Fire Safety Journal xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Fire Safety Journal

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

Modeling for predicting the temperature distribution of smoke during a fire in an underground road tunnel with vertical shafts

Shota Takeuchi[a], Takayuki Aoki[a], Futoshi Tanaka[b,*], Khalid A.M. Moinuddin[c]

[a] *Graduate School of Engineering, University of Fukui, Fukui 910-8507, Japan*
[b] *Mechanical Engineering, Faculty of Engineering, University of Fukui, Fukui 910-8507, Japan*
[c] *Center for Environmental Safety and Risk Engineering, Victoria University, Victoria 3030, Australia*

ARTICLE INFO

Keywords:
Modeling
Tunnel fire
Natural ventilation
Vertical shaft
Fire experiments

ABSTRACT

In this study, fire experiments using a 1:20 model-scale tunnel were conducted to investigate the performance of natural ventilation in an underground road tunnel with six vertical shafts. The experimental parameters were the heat release rate of a fire source and the height of the shafts, and nine experiments were conducted in total. Furthermore, simple models were developed for predicting the temperature distribution of the smoke flowing under the tunnel ceiling. The following results were obtained: (1) In the experiments, the form of the smoke exhausted from the shaft became plug-holing when the shaft height was $1.0H_t$, and became boundary layer separation when the height was $0.24H_t$. (2) The average efficiency of heat exhaust was 0.16 when the form was plug-holing, and was 0.12 when the form was boundary layer separation. (3) When the form was plug-holing, the ratio of entrainment of fresh air became almost constant regardless of Ri. On the other hand, when the form was boundary layer separation, the ratio of entrainment of fresh air was smaller than that under the condition of plug-holing. (4) The temperature distribution under the tunnel ceiling predicted by the models agreed with that measured by the fire experiments in all cases.

1. Introduction

In the world's metropolises, highly developed road networks are suffering from increasing congestion. This problem could be effectively solved by constructing road tunnels. Therefore, road tunnels constructed in shallow underground space in urban areas have begun to attract attention, such as the Xianmen Road Tunnel in China and the Toranomon Tunnel in Japan. In this type of tunnel, the natural ventilation system with vertical shafts can be used to exhaust car fumes under normal conditions. Furthermore, in an emergency situation such as a fire caused by an automobile accident, the natural ventilation system exhausts the smoke, so it must provide sufficient exhaust performance to ensure safety in the tunnel. For this reason, researchers are studying natural ventilation systems. For example, Ji et al. [1] 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. Fan et al. [2] also conducted fire experiments using a 1:6 scale model tunnel with a vertical shaft to investigate the performance of natural ventilation when the form was plug-holing, and showed that about two-thirds of the smoke exhausting rate of the shaft was entrainment air. Moreover, numerical simulations have also been conducted to investigate the performance of natural ventilation. Fan et al. [3] conducted numerical simulations to study the influence of the number of shafts and the distance from the fire source to the shaft.

However, there are few studies in which the performance of a natural ventilation system with many shafts is investigated by fire experiments. In the present study, fire experiments using a 1:20 scale model tunnel with six vertical shafts were conducted to evaluate the smoke exhaust performance of a natural ventilation system with many vertical shafts. The purpose of this study was to clarify the usefulness of natural ventilation with many vertical shafts through fire experiments. Furthermore, simple models were developed to predict the temperature distribution under the tunnel ceiling. The models are helpful for understanding the performance of a natural ventilation system with vertical shafts. The theoretical results obtained by the simple models were compared with the experimental results to evaluate the models.

2. Experimental method

2.1. Experimental apparatus

Figs. 1 and 2 show schematic diagrams of the 1:20 scale model

---

[*] Corresponding author.
E-mail address: f-tanaka@u-fukui.ac.jp (F. Tanaka).

http://dx.doi.org/10.1016/j.firesaf.2017.03.063
Received 14 February 2017; Accepted 15 March 2017

Please cite this article as: Takeuchi, S., Fire Safety Journal (2017), http://dx.doi.org/10.1016/j.firesaf.2017.03.063

Nomenclature

A	cross sectional area (m^2)
C_p	specific heat (J/kg K)
d	thickness of smoke layer (m)
E	efficiency of heat exhaust
g	gravitational acceleration (m/s^2)
H	height (m)
h	heat transfer coefficient (W/m^2 K)
L	hydraulic diameter of tunnel (m)
$\dot{m}$	mass flow rate (kg/s)
Q	heat release/flow rate (W)
R	gas constant (J/kg K)
ΔT	rise in temperature (K)
u	smoke velocity (m/s)
W	width of tunnel (m)
x	distance from fire source (m)

Greek

ρ	density of smoke (kg/m^3)
$\Delta\rho$	density difference (kg/m^3)

subscripts

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

tunnel made of autoclaved lightweight aerated concrete (ALC) board. The tunnel height is H_t (H_t=0.25 m), the length is 20H_t, and the width is 2.0H_t. A propane gas burner 0.08 m in diameter was used as the fire source and was installed at 0.3 m from the left portal of the tunnel. A wire net was installed at the left-side tunnel portal to avoid inclining the fire source by reducing the fresh air sucked in from the portal. As a result, the smoke generated from the fire source flowed symmetrically. Six square-sided (0.07 m) shafts were installed on the ceiling at 0.75, 1.45, 2.15, 2.85, 3.55 and 4.25 m from the fire source, respectively. The six shafts (Shaft 1 to Shaft 6) were of two heights, 0.24H_t and 1.0H_t. The shafts were made of float glass plates to enable observation the smoke flow inside the shafts. K-type thermocouples made of chromel/alumel wire with a 0.1-mm diameter were installed along the centerline under the ceiling (at 5 mm from the surface of the tunnel ceiling) at 0.1-m intervals. The thermocouple bead diameter was about 0.25 mm, and its precision was ± 2.5 K. Furthermore, thermocouple trees were installed at 0.125 m toward the fire source from the center of each shaft. The tree height is 245 mm, and K-type thermocouples were installed at 40-mm intervals between 0 and 200 mm, and at 5-mm intervals between 200 and 245 mm. Fig. 3 shows the arrangement of the thermocouples on each tree. The thermocouples under the ceiling and the thermocouple trees measured the distributions of the smoke temperature in the horizontal and vertical directions. The average temperature for 10 min after preheating was measured in the experiments, and were used as the result. The sampling time of the thermocouple was 1 s. Part of the side wall of the model tunnel was made of acrylic board to enable observation of the flow of smoke inside the tunnel.

2.2. Experimental conditions

Table 1 lists the experimental conditions. The first column is the case number of the fire experiments; there were nine cases in total. The second column is the heat release rate of the fire source, and it was in the range of 1.5–4.4 kW. This study was the first step toward clarifying the performance of a natural ventilation system using many vertical shafts, so small HRRs were used. The heat release rate was calculated as the product of the mass flow rate of propane gas, the lower calorific value of propane gas, and the combustion efficiency. The mass flow rate of propane gas was directly measured in the fire experiments. The lower calorific value of propane gas, 46.0 MJ/kg, was used. The combustion efficiency was assumed to be 100% because oxygen was readily supplied through the tunnel portals. These heat release rates correspond to 2.7, 5.5 and 8.0 MW in a full-scale tunnel, respectively, as shown in the third column. The forth column shows the heights of the shafts (H_s). The fire experiments were conducted for two shaft heights, and also under the condition of no shaft by covering the openings with a square board made of ALC. The last column shows the preheating time. The experiments were conducted under steady-state conditions, so the model tunnel was preheated for the time listed in the last column.

3. Results and discussion

3.1. Form of the smoke exhausted from shafts

Ji et al. [1] showed that there are two types of form of the smoke exhausted from shafts, plug-holing (PH) and boundary layer separation (BLS), and these can be classified by the Richardson number, *Ri*. Fig. 4 shows schematic diagrams of forms of PH and BLS. According to the study, the form became BLS when *Ri* was less than 1.4, and became PH when *Ri* was greater than 1.4. The Richardson number is a dimensionless number and is defined as the ratio of buoyancy and inertia force of the smoke, and is given by:

$$Ri = \frac{\Delta\rho g H_s A_s}{\rho u^2 d W} \tag{1}$$

where $\Delta\rho$ [kg/m^3] is the density difference between the smoke and ambient air, g [m/s^2] is gravitational acceleration, H_s [m] is the height of the shaft, A_s [m^2] is the cross-sectional area of the shaft, ρ [kg/m^3] is the smoke density, u [m/s] is the smoke velocity, d [m] is the thickness of the smoke layer, and W [m] is the width of the model tunnel. In the

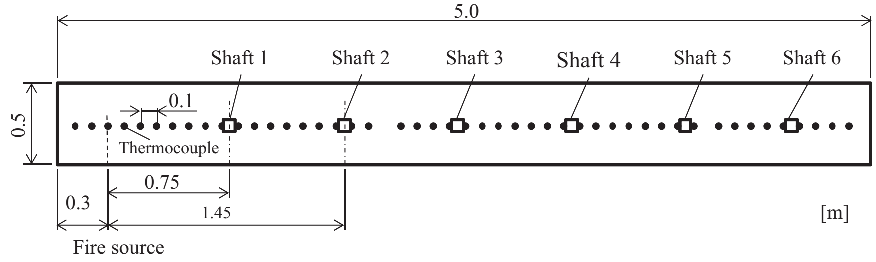

Fig. 1. Top view of the model tunnel.