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Comparison of results from large-scale and small-scale tunnel experiments

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ABSTRACT

A series of 1:20 small-scale tunnel experiments have been carried out as a scaled down representation of a previously undertaken large-scale heavy goods vehicle (HGV) cargo load tunnel fire experiment. The small-scale tunnel has dimensions of 0.365 m (W) × 0.260 m (H) × 11.9 m (L) and a maximum forced ventilation velocity of 0.68 m/s is adopted corresponding to the velocity of 3 m/s used at large-scale. A gas burner and cribs constructed of medium density fireboard (MDF) have been used as the fuel sources with temperatures, heat release rate (HRR) and velocity data recorded in the small-scale tunnel experiments. A scaled down HRR curve derived from the large-scale experiment was reproduced by the gas burner. Temperatures in the small-scale gas burner experiment can effectively represent those at large-scale during the fire growth and decay stages although measurements at the fully developed stage are lower than the results from the large-scale tunnel experiment. In the small-scale tunnel experiments using the cribs time delays are applied to correct the recorded data in order to obtain the instantaneous HRR. Temperature profile comparisons between the small-scale crib and large-scale HGV cargo load experiments are not applicable since the HRR curves from the crib experiments only approximately reproduce the large-scale HRR profile.

Nomenclature

ΔH_c	heat of combustion (MJ/kg)	**Subscripts**	
l	length (m)	L	large-scale
Q	energy (kJ or MJ)	S	small-scale
$\dot{Q}$	heat release rate (kW)		
t	time (s)		
T	temperature (K)		
v	velocity (m/s)		

1. Introduction

Fires involving heavy goods vehicles (HGVs) in tunnels can have a major impact on the life safety of people and cause extensive damage to the structure as exemplified by the Mont Blanc tunnel incident [1]. Various large-scale road tunnel HGV fire experiments [2] have been carried out to obtain information on heat release rate (HRR), flame lengths, gas temperatures etc. and also to understand the influences of different factors such as the impact of forced ventilation and fire suppression systems. The information obtained from such large-scale tunnel experiments can represent the burning phenomena in an actual incident however they are usually expensive and time consuming. It is generally impractical to carry out large-scale experiments in order to carry out parametric studies of the burning behaviour of tunnel fires which can be used to assess the capability of numerical models, for example. Instead small-scale tunnel fire experiments have been used such as the studies on the influence of forced ventilation [3,4] and the effect of tunnel cross-section area [5]. The relatively low cost of doing small-scale tunnel experiments allows the flexibility to conduct more extensive experimental analyses and to also ensure a level of repeatability. However, it is important to evaluate whether the measurements from small-scale experiments can sufficiently represent the burning phenomena in a large-scale tunnel, thus, it is useful to compare the results obtained from corresponding sets of experiments.

In this work, a series of small-scale tunnel experiments are described which are a scaled down representation of a large-scale tunnel experiment which has been previously carried out by Cheong et al. [6]. In the small-scale experiments a gas burner and cribs have been adopted as the fuel source to represent the cargo load of a burning HGV that was simulated in the large-scale tunnel experiment. Both the gas burner and cribs were specifically configured to have a comparable energy profile to the large-scale experiment. In the burner experiments the flow of gas to the burner was controlled to produce a scaled HRR curve to match the results from the large-scale experiment. In order to assess the ability of the small-scale tunnel experiments to reproduce the results at the

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large-scale the temperature results are recorded from the gas burner experiment and are compared with the corresponding results from the large-scale tunnel experiment. Since the majority of the fuel source adopted in the large-scale tunnel experiments comprised of wood materials, the use of wood-based material in a crib arrangement as the fuel source in the small-scale tunnel experiments were also conducted to evaluate the influence of the ventilation on the fuel for further parametric studies at forced ventilation velocities other than that used in the large-scale experiment. In the experiments used in this work the crib geometrical form was scaled to the simulated cargo load in the large-scale experiment.

Measurements of HRR, temperature and velocity from the small-scale experiments are reported and discussions are carried out in terms of using the different fuel sources. The results presented in this paper are to be used in follow-up work to compare with numerical simulations at both small- and large-scale. This future work will model the burning of the cribs using material properties taken from Refs. [7,8] when subjected to the range of forced ventilation velocities the small-scale tunnel environment. The objective of the work presented in this paper has been to use the gas burner experiments to confirm the scaling is appropriate and the crib experiments to provide a relevant set of data to further comparison with planned modelling exercises.

2. Theory and experiment design

In order to achieve similarity between the small-scale and full-scale experiments, Froude number scaling is applied in this study, a technique that has been widely applied to conduct small-scale tunnel fire experiments [3–5]. Based on the Froude scaling theory, the HRR, velocity, energy content, time and temperature are scaled following Eq. 1 to Eq. 5, however thermal inertia, turbulence intensity and radiation cannot be scaled in this work.

Parameter	Scaling Eq.	
Heat release rate (kW)	$\frac{\dot{Q}_s}{\dot{Q}_L} = \left(\frac{l_s}{l_L}\right)^{5/2}$	(1)
Velocity (m/s)	$\frac{v_s}{v_L} = \left(\frac{l_s}{l_L}\right)^{1/2}$	(2)
Energy (kJ)	$\frac{Q_s}{Q_L} = \left(\frac{l_s}{l_L}\right)^{3}\left(\frac{\Delta H_{c,L}}{\Delta H_{c,S}}\right)$	(3)
Time (s)	$\frac{t_s}{t_L} = \left(\frac{l_s}{l_L}\right)^{1/2}$	(4)
Temperature (K)	$\frac{T_s}{T_L} = \left(\frac{l_s}{l_L}\right)^{0}$	(5)

2.1. Large-scale tunnel experiments

The small-scale tunnel experiments in this study are based on one experiment from a series of seven large-scale tunnel fire experiments conducted on behalf of the Land Transport Authority of Singapore in a tunnel test facility in Spain. The tunnel test facility represents a two lane road tunnel and was built of concrete in which the section used for the experiments was rectangular in shape with minimum dimensions of 7.3 m wide and 5.2 m high. The total length of the tunnel was 600 m and measurement points were located from 30 m away from the upstream edge of the fire to 170 m away from the downstream edge of the fire. An overall view of the tunnel section is shown in Fig. 1(a) together with the instrumentation locations. Temperatures were measured using thermocouples at the different cross-sections shown in Fig. 1(a) and gas concentrations of O_2, CO_2 and CO were measured at location D170. The cross-sections with the thermocouples at the D10, D15 and D30 locations are illustrated in Fig. 1(b). The detailed thermocouple arrangements for other cross-sections can be found in Cheong et al. [6].

In the LTA-sponsored large-scale experiment the fuel source consisted of wood and plastic pallets (arranged in 12 stacks and 19 layers) to represent the cargo of a fully loaded HGV (7.5 m (L) × 2 m (W) × 3 m (H)). The fuel source was raised 1 m above the tunnel floor on concrete supports. A target with two pallet stacks, which had the same height as the cargo load, was located 5 m downstream from the rear of the fuel source. Jet fans at one end of the tunnel were used to generate an average cold air velocity of 3 m/s along the centre-line of the tunnel for the entire duration of all of the experiments. Of the seven experiments, six were conducted using a deluge system and one experiment did not use the deluge system but a water spray was applied around 9 min (540 s) after ignition at the D45 location to cool down the tunnel structure. The temperature results at the D10, D15 and D30 locations were not influenced by the discharge of this water spray. In this study, only the experimental results without the operation of the deluge system is used as a comparison with the small-scale tunnel experiments.

The HRR curve from the large-scale experiment using data measured at the D170 location is shown in Fig. 2. The fire had a total energy release of 99.2 GJ, a peak HRR of 150 MW and a maximum steady-state HRR of the order of 120 MW. The target pallet stack ignited at 7 min 50 s (470 s) and also contributed to the overall recorded HRR in the experiment.

2.2. Small-scale tunnel geometry

The series of small-scale experiments described in this paper was conducted in the medium-scale fire laboratory at the University of Canterbury. The geometry of the small-scale tunnel was scaled down based on the tunnel section illustrated in Fig. 1. In order fit the small-scale tunnel into the laboratory a scaling ratio of 1:20 was adopted in this work, which is recommended by Ingason and Li [4] to minimise the turbulences in flows and flames caused by the scaling effect. The body of the small-scale tunnel was divided into nine separate sections. Each tunnel section had an inner dimension of 0.365 m (W) × 0.260 m (H) × 1.22 m (L) to give a total length of approximately 11.9 m. One section was used as the combustion chamber where the fire was located. The ceiling, floor and rear wall of the combustion chamber were made of 0.9 mm thick stainless steel 304, with a 15 mm thick insulation material (density: 336 kg/m^3, thermal conductivity: 0.07 W/m/K, specific heat: 1.08 J/g/K). Fire resistant glass (6 mm) was installed in the front of the combustion chamber. The remaining sections were constructed with the same stainless steel with 5 mm thick insulation blanket on the outer surface.

An electrical fan was attached to the upstream end of the tunnel with a section of half metre long flow straighteners to establish a uniform longitudinal ventilation system. In all of the experiments the fan was controlled to give a 0.68 m/s forced air velocity in cold flow conditions along the centre-line of the tunnel scaled from the large-scale tunnel experiment at 3 m/s using Eq. 2.

A vertical circular duct (300 mm in diameter and 1.3 m tall) was installed at the downstream end of tunnel. The duct was placed under the hood of a furniture calorimeter which was simply used to extract the flue gases. When the tunnel was assembled, all connections were sealed and insulated to reduce heat losses. Fig. 3 illustrates the geometry of the small-scale tunnel.

2.3. Fuel sources in the small-scale experiments

Medium density fireboard (MDF) was used to construct the crib fuel source. Since the material properties of MDF have been comprehensively investigated by Li et al. [7–9], the use of the MDF as fuel materials is convenient for further computer modelling purposes. The cribs were scaled to the profile of the large-scale HGV cargo load and configured to achieve the equivalent fuel load. Each crib was comprised of five layers with three 375 mm long-sticks, six 100 mm short-sticks equally spaced and the thickness of each stick of 15 mm. Applying Eq. (1) and (3) to the recorded total energy release and steady-state HRR shown in Fig. 2, the