal smoke-temperature distribution by numerical simulations. They proposed a correlation between longitudinal smoke-temperature distribution and the distance from the reference position taking into account the effect of ambient pressure.

However, the research on NVS discussed above used one shaft. In other words, there is little data obtained by fire experiments using multiple shafts. Furthermore, most modeling studies on smoke movement and longitudinal smoke-temperature distribution (Oka et al., 2016; Jiang et al., 2016; Gong et al., 2016) did not investigate the influence of vertical shafts, so the smoke movement and temperature distribution during a fire in a tunnel with vertical shafts are not well understood. To fill in these research gaps, Takeuchi et al. (2017) conducted fire experiments using a 1:20 scale model tunnel with six vertical shafts and developed the model for predicting the longitudinal smoke-temperature distribution. However, their study did not examine the effects of the scale ratio and aspect ratio of the model tunnel on the temperature distribution or on the developed model. In the present study, we conducted fire experiments using a 1:10 scale model tunnel with an aspect ratio of unity and a 1:20 scale model tunnel with an aspect ratio of two. Furthermore, we improved the model for predicting the longitudinal smoke-temperature distribution proposed in the previous study (Takeuchi et al., 2017).

2. Experimental method

In this study, fire experiments using a 1:10 scale model tunnel with five vertical shafts (Tunnel A) and a 1:20 scale model tunnel with six vertical shafts (Tunnel B) were conducted. The aspect ratios of Tunnel A and Tunnel B were unity and two, respectively. We applied Froude's scaling law to the model tunnels. Table 1 lists the scaling correlations of Froude's scaling law (Ingason et al., 2015b).

2.1. 1:10 scale model tunnel (Tunnel A)

Fig. 1 shows schematic diagrams of the 1:10 scale model tunnel (Tunnel A). The tunnel height was H_t (= 0.5 m), the length was 24 H_t (= 12 m), the width was 1.0 H_t (= 0.5 m), and the aspect ratio of the tunnel cross section was unity. The model tunnel was made of