The Effect of Air Velocity on Heat Release Rate and Fire Development during Fires in Tunnels

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ABSTRACT

Model scale fire tests using wood cribs of different porosity in a ventilated tunnel are presented. The study focuses on the effect of air velocity on maximum Heat Release Rate (HRR) and fire growth rate. To study the influence of different parameters, free burn tests and fire tests inside a model-scale tunnel were performed. The tunnel was 10 m long, the widths used were 0.3 m, 0.45 m, and 0.6 m and the heights used were 0.25 m and 0.4 m. If compared to a normal traffic tunnel, these measures can correspond to a tunnel with a scale of 1:20.

The tests show that for a higher porosity wood crib and higher velocities than 0.45 m/s an increasing ventilation rate increases the maximum HRR in the range of 1.3 to 1.7 times the value measured outside the tunnel under ambient conditions. For the lower porosity wood crib and higher velocities, the corresponding increase in the maximum HRR was 1.8 and 2.0, respectively. When compared to ambient conditions inside the tunnel based mass loss rate, this increase was found lower. For all cases when the velocity was 0.22 m/s and the low ceiling height was used, the ratio was found to be lower than one. This was not the case when high ceiling height was used. For the case with a velocity of 0.67 m/s, the fire growth rate increased by a factor of 5–10 times the free burn case. The value depends on the dimensions of the tunnel cross section.

KEYWORDS: tunnel fires, heat release rate, ventilation, porosity, air velocity

NOMENCLATURE LISTING

A	cross-sectional area (m^2)	Δt	time period (s)
E	amount of energy developed per consumed kilogram of oxygen (MJ/kg),	X	mole fraction
H	tunnel height (m)	W	tunnel width (m)
K	defined by Eq. 2	**Greek**	
M	molar mass (kg/mol)	α	expansion factor
$\dot{m}$	air mass flow rate (kg/s)	ρ	density of air (kg/m^3)
$\dot{Q}$	heat release rate (HRR) (kW)	ζ	ratio between the average velocity and the maximum (central) velocity
T	temperature (K)	**subscripts**	
u	air velocity (m/s)	$_0$	ambient conditions
$\bar{u}$	average air velocity (m/s)	$_{fb}$	free burn
u_{max}	maximum centerline air velocity (m/s)	$_{nv}$	Natural ventilation inside tunnel
t	time (s)		

INTRODUCTION

The severity and outcome of a fire in a tunnel is very much dependent on what is burning and how fast the fire spreads. In the light of the recent catastrophic fires in tunnels and results from large scale fire tests during the past few years, much effort has been put into finding representative design fires for tunnel safety. Such work usually includes the definition of different types of fire scenarios. The situation inside a tunnel and selected fire scenario can depend on many different factors: tunnel length, tunnel location, traffic intensity, type of transport through the tunnel, etc.

When a fire scenario or a certain tunnel or traffic situation has been selected, an important part is then to determine what fire development (especially fire growth) and maximum heat release rate (HRR) can be assigned to the defined design fire. Such information can be based on conclusions from real fires or data

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from fire tests in tunnels [1]. For some cases, HRR data is only available from free burn tests, i.e. not from tests inside a tunnel. In other cases the available results corresponds to a ventilation situation different from the actual case. In such cases it is important to be able to convert the available results so that they are relevant for the corresponding situation inside a tunnel.

Using free burn results can lead to an underestimation of the HRR, since the fire growth rate, fire spread rate and the maximum HRR can increase in a tunnel, relative to free burn situation. This is thought to be mainly due to the increased radiation feedback from the flame volume and the hot smoke layer. This is a well known phenomenon from enclosure fires [2], but has also been seen in tunnel fire tests [3]. The effect of the tunnel itself on the burning rate and consequently the heat release rate has been studied by numerous researchers.

Ingason performed pool fire tests in a model scale tunnel, using heptane, methanol, and xylene as fuels [4, 5]. For heptane, the maximum increase of the burning rate due to the tunnel was by a factor of 3.3 (0.13 kg/s/m^2 (u = 1 m/s) compared to 0.04 kg/s/m^2 (free-burn)). Saito *et al.* [6] showed that the mass loss rate for liquid fires increased in a tunnel compared to free-burning conditions. The tests were performed with pool fires with methanol (0.1 m, 0.15 m, 0.2 m, and 0.25 m in diameter) and heptane (0.15 m in diameter). For the two smallest pools the effect of the tunnel (with an air velocity 0.08 m/s) on the mass loss rate of methanol was only a few percent, while for the 0.25 m diameter pool the mass loss rate in the tunnel was increased by a factor 2.7 compared to free-burning conditions. For heptane, the tunnel (with an air velocity of 0.43 m/s) increased the mass loss rate by approximately a factor 4. For both fuels the mass loss rate was significantly decreased with increasing air velocity. This illustrates the importance of the heat feed back from the flames, hot gases, and tunnel structure on the mass loss rate.

Carvel *et al.* performed an analysis of the HRR enhancement of a tunnel compared to corresponding fire situation in the open air [7]. Results from a number of different experimental test series published in the literature were studied. These test series included a wide range of cross-sectional areas: from model-scale (0.09 m^2) to real-scale (80 m^2).

Lönnermark and Ingason performed a test series in a model-scale tunnel (1:20) and studied the effect of the width and the height of a tunnel on the mass loss rate (MLR) and HRR [8]. They showed that the dependency of the MLR and the HRR on the tunnel dimensions are different from each other and that the effect of the height and the width of the tunnel on the MLR and HRR depends on the starting conditions. Here ventilation is an important factor.

Takeda and Akita studied the phenomenon of the effect of the tunnel and also showed that it is related to the ventilation factor [9]. They showed that the enhancement of the burning rate was associated with the dynamic balance between the rate of air supply and fuel gas supply. Others who have studied this phenomena are Carvel *et al.* who. in addition to the effect of the tunnel, have studied effect of the ventilation on the HRR from a fire in a tunnel [10, 11]. From a number of test series including tests with wood cribs and HGVs (heavy goods vehicles), they estimated that for a two-lane tunnel with an air flow velocity of 2 m/s the fire growth rate would increase with 3-4 times and the maximum HRR with 1.5 times compared to the natural ventilation case [11]. For a velocity of 10 m/s, the corresponding values were estimated to be 6 and 3, respectively.

Ingason showed with aid of model scale tests (1:23), using wood cribs similar to the one used in the present study, and which were well ventilated under normal conditions, that the maximum HRR is increased by a factor of 1.4 to 1.55 and the fire growth rate up to a factor of 3 [12]. This is lower than earlier studies by Carvel et. al. [10, 11, 13] on influences of ventilation on HGV fires. One should note that only ref. [11] refers to a case for a two lane tunnel; ref. [10, 13] refer to fires in a single lane tunnel. Ingason [12] concluded that one possible explanation why Carvel et al. exhibit such high increase in the maximum heat release rate is the way the fuel was compared. Fuel that is under-ventilated during ambient conditions was used in the comparison. If a fuel have a low porosity factor [14] an increase of the order as presented by Carvel et al. can be easily obtained. In the study by Ingason [12], the increase was related to free burn tests carried out outside the tunnel under normal atmospheric conditions. Inside the ventilated tunnel the ignition source was upstream the fire source but at the centre of the wood crib in the free burn tests in order to obtain maximum HRR involving the entire wood crib. The influence of the tunnel cross-section, type of fuel and wood crib porosity was not considered in Ingason study.

Since HGVs play such an important role for the outcome of fires in tunnel [15], the knowledge on the effect of the tunnel itself and of the air velocity inside the tunnel is important. One of the main problems when studying the effect of ventilation using different test series is that the conditions (tunnel dimension, starting ventilation conditions, etc.) vary between the test series. Therefore, a systematic study is one of the reasons for performing the test series presented in this paper. It is important to realise that several parameters affect the shape of the heat release curve, e.g. the type of fuel used to represent the scenario, the air velocity inside the tunnel, and the tunnel geometry. This study is a continuation of the work carried out by Ingason [12] and focuses on the effect of the air velocity, tunnel dimensions, and the porosity of the fuel on the maximum HRR and fire growth rate.

EXPERIMENTAL SET-UP

When using scale modelling it is important that the similarity between the full-scale situation and the scale model is well-defined. A complete similarity involves for example both gas flow conditions and the effect of material properties. The gas flow conditions can be described by a number of non-dimensional numbers, e.g. the Froude number, the Reynolds number, and the Richardson number. For a perfect scaling all of these numbers should be the same in the model-scale model as in the full-scale case. This is, however, in most cases not possible and it is often enough to focus on the Froude number: $Fr = u^2/(gL)$, where u is the velocity, g is the acceleration of gravity, and L is the length. This so called Froude scaling has been used in the present study, i.e. the Froude number alone has been used to scale the conditions from the large scale to the model scale and vice versa. Information about scaling theories can be obtained from for example references [6, 14, 16, 17].

To study the influence of different parameters on the fire development and size of a fire inside a tunnel, free burn tests and fire tests inside a model-scale tunnel were performed. The tunnel was 10 m long (see Figure 1). The width and height of the tunnel were varied during the test series. The widths used were 0.3 m, 0.45 m, and 0.6 m and the height was varied between 0.25 m and 0.4 m. If compared to a normal traffic tunnel, these measures can correspond to a tunnel with a scale of 1:20. The widths would then correspond to 6 m, 9 m and 12 m, while the heights correspond to 5 m and 8 m in real scale. The different cross sections used are presented in Figure 2. The ceiling, floor, and one of the walls were made of 15 mm thick PROMATECT®-H boards (thermal conductivity = 0.17 W/(m K) and heat capacity = 0.74 kJ/(kg K), both at 20 °C). One of the walls was comprised of 15 windows of 5 mm thick fire proof glass set in steel frames.

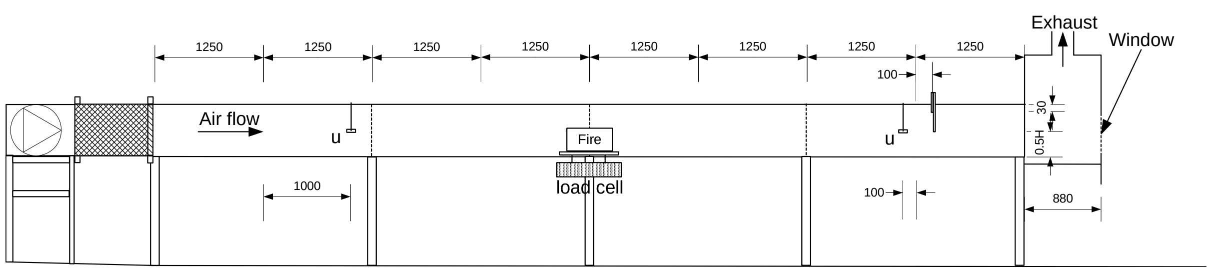


Fig. 1. Experimental set-up of the model-scale tunnel. Dimensions in mm.

In most of the tests a longitudinal flow was established inside the tunnel using a fan. The air velocity was varied between the tests. Mass loss of fuel, gas temperature, heat flux, gas velocity, and gas concentrations were measured during the tests. In the present paper, the focus is on the mass loss rate (MLR) and HRR. The other measurements and results from these are presented elsewhere [18, 19].

The MLR and HRR were determined for the different cases and were compared to the corresponding results from free burn tests under a hood calorimeter. The MLR inside the model tunnel was calculated from measurements collected from a digital balance that continuously measured the weight of the fuel, while the HRR was determined by collecting the smoke from the tunnel outlet and using oxygen calorimetry [20, 21]. The HRR can be calculated by using Eq. 1, according to formulas often used in fire tests [22]:

$$\dot{Q} = \frac{E \cdot \dot{m} \cdot \left(M_{O_2} / M_{air}\right) \cdot \left(1 - X^0_{H_2O}\right)}{\frac{\alpha - 1}{X^0_{O_2}} + \frac{1 - \left(X_{O_2} / \left(1 - X_{CO_2}\right)\right)}{X^0_{O_2} - \left(X_{O_2} \cdot \left(1 - X^0_{CO_2}\right) / \left(1 - X_{CO_2}\right)\right)}} \tag{1}$$

where E is the amount of energy developed per consumed kilogram of oxygen (13.1 MJ/kg was used for wood and 12.7 MJ/kg when calibrating with heptane), M is the molar mass, X is the mole fraction (the superscript 0 refers to ambient conditions), and α is expansion factor (the ratio between the number of moles of combustion products including nitrogen and the number of moles of reactants including nitrogen).The mass flow rate, $\dot{m}$, in Eq. 1 was calculated from the relation $\dot{m} = \zeta \cdot A \cdot u \cdot \rho_0 \cdot \left(T_0 / T\right)$ where $\zeta = \bar{u} / u_{max}$ is the ratio between the average velocity and the maximum (central) velocity in the tube. This was controlled to be 0.87. In the relation for the mass flow rate A is the cross-sectional area of the tube (m^2), u is the velocity (m/s), ρ_0 the density of air at ambient temperature (kg/m^3), T_0 the ambient temperature (K), and T the actual temperature (K). The uncertainty of the method to determine the HRR depends on the instruments and procedures used to determine the different parameters. An analysis has shown the uncertainty of a single measurement value for HRR to be in the order of 10 % [23].

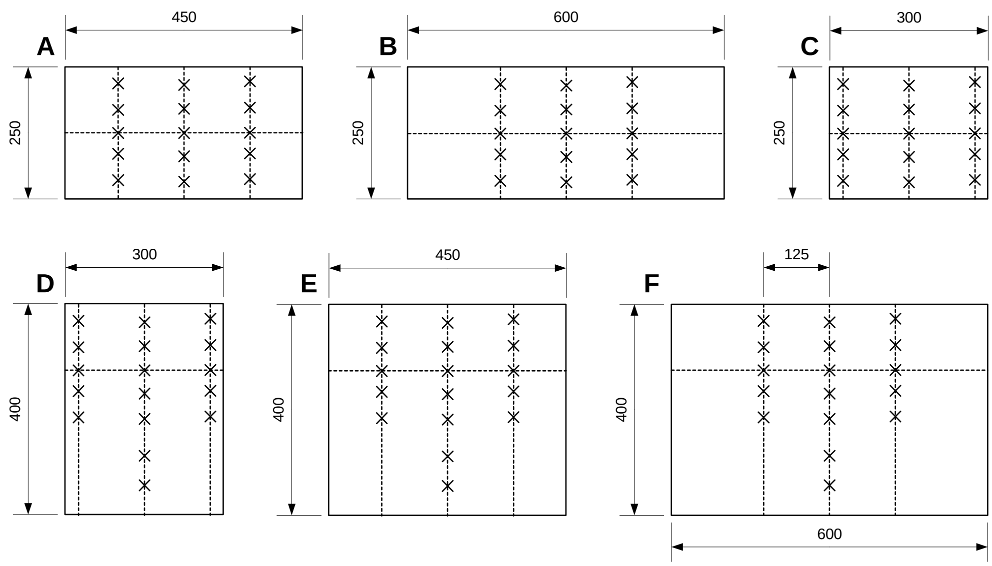


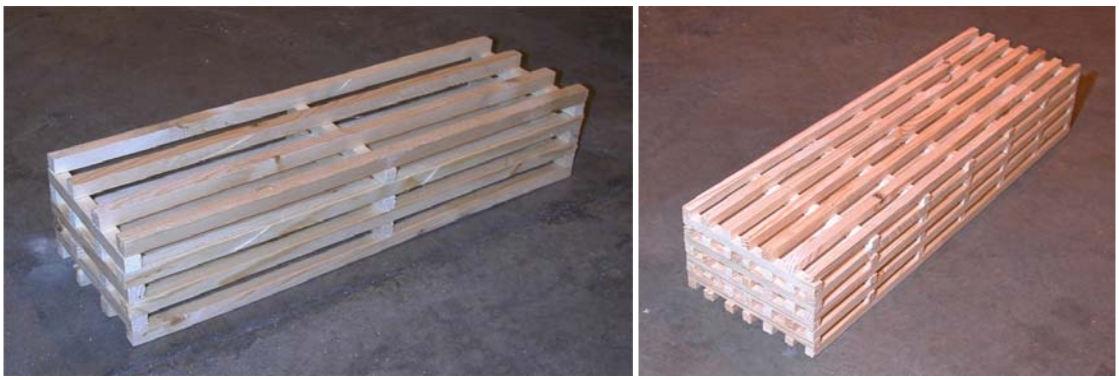
Fig. 2. The different cross sections (A to F) used during the test series. Dimensions in mm.

The fuel load was centred in the width and the length directions. This means that the fuel load was placed 5 m from the inlet and 5 m from the outlet of the tunnel. Two different types of wood cribs, with different porosity, were used as fuel.

The standard wood crib (P1) was constructed of four layers of long sticks (0.5 m) with four sticks in each layer and three layers of short sticks (0.15 m) with three sticks in each layer (see Figure 3). The porosity factor P for wood cribs was defined by Heskestad [14]. This porosity factor has been modified by Ingason [12]. The cross section of the sticks was 0.015 m × 0.015 m for both the long and the short sticks. This gave a total height for the wood crib of 0.105 m. The porosity (P1) of this wood crib was 2.1 mm [12, 18].

To study the effect of the porosity of the wood crib on the results (e.g. the effect of the ventilation on the heat release rate), tests with a wood crib, with a porosity (P2) differing from the standard wood crib, were performed. In this case the sides of the square cross section of the sticks were 0.010 m. The wood crib was constructed of five layers of long (0.5 m) sticks and four layers of short (0.15 m) sticks. For both long and short sticks there were seven sticks in each layer. This gave a total height of 0.09 m. The porosity of this wood crib (P2) was 0.62 mm.

The wood cribs were placed on four 0.05 m high piles with pieces of PROMATECT®-H standing on a 0.34 m × 0.55 m × 0.010 m PROMATECT®-H board connected by metals rods to the digital balance beneath the tunnel floor. The top of the board was 0.02 m above the floor. This means that the bottom of the wood crib was 0.07 m above the tunnel floor. In a few of the tests the height was varied so that the bottom of the wood crib instead was 0.20 m above the tunnel floor. In the test series also test with heptane and cribs with both wood and plastics were performed, but the details on and results from those tests are reported elsewhere [8, 18]



a) b)

Fig. 3. Wood cribs used as fuel: a) with porosity P1 and b) with porosity P2.

TEST PROCEDURE

The fuel was in all cases placed on the PROMATECT®-H board resting on the stands connected to the scales. In the tests with wood cribs, the ignition source was placed under the upstream end. This was done both in the tunnel tests and the free burn tests. The procedure was such that the dried PROMATECT®-H board, fuel, and ignition source were put into place before the air velocity in the tunnel was adjusted and registered. All measurements were started two minutes before ignition to register background conditions and to se that everything was running. The ignition sources consisted of pieces of fibre board (3 cm × 3 cm × 2.4 cm) soaked with 9 mL heptane and wrapped in a piece of polyethene.

The fuel was weighted in advance and let burn out in order to control the accuracy of the HRR measurements by integrating the curve. The accuracy was found to be very good for the test series. During the test series the type of fuel, porosity of the fuel, the height of the tunnel, the width of the tunnel, and the height between the floor of the tunnel and the fuel were varied. In Table 1 the details on selected tests in the test series and how the mentioned parameters were varied are presented.

Four different air velocities in the tunnel were used: 0.22 m/s, 0.45 m/s, 9.67 m/s, and 1.12 m/s. This corresponds to 1 m/s, 2 m/s, 3 m/s, and 5 m/s, respectively, according to scaling laws [18]. A fifth ventilation condition with no forced ventilation was also used. In this case the fan and the mixing box on the “upstream” side and the exhaust duct on the “downstream” side were disconnected. The consequence of this was that it was not possible to measure the HRR based on oxygen calorimetry. The only parameter that could be related to the fire development during the test was the mass loss rate measurements.

RESULTS

Most of the tests were performed in a tunnel with the width 0.45 m and height 0.25 m. The HRR results for the tests in this tunnel are presented in Fig. 4. There are two apparent groups of curves in each figure. For both porosities, the HRR for the highest velocities (0.45 m/s, 0.67 m/s, and 1.12 m/s) increase rapidly to a high level. The HRR curves for the cases with lower velocity (0.22 m/s) have a different shape: slower increase and a lower, not so sharp peak. The free burn HRR curve is more similar to the group of lower velocity.

Table 1. Description of conditions for the tests reported.

Test no	Porosity	*u* [m/s]	*H* (m)	*W* (m)
11	P1	n.v.	0.25	0.45
3	P1	0.22	0.25	0.45
4	P1	0.45	0.25	0.45
9	P1	0.67	0.25	0.45
5	P1	1.12	0.25	0.45
8	P2	0.22	0.25	0.45
6	P2	0.67	0.25	0.45
7	P2	1.12	0.25	0.45
13	P1	0.22	0.25	0.60
12	P1	0.67	0.25	0.60
17	P1	0.22	0.25	0.30
16	P1	0.67	0.25	0.30
21	P1	0.22	0.40	0.30
20	P1	0.67	0.40	0.30
25	P1	0.22	0.40	0.45
23	P1	0.67	0.40	0.45
26[a)]	P1	0.67	0.40	0.45
36	P1	f.b.	-	-
38	P2	f.b.	-	-

n.v. = natural ventilation (inside the tunnel)
f.b. = free burning (outside the tunnel)

The test with natural ventilation is not included since no HRR was measured. Instead the mass loss rate can be used to study how the burning behavior is affected by the variation in velocity. In Fig. 5 mass loss rate curves corresponding to different ventilation conditions are presented. One can see that the MLR curves have the same shapes as the HRR curves. However, the difference between the case with 0.22 m/s and the free burn case is larger in the MLR than in the HRR. The MLR for the case with natural ventilation develops more slowly but reaches a higher maximum value than MLR for the test with the velocity 0.22 m/s.

In Fig. 6 HRR curves for wood cribs with the porosity P1 and P2 are compared for two different velocities. The tests were performed in a tunnel with the width 0.45 m and a height of 0.25 m. Again, the HRR for the cases with a velocity of 0.22 m/s is significantly lower than the HRR for the higher velocity (0.67 m/s). There is, however, a difference between the two porosities. The maximum HRR at 0.22 m/s is for P2 lower than the corresponding for P1, but at 0.67 m/s the maximum HRR for P2 is significantly higher than the corresponding for P1. The total area of exposed fuel surface, A_s, for P1 is 0.54 m^2 and 0.8 m^2 for P2. Therefore, when both P1 and P2 are in a well ventilated flow we should expect differences in the maximum HRR.

According to Ingason [12] for a wood crib similar in shape and size, the maximum HRR was in average for all tests 155 kW per exposed fuel surface area (kW/m^2) This means that we could expect a maximum of 84 kW for P1 and 124 kW for P2. These values are very close to the one measured here for P1 and P2 under well ventilated conditions inside the tunnel (see Fig. 4). The reason why P1 and P2 do not show higher peak HRR in a free-burn and natural ventilation is mainly due to the fact that the fire did not engulf the entire wood crib during the test at one time, i.e. it spreads much slower across the wood crib compared to when the higher ventilation was used. Further, when P2 is burning under ambient conditions or low velocity conditions, the influence of the porosity reduces additionally the maximum value due to lower access of oxygen to the core of the wood crib. When the forced ventilation is activated the relative increase in maximum HRR will be higher for P2 compared to P1.

So far the time resolved curves have been presented. If a certain time or time period for each test is selected, the differences between the different cases can be quantified. In Fig. 7 the ratio between the maximum HRR for the test with wood cribs (P1) inside the tunnel and the maximum HRR for the free burning test is presented as function of the air velocity. The test data from Ingason [12], which is approximately P1 crib, is plotted as well for comparison since it was very similar conditions. Also the P2 data is shown in order to show the difference in increase for P1 and P2 wood crib. There is a slight increase in maximum HRR with increasing velocity for a P1 crib. The ratio between the HRRmax inside the tunnel and the free burn maximum seems to level off at a level somewhat higher the 1.5 for velocities equal to or higher than 0.67 m/s. Largest spread in the results is it for the velocity 0.22 m/s where the ratio actually is lower than one for three of the tunnel cross section. All these three tests were performed in the tunnel with the lower height, 0.25 m. Note that the comparisons here are made to the free-burning case, while many reported comparisons are made to a case with natural ventilation. A comparison between the maximum MLR to the natural ventilation case is presented below. The agreement of P1crib with the test data from Ingason [12] is good.

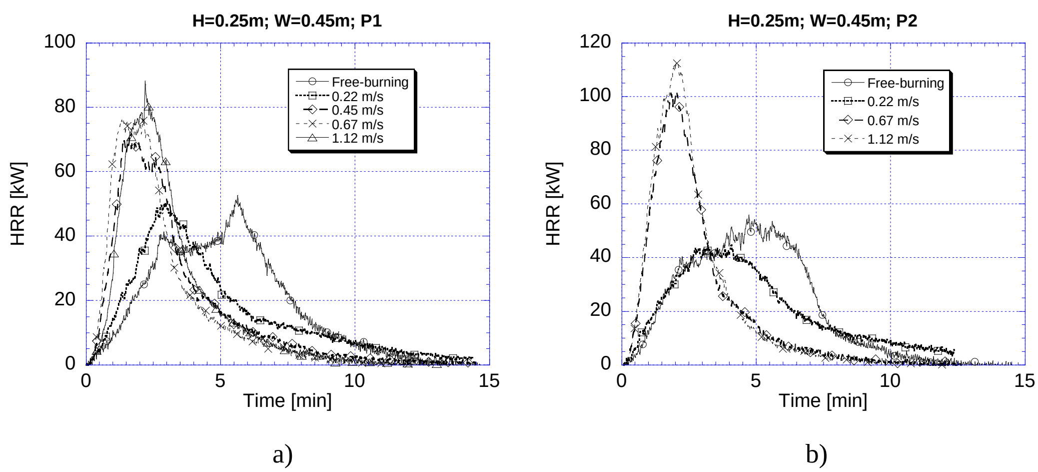


Fig. 4. Heat release rate curves for the tests in the tunnel with the width 0.45 m and height 0.25 m. The fuel was wood cribs with the porosity a) P1 and b) P2, respectively.

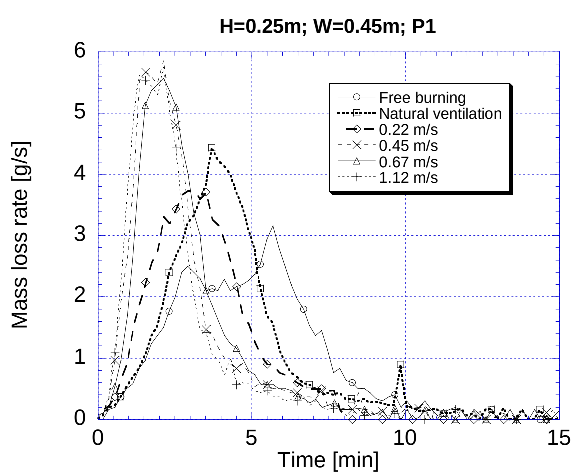


Fig. 5 Comparison of mass loss rates for different ventilation conditions inside the tunnel with a width of 0.45 m and a height of 0.25 m. A wood crib with the porosity 2.1 mm (P1) was used as fuel.

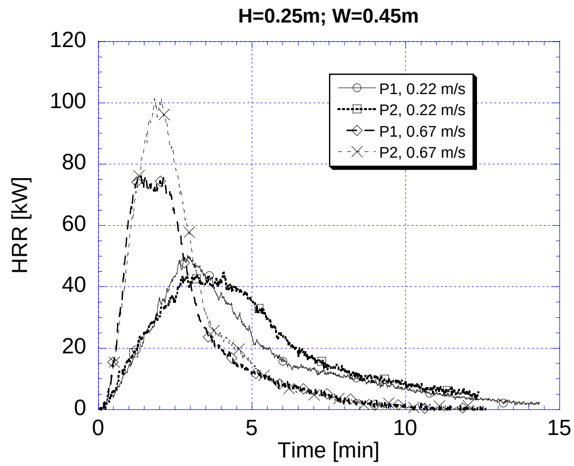


Fig. 6. Comparison of HRR for porosity P1 and P2 for two velocities. The tests were performed in a tunnel with the width 0.45 m and a height of 0.25 m.

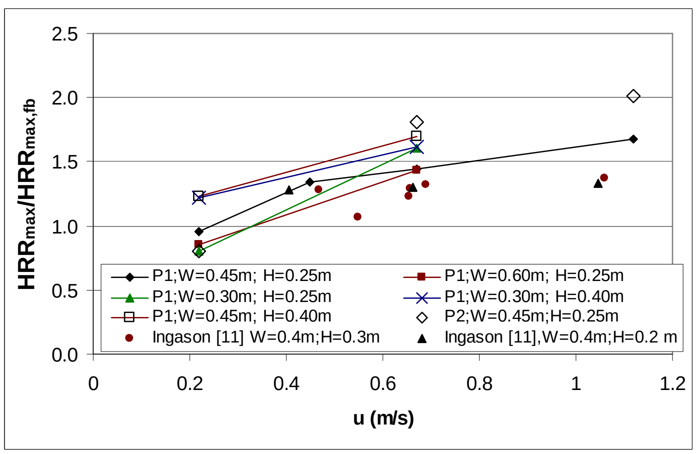


Fig. 7. Maximum HRR as function of velocity for different tunnel cross sections, compared to the free burn case.

As can be seen in Fig. 7, the relative increase of HRR for P2 is higher than for P1 at corresponding conditions. For the low velocity (0.22 m/s) the ratio was lower than one or 0.8 and for the higher velocities (0.67 m/s or higher) it was 1.8 and 2.0, respectively. This shows that it is important to have in mind the porosity of the fuel when comparing the ambient fuel set-up with a fuel in a forced ventilation flow.

Even if the maximum HRR often is used to represent design fires, the fire growth rate can in most cases be at least as interesting and important. The fire growth rate can be represented by different values depending on definition, e.g. by the time to maximum HRR. In Table 2 the result for this parameter is presented. The fire growth rate can be defined as:

$$K = \frac{\dot{Q}}{\Delta t} \qquad (2)$$

Table 2. Fire growth rate, calculated for three different time periods: 0 – time for HRRmax (K_1), 10 % to 90 % of HRRmax (K_2), and 0 to 63.2 % of HRRmax (K_3).

Test no	***P***	***u* [m/s]**	**$K_1/K_{1,fb}$ (kW/min)**	**$K_2/K_{2,fb}$ (kW/min)**	**$K_3/K_{3,fb}$ (kW/min)**
11	P1	n.v.	-	-	-
3	P1	0.22	1.85	2.27	1.31
4	P1	0.45	4.65	7.27	3.38
9	P1	0.67	5.85	9.42	4.45
5	P1	1.12	4.30	5.14	3.36
8	P2	0.22	0.92	1.24	0.99
6	P2	0.67	4.20	5.09	3.34
7	P2	1.12	4.69	5.16	3.65
13	P1	0.22	1.39	2.24	1.19
12	P1	0.67	6.04	8.37	3.73
17	P1	0.22	1.71	1.86	1.21
16	P1	0.67	4.05	5.26	4.88
21	P1	0.22	3.17	3.60	2.84
20	P1	0.67	3.61	7.77	3.90
25	P1	0.22	2.71	3.03	1.93
23	P1	0.67	7.00	10.47	4.48
26[a)]	P1	0.67	3.42	5.25	3.27
36	P1	f.b.	1	1	1
38	P2	f.b.	1	1	1

n.v. = natural ventilation (inside the tunnel)
f.b. = free burning (outside the tunnel)

The value of k depends on the selection of Δt. This is shown in Table 2, where three different time periods have been used: time corresponding to ignition to time for maximum HRR (K_1), time corresponding to 10 % and 90 %, respectively, of the maximum HRR (K_2) and time corresponding to 0 to 63.2 % (=1-1/e) of the maximum HRR (K_3). As can be seen in the table, there are large differences between the different ways of calculating the fire growth rate. However, the trends when comparing different tests are the same for the three groups. Ingason [12] calculated the fire growth rate as the difference between 100 kW and 20 kW divided by corresponding time difference in minutes. Here, the K_2 represents a similar way of calculating the fire growth and therefore we have compared the present data with Ingason data. The results are shown graphically in Fig. 8 (for K_2) where $K_{2,fb}$ obtained in the present study have been used to calculate Ingason data. The reason is that Ingason [12] did not have a free burn test with a crib ignited at one end. As can be seen in Table 2, the ratio between the maximum and minimum values are the same for the two different growth rates, but the values are generally higher for $K_2/K_{2,fb}$. Furthermore, the order and slope of the curves for the different cross sections vary. For both cases the increase factor of the growth rate for the highest velocity (1.12 m/s) is lower than several of the cases with lower velocities. The main explanation for this might be the different shape of the HRR curve near the HRR peak compared to the other tests. If the fire growth rate is calculated between 10 % and 80 % (instead of 90 %) of the maximum HRR, the factor for the 1.12 m/s case becomes 7.7 (compared to 5.1). Again, this shows the effect of how the fire growth rate is defined.

Since no HRR was available for the case of natural ventilation, the comparisons above were made to the free burn case. However, comparison to the natural ventilation case (test with no ventilation inside the tunnel) can be made for the MLR. In Fig. 9 the ratio of the maximum MLR with forced ventilation and the maximum MLR with natural ventilation are presented for different ventilation velocities. As for the HRR, there is an increase with the velocity up to a certain velocity level after which it seems to become almost constant. The increase factor values for MLR seems to be somewhat lower than the corresponding values presented for HRR in Fig. 7. One should, however, remember that the normalization is made to different test conditions: to free burn conditions for HRR and to natural ventilation conditions inside a tunnel for MLR. The ratio between the maximum MLR for natural ventilation inside the model tunnel and the maximum MLR for free burn conditions is between 1.3 and 1.4 and if this factor is multiplied to the results in Fig. 9 the curves are raised to a level closer to the one for HRR.

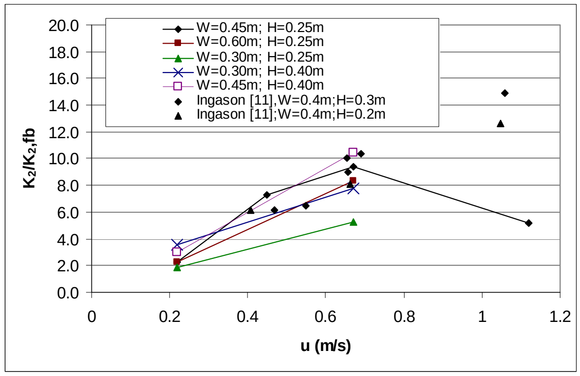


Fig. 8. Fire growth rate calculated for 10 % to 90 % of HRRmax (K_2), presented as function of the air velocity.

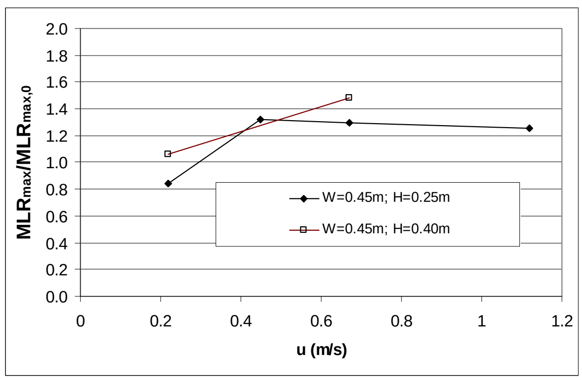


Fig. 9. Maximum MLR as function of velocity for different tunnel cross sections, compared to the cases with natural ventilation.

DISCUSSION

The results presented in this paper show that there is an effect of the ventilation both on the maximum HRR and on the fire growth rate. The results on maximum HRR and on fire growth rate of P1 correspond very well to the data presented by Ingason [12]. Further, the results in this paper show that the effect of the velocity on the increase factor depends on the tunnel dimensions and the conditions inside the tunnel. The height and the width of the tunnel influence the results. However, how much the fire growth results are affected by the dimensions also seems to depend on how the fire growth rate is calculated, i.e. time periods or intervals are used.

The effect of initial conditions of the fuel and the tunnel flow is also illustrated by the HRR ratio between the lowest velocity and the cases with higher velocity. For the case with the lowest velocity (0.22 m/s), the fire develops more slowly and reaches a lower maximum value compared to the cases with higher velocities. Almost all cases with the velocity 0.22 m/s (corresponding to a velocity of 1 m/s in real scale) became somewhat under-ventilated at the time of the highest mass loss rate. This is important to keep in mind since this can also be the case for real tunnels. This can significantly affect the effect of the velocity on the increase factors.

Not only the local ventilation conditions are important, but also other factors as for example geometry of the tunnel, type of fuel, and the position and extension of the flame. This has been discussed in previous papers on the effect of the tunnel dimensions on the burning characteristics [8, 24]. Also the geometry of fuel, here represented by the porosity, is important. The wood crib with the lower porosity (P2) was more affected by the velocity than was the wood crib with the higher velocity (P1).

It is also interesting to note that the increase factor, both for the maximum HRR and for the fire growth rate, seems to reach a constant value or at least increase more slowly when reaching above a certain velocity.

The tests were performed in a model-scale tunnel and one should be aware of that not all parameters, e.g. radiation, scale perfectly when transforming the results into real scale. However, experience from previous test series in model scale has shown that this kind of test series can be very valuable for studying different phenomena, processes and parameter variations.

CONCLUSIONS

An essential aim of this study was to investigate the influence of the ventilation rate on the maximum heat release rate and the fire growth rate for wood crib. An important aspect was to study it for fuels that are comparable from a porosity point of view. It was found that an increasing ventilation rate increases the maximum HRR. The increase in the maximum HRR of the P1 crib is in the range of 1.3 to 1.7 times the value measured outside the tunnel under ambient conditions and for wind velocities equal or higher than 0.45 m/s. When compared to ambient conditions inside the tunnel based mass loss rate, this increase is lower. For all cases when the velocity was 0.22 m/s and the low ceiling height was used, the ratio was found to be lower than one. This was not the case when high ceiling height was used. For the case with a velocity of 0.67 m/s, the fire growth rate increased by a factor of 5–10 times the free burn case, the value depending on the dimensions of the tunnel cross section. The increase in the maximum HRR of P2 was 1.8 and 2.0, respectively, for the higher velocities.

Above a certain air velocity, the ratio for HRR does not seem to vary significantly with the velocity. In general we can say that this ratio is highly dependent on the starting conditions of the fuel, i.e. its porosity, the velocity, the ceiling height etc. Especially if the wood crib is under-ventilated under ambient conditions, we can expect very high changes in the maximum HRR when the ventilation conditions are changed. The influence of velocity on the fire growth rate is much higher than on the maximum HRR. As the fire growth rate is one of the most important design parameters for tunnel safety these results are considered as important.

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