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Investigation of the effect of tunnel ventilation on crib fires through small-scale experiments

X.Y. Wang*, M.J. Spearpoint, C.M. Fleischmann

Department of Civil and Natural Resources Engineering, University of Canterbury, New Zealand

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ABSTRACT

This paper adopts a series of 1:20 scale tunnel experiments based on a series of large-scale tunnel experiments to study the influence of forced ventilation on fires. The small-scale tunnel has dimensions of 0.365 m (W)×0.26 m (H)×11.9 m (L). Cribs using a wood-based material provide the fuel source and forced ventilation velocities from 0.23 to 1.90 m/s are used. From the study of the measured heat release rate (HRR) and mass loss rate data it is found that the forced air velocity affects the fire spread rate and burning efficiency and further affects peak HRR values at different air velocities. A simple model to describe these influences is proposed. This model is used to reproduce the enhancement of peak HRR for cribs with different porosity factors noted by Ingason [1] and to assess the effects of using different length of cribs on peak HRR. The results from these analyses suggest that different porosity fuels result different involvement of burning surface area and result different changes in peak HRR. However, no significant difference to the enhancement on fire size is found when the burning surface area is similar. It is also found that the trend in the enhancement on fire size by using sufficiently long crib and available ventilation conditions matches the predictions of Carvel and Beard [2] for two-lane tunnel heavy goods vehicle fires.

1. Introduction

The effect of longitudinal forced ventilation on heavy goods vehicle (HGV) fires in tunnels has been widely investigated through different approaches. The most direct approach is to use large-scale tunnel experiments, such as the Benelux tunnel test series [3], in which HGV mock-ups were simulated using wood pallets and three different ventilation velocities of ~0.5 m/s, between 4 and 6 m/s and 6 m/s were used to observe the influence on the fires. The obtained peak heat release rates (HRR) of 13.5 MW, 19 MW and 16.5 MW for the three different scenarios show changes in fire size when velocity is altered.

In the work of Carvel and Beard [2], a Bayesian probabilistic method has been applied to analyse data from the limited number of tunnel fire experiments then available in the literature. Their work quantified the influence of forced tunnel ventilation on the enhancement of the HRR. For example, they estimated that the HRR increases up to 2 times and 3 times respectively, compared to a corresponding natural ventilation scenario for a two-lane tunnel HGV fire when ventilation velocity is at 3 m/s and 10 m/s. Carvel and Beard's analysis also suggest there is a constant enhancement to the HRR when velocities are more than 6 m/s.

SP Technical Research Institute of Sweden has carried out several series of small-scale tunnel experiments to further explain the ventilation impact on tunnel fires. Initially, Ingason [1] used a 1:23 small-scale tunnel to study the influence of longitudinal ventilation on fires in which wood cribs were adopted to represent HGVs. Velocities of 0.42 m/s, 0.52 m/s ,0.62 m/s and 1.04 m/s (corresponding to large-scale velocities of 2 m/s, 2.5 m/s, 3 m/s and 5 m/s respectively) were used in the experiments. The maximum HRR was found to increase by a factor of 1.4–1.55 under forced ventilation conditions compared to natural ventilation conditions, and these findings are lower than what is obtained from the Carvel and Beard approach. Furthermore, Lönnermark and Ingason [4] conducted another series of small-scale tunnel experiments using different porosity wood cribs to represent HGVs in tunnels. Four ventilation scenarios (1 m/s, 2 m/s, 3 m/s and 5 m/s for the corresponding large-scale velocities) were investigated. They found that when different ventilation velocities were used then low porosity fuels showed greater changes in the maximum HRR than for high porosity fuels. Ingason [1] concluded that the reason for these differences when compared with Carvel and Beard's approach was due to fuel porosity.

Given the findings discussed above with regard to the influence of forced ventilation on the HRR, the topic is still open to further analysis. Since using small-scale experiments is a cost-effective method to obtain

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* Corresponding author.
E-mail address: xiaoyun.wang@pg.canterbury.ac.nz (X.Y. Wang).

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Nomenclature

b	thickness of stick (mm)
g	gravitational acceleration (m s^{-2})
k	conversion factor of fire size
l	length (m)
$\dot{m}$	mass burning rate (g s^{-1})
$\dot{m}''$	mass burning rate per unit area (g s^{-1} m^{-2})
t	time (s)
v	velocity (m s^{-1})
A	Area (m^2)
C	fuel property constant (g s^{-1} cm$^{-1.5}$)
Fr	Froude number
ΔH	heat of combustion (MJ kg^{-1})
m	mass (kg)
Q	energy (kJ or MJ)
$\dot{Q}$	heat release rate (kW)
P	porosity factor (mm)
T	temperature (K)

Greek symbols

γ	enhancement factor

Acronyms

HGV	heavy goods vehicle
HRR	heat release rate
MDF	medium density fireboard
MLR	mass loss rate

Subscripts

0	forced ventilation velocity at 0 m/s
be	burning efficiency
e	effective
fs	fire spread
fv	forced ventilation
nv	natural ventilation
p	peak value
v	velocity
s	surface area
L	large-scale
S	small-scale

quantitative results and to monitor fire behaviour this work adopts a ratio of 1:20 small-scale tunnel, which is scaled down from a recent large-scale tunnel HGV fire experiment, to conduct a series of experiments for the study of the impact of forced ventilation on fires. The 1:20 scaling ratio is different from the 1:23 adopted by Ingason [1], other work by Ingason and Li [5] showed that this ratio gives good agreements between small-scale and large-scale based on many applications. With consideration of the need to fit the experiment into the available laboratory space the 1:20 ratio is used in this work.

Cribs give consistent HRR results in fire experiments and there are many applications using wood cribs to represent fuels in tunnel experiments [1,4–6]. In this work cribs using a wood-based material have been used to represent fuel source and these have been subjected to forced ventilation velocities from 0.23 to 1.90 m/s (1.0–8.5 m/s for the corresponding large-scale velocity) in addition to a natural ventilation (i.e. no forced ventilation) condition. Details of the impact of forced ventilation on the tunnel fires, particularly the results on the peak fire HRR are presented and the reason for this impact is explained. The consistencies and differences between the results from this work and previous studies are also discussed.

2. Small-scale tunnel experiments

2.1. Scaling theory

In order to achieve the similarity between a small-scale tunnel and a large-scale tunnel, the Froude scaling [7] law is applied in this study. The Froude scaling law defines the dimensionless Froude number as the ratio of velocity to length as shown in Eq. (1):

$$Fr = \frac{v}{\sqrt{gl}} \tag{1}$$

Froude scaling has been widely used to conduct small-scale tunnel fire experiments [1,5,8]. When the Froude number in the small-scale tunnel is the same as the large-scale tunnel, the HRR, velocity, energy content, time and temperature can be scaled following Eqs. (2)–(6) [1]. However, similar to other small-scale tunnel experimental studies [1,5,8], the influence of thermal inertia of the material, turbulence intensity and radiation is not considered in this work.

Parameter	Scaling equations	
Heat release rate	$\dot{Q}_S/\dot{Q}_L = (l_S/l_L)^{5/2}$	(2)
Velocity	$v_S/v_L = (l_S/l_L)^{1/2}$	(3)
Energy	$Q_S/Q_L = (l_S/l_L)^3(\Delta H_L/\Delta H_S)$	(4)
Time	$t_S/t_L = (l_S/l_L)^{1/2}$	(5)
Temperature	$T_S/T_L = (l_S/l_L)^0$	(6)

2.2. Large-scale tunnel experiments

The small-scale tunnel experiments in this study are based on an experiment from a series of large-scale HGV tunnel fire experiments which were conducted on behalf of the Land Transport Authority of Singapore in a tunnel test facility. According to Cheong et al. [9], the tunnel facility was a two-lane road tunnel built in concrete and the section used for testing was in a rectangular shape with minimum dimensions of 7.3 m wide and 5.2 m high. The total length of the tunnel

Fig. 1. Full-scale tunnel experiment instrumentation locations with upstream (U) and downstream (D) distances in metres.