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Effect of cross section and ventilation on heat release rates in tunnel fires

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A B S T R A C T

Model scale fire tests were performed in tunnels with varying tunnel widths and heights in order to study the effect of tunnel cross-section and ventilation velocity on the heat release rate (HRR) for both liquid pool fires and solid fuel fires. The results showed that for well ventilated heptane pool fires, the tunnel width nearly has no influence on the HRR whilst a lower tunnel height clearly increases the HRR. For well ventilated solid fuel fires, the HRR increases by approximately 25% relative to a free burn test but the HRR is not sensitive to either tunnel width, tunnel height or ventilation velocity. For solid fuel fires that were not well ventilated, the HRRs could be less than those in free burn laboratory tests. In the case of ventilation controlled fires the HRRs approximately lie at the same level as for cases with natural ventilation.

1. Introduction

In the light of recent catastrophic tunnel fires and results from large scale tunnel fire tests, much effort has been put into finding representative design fires for tunnel fire safety design. Such work usually includes the definition of different types of fire scenarios in different types of tunnels. The design fires may depends on tunnel geometry, type of transport through the tunnel, etc.

Tunnel geometry and ventilation condition can affect the fire development, making a tunnel fire different to an open fire or an enclosure fire. From the point of view of design fire, there are two key parameters that attract special attention, i.e. the maximum heat release rate (HRR) and the fire growth rate. Important findings of the fire growth rate in ventilated tunnel fires were reported by Li and Ingason (2011). They proposed a theoretical model of fire growth rate in tunnel fires, explored the relationship between the flame spread rate and the fire growth rate in a ventilated flow, and used a large amount of data relevant to the fire growth rate from model scale and full scale tunnel fire tests for validation. The study showed that for fully wind exposed fuels the fire growth rate increases linearly with the ventilation velocity. The thermal inertia, the heat of combustion, the wet perimeter, and the mass burning rate per unit area of the fuel play important roles in the fire growth rate (Li and Ingason, 2011). For fuels not directly exposed to wind, the enhancement effect of ventilation on fire growth rate is expected to be less. In case that the ignition source was on the downstream side of the fuel in a tunnel with forced ventilation, the fire may even grow more slowly than in a free burn test, see for example the car fire tests carried out by Lemaire and Kenyon (2006).

Another important parameter is the maximum HRR, which is the main topic of this paper. For vehicle fires in road tunnels, fixed design fire values can be found in different guidelines or standards for road tunnels, depending on type of the vehicle, e.g. NFPA 502 (2011) and PIARC (1999). These values are based on experimental data and consensus amongst members of technical committees working with these documents. Although it is known that the tunnel geometry and tunnel ventilation have influence on the maximum HRR, there has not been any consensus on this.

Carvel et al. (2004) performed an analysis of HRR enhancement in a tunnel fire compared to corresponding fire situation in the open. Results from a number of experimental test series published in the literature, including a wide range of cross sections from model scale ($0.09\ m^2$) to real scale ($80\ m^2$), were collected and analysed. Bayes' theorem concerning conditional probability was used to study which of the parameters, i.e., tunnel height, tunnel width, blockage ratio of the fire load and hydraulic diameter, had a significant influence on the HRR enhancement. The authors came to the conclusion that the tunnel width has a significant influence on the HRR and thus a fire will tend to have a higher HRR in a narrow tunnel. The analysis also showed that the tunnel height (or distance from fuel to ceiling) does not significantly affect the HRR enhancement. However, in most of the test series, the distance between the fire load and the ceiling was not varied and therefore the conclusion is questioned. This is one of the reasons

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Nomenclature

A	tunnel cross-sectional area (m^2)
A_f	fuel surface area (m^2)
H	tunnel height (m)
$\dot{m}_f$	fuel mass loss rate (kg/s)
Q	heat release rate (kW)
$\dot{q}''_{stoi}$	stoichiometric HRR for a specific longitudinal velocity (kW/m^2)
t	time (min)
u_o	longitudinal ventilation velocity at ambient conditions (m/s)
W	tunnel width (m)
W_f	fuel width (m)
x	distance from the fire site (m)
Greek	
ρ_o	air density at ambient conditions (kg/m^3)
ψ	HRR enhancement coefficient
Subscripts	
c	ceiling
f	fuel
freeburn	in a free-burn test
F	full scale
M	model scale
max	maximum value
stoi	stoichiometric
tunnel	in a tunnel fire

for performing the test series presented here. Moreover, in the work of Carvel et al. (2004), most of the fuels used to make comparisons were liquid and the fire size was limited. The solid fuel fires, which are more realistic fuel in tunnels, especially heavy goods vehicle (HGV) fires, were not considered fully. Tests with natural ventilation or forced ventilation at velocities less than 1 m/s were considered and the authors claimed that the tests were in the fuel controlled/radiation-dominant regime. However, for HGV fires, they may be under the ventilation controlled regime at a low velocity. In the memorial tunnel fire tests (Bendelius, 1996), two tests were carried out for natural ventilation, one involving a rectangular pool of about 9 m^2 and the other involving a combination of rectangular pools totalling 22 m^2. Based on the test data in the open, the HRR enhancement coefficient is slightly less than 1 for the smaller pool fire and 0.8 for the larger one. Therefore, as also stated by Carvel et al. (2004), there are insufficient experimental data available to support or deny the theory. The effect of geometry on the maximum HRR was also investigated by Lönnermark and Ingason (2007) using model scale tests and it was found that the dependency of the mass loss rate and the HRR on the tunnel dimensions differ, especially for pool fires. The results indicate that the influence of tunnel dimensions is not only a radiation effect, as often assumed, but is probably a combination of radiation from surfaces and hot gases, influence of air flow patterns, the shape and position of the flame and combustion zone, and temperature distribution. The analysis shows that as several factors and processes are interacting, it is important to know the starting conditions to be able to predict the effect of a change in a specific parameter.

Ingason and Li (2010, 2011) carried out model scale tunnel fire tests with both longitudinal ventilation and point extraction ventilation to investigate the effect of ventilation and tunnel geometry on the HRR. The fire sources used were wood cribs, corresponding to one or several HGV trailers. The results showed that for well ventilated fires, the maximum HRR in a tunnel is only 1.3–1.4 times that in the open. This is much lower than what was reported in earlier study by Carvel et al. (2004). One possible explanation was thought to be the way the fuel was compared. Ingason and Li (2011) also showed that when the tunnel is not well ventilated, the maximum HRR could depend on the ventilation flow, that is, the fire tends to be ventilation controlled under this circumstance. The data from these model scale tests were applied to predict the HRRs obtained from the large scale Runehamar tunnel fire tests, and the results showed that the predictions are very good which proves the good correlation between different scales of tests (Ingason et al., 2015). In other words, the full scale test data indicate that the velocity of around 2 m/s in the full scale tunnel increases the maximum HRR by a factor of 1.3–1.4. However, the tunnel aspect ratio (width/height) was in a range of 1.5–2.0. More test data covering a wider range of tunnel aspect ratio are required to validate the findings.

Kayili et al. (2011) carried out an experimental study on the effect of blockage ratio and ventilation velocity on the heat release rates from wood crib fires in a 1:13 model scale tunnel. Their results show that the heat release rate increases with ventilation velocity. However, it should be noticed that the wood crib used was of arbitrary shape and densely packed. The corresponding porosity is mainly in a range of 0.3 mm and 0.4 mm. It is known that when the crib porosity is less than about 0.7 mm, the mass burning rate starts to be influenced by the geometry of the porosity (Croce and Xin, 2005; Ingason, 2005; Ingason and Li, 2010). Therefore, the test data obtained cannot be used for fair comparison of the effect of ventilation on the heat release rate.

Lemaire and Kenyon (2006) presented results from large scale fire tests in the Second Benelux tunnel. The results showed that for car fires the maximum HRR with a ventilation velocity of 6 m/s is closely the same as that without ventilation (despite a long delay for 6 m/s), and for truck fires the maximum HRR is around 1.2–1.5 times that without ventilation. This correlates very well with Ingason and Li's test data (Ingason and Li, 2010, 2011). Note that in the car fire test 6 with no ventilation, the fire was extinguished at 25 min (Lemaire and Kenyon, 2006). Despite this, the HRR is not expected to increase further afterwards. One reason is that the car fire at around 10 min was fully developed and all parts were involved in combustion including the tyres. The HRR was kept at the level of 4 MW between 9 and 15 min. The HRR then decreased due to lack of fuel. In such cases, even the fire was not extinguished at 25 min the HRR is not expected to rise again to a level over 4 MW. In comparison, the HRR in test 7 was kept low before 37 min and rose to around 4.5 MW at 38 min. This could probably be due to the breakage of the backside windshield which allowed better access to oxygen. Another reason is that a comparison of the energy contents (area below the HRR curve) of these two tests indicates a low possibility of sharp HRR increase in test 6 after 25 min.

By analysing the test data of burning rates of pool fires obtained by Roh et al. (2007) in a 1:20 model scale tunnel, Li et al. (2012) found a linear correlation between the ventilation velocity and mass burning rate. However, it should be noticed that the heat release rates of these pool fires were in a range of 1.08 kW and 15.6 kW. This enhancement effect of wind on heat release rate was also reported by Hu et al. (2011). Note that it is well known that the burning of pool fires is highly dependent on the scales of the pool pans, see for example (Drysdale, 2011). Therefore this finding could not be applicable to large pool fires.

In this study, model scale fire tests with varying widths and heights to investigate the effect of tunnel cross section as well as