Effects of longitudinal ventilation on fire growth and maximum heat release rate

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ABSTRACT

An analysis, based on two different series of model scale tests, of the effects of ventilation on maximum heat release rate and fire growth rates is presented. In both model scale test series, wood cribs of different porosity, size and numbers were used. Both ambient free burn tests and tests inside a model-scale tunnel were performed. The tunnels varied from 0.3 m to 0.6 m in width and from 0.2 m to 0.4 m in height. The longitudinal velocity varied between 0.22 m/s and 1.12 m/s.

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 heat release rate 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 heat release rates was 1.8 and 2.2, respectively. For the case with a velocity of 0.67 m/s, the linear fire growth rate increased by a factor of 5–10 times compared to the free burn case, depending on the dimensions of the tunnel cross-section.

KEYWORDS: Model scale tunnel, longitudinal ventilation, fire growth rate, heat release rate, wood crib, liquid fire

INTRODUCTION

A common feature in all large tunnel fire incidents has been the significance of ventilation on the growth rate and size of the fire. In several of the fires, the type of load being carried by goods vehicles played an important part in determining the severity of the fire. The main reasons for this are that heavy goods vehicles (HGVs) consist of, or carry, highly flammable materials, and that the fire spreads very rapidly due to the longitudinal ventilation in the tunnel.

The effect of longitudinal ventilation on the fire development in HGV fires is an important design issue and depends on the fuel geometry and the outer protection of the fuel. The interaction between the ventilation flow and the heat release rate (HRR) was investigated by Carvel et al. [1-4]. Their results were probabilistic in nature. From a number of test series including tests with wood cribs and HGVs, they estimated that for a two-lane tunnel with an air flow velocity of 2 m/s the fire growth rate would increase by 3-4 times and the maximum HRR by 1.5 times compared to the natural ventilation case [4]. For a velocity of 10 m/s, the corresponding values were estimated to be 6 and 3, respectively. A Bayesian probabilistic approach was used to refine estimates, using a panel of experts, with data from experimental fire tests in tunnels. Their conclusions were, however, based on rather limited experimental data.

Since HGVs play such an important role for the outcome of fires in tunnel, knowledge of 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 dimensions, fuel porosity, starting ventilation conditions, etc.) vary between the tests. An understanding of the
main mechanism of the effects of the ventilation on burning solid fuel is, therefore, of great interest for tunnel designers. Model-scale results, in combination with large-scale tests, provide new data to investigate the effects of longitudinal ventilation on maximum heat release rates and fire growth rates for solid materials in tunnels.

EARLIER STUDIES

Ingason [5] showed that when using wood cribs in model scale tests (1:23), the maximum heat release rate is increased by a factor of 1.4 to 1.55 compared to ambient conditions and the fire growth rate up to a factor of 3, as an effect of the ventilation. Above a certain air velocity, the maximum heat release rate does not seem to vary significantly with the velocity. Lönnemark and Ingason [6] found that the increase in the maximum heat release rate of a crib with high porosity was in the range of 1.3 to 1.7 times the value measured outside the tunnel under ambient conditions and for a given wind velocity. The increase in the maximum heat release rate of a wood crib with low porosity was between 1.8 and 2.0, respectively, for the higher velocities. This is lower than earlier studies by Carvel et al. [4] on the influence of ventilation on maximum heat release rate of HGV fires, but in line with their results on increase in fire growth rates.

Lönnemark and Ingason [6] concluded that the maximum heat release rate is highly dependent on the starting conditions of the fuel, i.e. its porosity, the ventilation velocity, the ceiling height of the tunnel etc. In particular when the wood crib is under-ventilated under ambient conditions, very high changes in the maximum heat release rate can be expected when the ventilation conditions are altered. The influence of velocity on the fire growth rate was found to be much higher than on the maximum heat release rate. The fire growth rate increased by a factor of 5–10 times compared to the free burn case [6].

There are few large scale tests series available where the effects of the longitudinal flow can be estimated. For example in the case of the Benelux tunnel test series [7], three tests consisting of 36 standardized wood pallets (9 in each stack), were performed with different longitudinal velocities (~0.5 m/s (natural ventilation), 4-6 m/s and 6 m/s) and one test with 72 wood pallets and a longitudinal velocity of 1-2 m/s. The outer dimensions of the 36 wood pallet fire load were 4.5 m long, 2.4 m wide, and 2.5 m high. The peak heat release rate was 13.5 MW without forced ventilation, 19 MW with 4-6 m/s ventilation and 16.5 MW with 6 m/s ventilation. The tests with the 36 wood pallet fire load show that the fire growth rate with ventilation was approximately 4 to 6 times faster than the fire growth rate without forced ventilation while the peak heat releaser rate was 1.4 and 1.2 times higher, respectively. The fire growth rate with 72 wood pallets was about 1.9 times faster than the 36 wood pallet fire load with no forced ventilation.

One of aims of this study is to try to explain the mechanism of ventilation impact on the fire growth rate and maximum heat release rates of wood cribs. One explanation given by Ingason [5] concerning why Carvel et al. exhibit such a large increase in the maximum heat release rate, was based on the way the fuel was compared. Fuel that is under-ventilated (low porosity) during ambient conditions was used in the comparison. If a fuel has a low porosity factor an increase of the order as presented by Carvel et al. can be easily obtained. In order to investigate this further a study given by Harmathy [8] and some of the work carried out on wood cribs for about 30 – 40 years ago has been investigated. The scaling effects from wood cribs to a fuel load in large scale may be difficult to interpret but the quantitative results indicate the order of magnitude of the changes and explain the behaviour.

WOOD CRIB POROSITY AND VENTILATION

The wood cribs used in the model-scale tests are shown in Figure 1. The wood cribs were long relative to their height and width, which traditionally is not the case. Usually the wood cribs have two sides equal in length whereas the height may vary.
Figure 1  Wood cribs used as fuel: a) with high porosity (P=2.1 mm) and b) with low porosity (P=0.62 mm) [9].

The exposed fuel surface area of the wood cribs and the porosity used in the model scale tests varied. A correlation between the reduced free burning rate versus crib porosity for square wood cribs (same length and thickness of all wood sticks but different number of sticks and layers) burning under quiescent atmospheric conditions has been presented by numerous authors [10-13]. In Figure 2, a plot of the data given on Sugar Pine wood cribs by Croce and Xin [13] together with a curve fit of the data is shown. This shows the correlation between reduced free-burning rate \( \left( \frac{m_f \times 10^3}{A_f \cdot b^{-1/2}} \right) \) versus the crib porosity, \( P \), given in [13]. The mass burning rate, \( m_f \), is used here instead of \( R_f \) as defined by Croce and Xin. The crib porosity in the abscissa is defined as in reference [12], i.e.:

\[ P = \frac{A_v}{A_s} s^{1/2} b^{1/2} \]  

where \( A_v \) is the total cross-sectional area of vertical crib shafts \((l - nb)^2\), \( A_s \) is the exposed surface area of crib \( 4blNn \left( 1 - \frac{b}{2l} \right) (n - 1 - \frac{n}{N}) \). Here \( b \) is the stick thickness (same width and height), \( l \) is the stick length, \( n \) is the number of sticks per layer and \( N \) is the number of layers [13].

Figure 2  Reduced free-burning rate versus crib porosity \( P \) [13].

As can be seen in Figure 2, when the crib porosity \( P \) is less than about 0.7 mm, the reduced mass burning
rate, \( m_f \times 10^3 / A_f \cdot b^{-1/2} \), starts to be influenced by the geometry (porosity) of the wood cribs. The fire becomes more and more dependent on the wood stick spacing and the wood crib fire is said to be under-ventilated or ventilation controlled. When the crib porosity is larger than about 0.7 mm, the wood crib fire is well-ventilated. A curve fit of the data given by Croce and Xin [13] gives the following equation (linear regression coefficient R=0.913):

\[
m_f \times 10^3 / (A_f \cdot b^{-1/2}) = 1.11 \cdot \left(1 - e^{-6.28 \cdot P}\right)
\]

This equation can be rewritten in order to calculate the burning rate per square metre exposed fuel surface area, which is of interest for this study, i.e.:

\[
m''_f = \frac{m_f}{A_s} = 1.11 \times 10^{-3} b^{-1/2} \left(1 - e^{-6.28 \cdot P}\right)
\]

If we neglect the term \(1 - e^{-6.28 \cdot P}\) in equation (3), which approaches about 0.99 when \(P\) is larger than 0.7, we can compare to the original work by Block [11] for Ponderosa Pine:

\[
m''_f = 1.05 \times 10^{-3} b^{-1/2}
\]

This shows that the maximum burning rates in well-ventilated wood cribs is similar in the both cases (factor 1.11 and 1.05, respectively). In the model scale tests by Ingason and Lönnermark [5, 6] the wood stick widths, \(b\), were either 10 mm, 15 mm or 21 mm. This means that the maximum burning rate for the wood cribs burning under ambient conditions (no ventilation) should be, using equation (4), about 0.007 and 0.0086 kg/m² s, respectively, for \(b=15\) mm and 21 mm. Corresponding values using the simplified equation (3) are 0.0077 and 0.0091 kg/m² s, respectively. An upper limit of the fuel mass loss rate per unit fuel surface area for wood were given by Tewarson and Pion [14]. They found that the maximum burning rate per fuel surface area that wood (Douglas fir) could achieve is 0.013 kg/(m²·s). The value found by Tewarson and Pion [14] is an ideal value based on the assumption that all heat losses were reduced to zero or exactly compensated for by an imposed heat flux equal to the total heat losses from the fire source.

Harmathy [8] presented experiments with square wood and plastic cribs (PMMA, polylite and phenolic) exposed to different ventilation rates. A crib was placed in a ventilation chamber where the air mass flow rate bypassing and through the wood crib was varied. The crib porosity factor, \(P\), varied from 0.07 mm to 1.58 mm and the mass flow rate of air \(m_a\) between 0.005 kg/s to 0.051 kg/s. In the wood crib test series W-1, \(P\) varied between 0.07 mm to 0.98 mm and 0.41 mm to 1.10 mm in wood crib tests series W-2.

Harmathy concluded from his study that the rate of burning of non-charring fuels (in their case PMMA, polylite), i.e., the majority of synthetic polymers (e.g. thermoplastics such as polyethylene) is apparently unaffected by the air flow. This conclusion is very important as it explains much of the behaviour of fuels that melt, and thereby create a pool fire on the fuel surface when they burn. This indicates that liquid fire and melted plastic exhibit a lesser tendency to be sensitive to the effects of ventilation.

Harmathy also concluded that the rate of burning of charring fuels (wood, phenolic plastic (which is a thermoset)) exhibit a definite dependence on ventilation. A thermoset is polymer material that irreversibly cures, i.e., cannot be remelted and reworked. Thermoset material is generally created by
The influence of the ventilation rate on the maximum heat release rate can be easily observed from Harmathys study. This indicates that wood (and thermosets) will show greater effects on the maximum heat release rate or burning rate than thermoplastics or pool fires.

In Harmathys experiments with charring fuels the burning rate first increased with increasing ventilation, reached a maximum burning rate and then decreased slightly as the air flow increased. Harmathy concluded that the heat released by the oxidation of the char played an important role in the process of pyrolysis. This may explain why charring fuel is more affected by the ventilation than non-charring fuels. This conclusion is central for work on the effect of ventilation rate on heat release rates in tunnel fires.

As could be observed in the work by Croce and Xin, the wood crib geometry in a free burn environment (quiescent air around the wood crib) plays an important role whether the free burn rate is affected or not. When the wood crib porosity is less than 0.7 mm the mass burning rate is reduced. It is possible, to compare the reduced burning rate, \[ m_f \times 10^3 / (A_f \cdot b^{-1/2}) \], from the work by Harmathy under well ventilated conditions and the work by Croce and Xin. The data points obtained in tests series W-1 by Harmathy, when the ventilation rate is at its highest peak, were plotted together with the data from Croce and Xin. The comparison is shown in Figure 3. This shows that the mass burning rate is similar in both cases, even when the crib porosity is low. This implies that a wood crib with low crib porosity can reach the same burning rate or more when it is exposed to sufficiently high air flow rates. Therefore, the burning rate is highly dependent on the ventilation rate around the wood crib when the crib porosity is low, whereas when it is high it is not so sensitive. When comparing the influence of ventilation on burning rates of fuels, it is important to be aware of this fact.

Based on the analysis given here we can conclude that the porosity of the fuel is an important factor for the maximum heat release rate. There is a relatively sharp limit where the fuel transitions from under-ventilated to well ventilated conditions (\( P \approx 0.7 \) mm) and when the maximum heat release rate becomes relatively constant independent of the porosity. Further, as we apply ventilation to a fuel that is under-ventilated under normal conditions, we can easily raise the heat release rate level up a level corresponding to a well-ventilated fuel as Figure 3 confirms.

We can therefore conclude that charring material, such as wood and thermosetting plastics, is expected to exhibit greater sensitivity to ventilation than thermoplastics that can create a pool fire on the surface.

In the following, a summary of the two model scale series concerning the influence of the ventilation on the maximum heat release rate and fire growth rate is presented.
INGASON TEST SERIES

Ingason [5] carried out a total of 12 tests were carried out in a 1:23 scale model tunnel. The parameters tested were: the number of wood cribs, the type of wood crib, the longitudinal ventilation velocity and the ceiling height. The fire spread between wood cribs with a free distance of 0.65 m (15 m in large scale) was also tested. The tunnel itself was 10 m long, 0.4 m wide and test series were conducted using two heights: 0.2 m and 0.3 m, respectively. The corresponding large scale dimensions were 230 m long, 9.2 m wide, and 4.6 m and 6.9 m high, respectively. The lower height (0.2 m) was created using a false ceiling with the same material as the structure of the tunnel as a whole. The model tunnel was constructed using non-combustible boards (PROMATECT®-H) with a thickness of 15 mm. The floor, ceiling and one of the vertical walls, were built in Promatect H boards while the front side of the tunnel was covered with a fire resistant window glaze. Longitudinal flow was supplied by using an electrical axial fan attached to the entrance of the model tunnel. The fire load consisted of two types of wood cribs (pine). Wood crib A was used in the first series of tests (Tests 1 – 9) with a tunnel height of 0.3 m and wood crib B used in the second series of tests (Tests 10 – 12) with a tunnel height of 0.2 m. Detailed descriptions of wood crib A and wood crib B are given in references [5].

Effect of ventilation on maximum heat release rate

For a solid fuel, the heat release rate is dependent on the net heat absorbed by the surfaces of the solid. This means that the total surface area is a very important parameter for the combustion. The fuel mass loss rate per unit fuel surface area against the ventilation velocity across the fire source has been plotted in Figure 4. The fuel mass loss rate was measured only for the first wood crib, even in tests involving several wood cribs. The measurements showed that the fuel mass loss rate per unit fuel surface area is only a weak function of the ventilation velocity. The reason for this is that the fire is fuel-controlled for such a ventilation velocity, i.e. the fuel porosity was high or P was 0.94 mm and 1.24 mm, respectively. As mentioned previously, the upper limit of the fuel mass loss rate per unit fuel surface area presented by Tewarson and Pion [14] was 0.013 kg/(m²s), which correlates well with the experimental data, see Figure 4. The fuel mass loss rate per unit fuel surface area lies below this limit. Further, as shown previously the maximum burning rate for the wood cribs under ambient conditions (no ventilation) should be about 0.007 kg/m²·s to 0.009 kg/m²·s. This corresponds very well with the data points (filled marks) in Figure 4. Ingason and Li also showed that the burning rate per fuel area for wood crib B is only little greater than that for wood crib A. The reason for this may be that wood crib B gets more heat feedback in a tunnel fire test due to relatively lower tunnel ceiling and same width. Comparing data from tunnel fire tests with that from free burning tests shows that the fuel mass loss rate per unit fuel surface area for the tested wood cribs in the tunnel is in a range of 1.4 to 1.55 times the value measured in a free burning test. The free burning test without any ventilation corresponds well with the value obtained earlier in the paper, i.e. 0.007 kg/m²·s to 0.009 kg/m²·s.

![Figure 4 The maximum fuel mass loss rate per unit fuel surface area as a function of the ventilation velocity (only first wood crib) [5]](image-url)
These results are very different from the results of Carvel et al.. The test results presented here do not reproduce the high increase as indicated by Carvel et al. [1-4]. As shown previously, the increase in maximum heat release rate from ambient conditions is of the order of 1.4 to 1.55 for the ventilation rates tested, whereas Carvel et al. indicate an increase in the order of 4 or more for HGVs. The ventilation rates used in this study correspond to ventilations rates of 1.6 m/s to 4.3 m/s in large scale.

The only possible explanation why Carvel et al. [1-4] exhibit such a high increase in the maximum heat release rate is the way the fuel was compared. Fuel that is under-ventilated during ambient or natural ventilated conditions, as was thoroughly explained earlier in this paper, has most likely been used in the comparison. If a fuel has a low porosity factor, the increase found from comparing the results presented here with Carvel et al.’s results can easily be obtained by increasing the ventilation, which was shown in Figure 3.

The above analysis is based on the data of fuel mass loss rate of the first wood crib. In some of the tests, several wood cribs were burnt together (the fire spread between the wood cribs) and the total heat release rate was measured by oxygen calorimetry instead of mass loss using the weighing platform. In Figure 5 the maximum heat release rate per unit fuel surface area as a function of the ventilation velocity is shown. For a fire with several wood cribs, the total fuel surface area of these wood cribs was used here. The same trend is obtained with several wood cribs, although the data does not correlate as well, see Figure 5. This was explained by the fact that in the case with several wood cribs, the surfaces are not burnt simultaneously. When a maximum heat release rate occurs, burning of the first wood crib has started to decay, i.e. burning is not simultaneous but partially staggered. As a consequence, the maximum heat release rate divided by the total fuel surface area is slightly lower than data with single wood crib [15]. One important observation is that the maximum heat release rate is not higher than the theoretical value for wood.

![Figure 5](image_url)

**Figure 5** The maximum heat release rate per unit fuel surface area as a function of the ventilation velocity [5]

**Effect of ventilation on fire growth rate**

The fire growth rate as a function of ventilation velocity is shown in Figure 6. The linear fire growth rate, $\Delta Q / \Delta t$, was taken from the time the heat release rate was 20 kW to the time when it reached 100 kW. Ingason showed that the fire growth rate increases linearly with the ventilation velocity. The fire growth rate is nearly 3 times larger than that in a free burn test, when the ventilation velocity equals to 0.9 m/s, corresponding to 4.3 m/s in large scale. This means that the ventilation velocity plays a very important role in the fire development. The fire growth rate in a tunnel fire test is close to that in a free burn test when the ventilation velocity is equal to 0.3 m/s. As the fire growth rate is one of the most important design parameters for tunnel safety these results are significant and impact on tunnel design. The main reason for the linear increase in fire growth rate as a function of the ventilation rate is the fact that this fosters the leaning of the flames along the fuel array.
A total of 19 wood crib tests were carried out [6] [9] in a model scale tunnel. The tunnel was 10 m long and the width and height of the tunnel were varied during the test series. The widths (W) used were: 0.3 m, 0.45 m, and 0.6 m, and the heights (H) were: 0.25 m and 0.4 m. The scale of the tunnel was assumed to be 1:20 and therefore the widths correspond to 6 m, 9 m and 12 m in real scale, while the heights correspond to 5 m and 8 m, respectively. The ceiling, floor, and one of the walls were made of 15 mm thick PROMATECT®-H boards. One of the walls was comprised of 15 windows of 5 mm thick fire proof glass set in steel frames (555 mm × 410 mm visual access plus frame). Two types of fuels were used: wood cribs and the liquid heptane. The wood cribs were of two different types: with porosities P1=2.1 mm and P2=0.62 mm.

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 1. The sides of the square cross section of the sticks were \( b = 0.015 \text{ m} \) for both the long and the short sticks. This gave a total height of 0.105 m. To study the effect of the porosity of the wood crib on the results (e.g. the effect of the ventilation on the HRR), 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 \( b = 0.010 \text{ m} \). The wood crib was constructed of five layers of long (0.5 m) sticks and four layers of short (0.15 m) sticks. Longitudinal ventilation was established using a fan in the upstream end of the tunnel.

**Effect of ventilation on maximum heat release rate**

In Figure 7 the heat release rate curves for wood cribs with the porosity P1 and P2 are compared at two different velocities, 0.22 m/s and 0.67 m/s, respectively. The heat release rate for the case with a velocity of 0.22 m/s is significantly lower than the heat release rate for the higher velocity (0.67 m/s). There is also a difference between the two porosities P1 and P2. The maximum heat release rate at 0.22 m/s is lower for P2 than the corresponding value for P1, but at 0.67 m/s the maximum heat release rate for P2 is significantly higher than the corresponding for P1. The total area of exposed fuel surface, \( A_s \), for P1 is 0.54 m² while the corresponding value for P2 is 0.8 m². Therefore, when both P1 and P2 are in a well ventilated flow we should expect differences in the maximum heat release rate. Based on fuel surface area, the difference should be about 0.8/0.54≈1.48. From Figure 7 we see that the ratio of heat release rate for P1 wood crib and P2 wood crib under higher ventilation conditions is approximately 100/75≈1.33, which is slightly less than that expected purely based on surface area. The ratio of heat release rate for P2 wood crib with higher ventilation rate (0.67 m/s) compared to lower ventilation (0.22 m/s) is 100/45≈2.2. The
corresponding ratio for P1 wood cribs is \(75/50 \approx 1.5\). These results show that a wood crib with a low porosity factor (P) is more sensitive to the ventilation rate than one with a higher porosity factor and will increase the maximum heat release rate considerably when it is exposed to higher longitudinal ventilation rate.

![Graph](image)

**Figure 7** Comparison of heat release rate (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 [6].

In Figure 8 the ratio between the maximum heat release rate for the test with wood cribs (P1) inside the tunnel and the maximum heat release rate obtained in free burning tests conducted on wood cribs with the same specification, is presented as function of the air velocity. The test data from Ingason [5], which is approximately a P1 crib, is plotted as well for comparison. The P2 data is also shown to illustrate the difference in increase for P1 and P2 wood cribs. There is a slight increase in maximum heat release rate with increasing velocity for a P1 crib. The ratio between the maximum heat release rate 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 for the velocity 0.22 m/s where the ratio actually is lower than one for three of the tunnel cross section. All these tests were performed in the tunnel with the lower height, 0.25 m. Note that the comparisons are made to the free-burning case, while many reported comparisons are made to a case with natural ventilation.

![Graph](image)

**Figure 8** Maximum heat release rate as function of velocity for different tunnel cross sections, compared to the free burn case [6].
As can be seen in Figure 8, the relative increase of heat release rate for \( P_2 \) is higher than for \( P_1 \) for 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.

**Effect of ventilation on fire growth rate**

The ratio of fire growth rate \( (k_2/k_{2,fb}) \) as defined by Lönnemark and Ingason, where \( k_2 \) is the linear slope of the fire growth rate in the tunnel and \( k_{2,fb} \) is the corresponding value for a free burn test, is plotted as a function of ventilation velocity in Figure 9 [5]. Lönnemark and Ingason showed that the value of \( k_2 \) depends on the selection of \( \Delta t \). They came to the conclusion that the time corresponding to 10 % and 90 %, respectively, of the maximum heat release rate gave reasonable results. The results are shown in Figure 9. The trend is the same for all the tests and in good correlation to the results given in Figure 6, although represented in a different manner. The results indicate the linear fire growth rate ratio varies between 2 and 10 or more.

**CONCLUSIONS**

In the paper an overview and analysis of the experiments carried out by Ingason [5] and Lönnemark and Ingason [6], is given. An effort to explain the differences and what phenomena are governing the results, was carried out. The results are explained in comparison to previous studies on wood cribs, such as Harmathy’s [8] work from 1978. The study provides useful information for those who work with tunnel fire safety engineering.

Harmathy’s work, together with that of Croce and Xin, show that the porosity of the fuel is an important factor for the prediction of the maximum heat release rate. There is a relatively sharp limit where the fuel goes from under-ventilated to well ventilated conditions and where the maximum heat release rate becomes a relatively constant value independent of the porosity. Further, as we apply forced ventilation to a fuel that is under-ventilated under normal conditions, we can easily raise the heat release rate level up a level corresponding to a well-ventilated fuel. These results comply very well with what has been observed in the model scale tests presented.

The increase in maximum heat release rates compared to ambient conditions for wood cribs is confirmed to be in the range of 1.4 to 1.7 for wood cribs that have high porosity. When the porosity is low, these effects increase from 1.8 up to 2.2. Comparing the results to the Benelux full scale tests indicates that these results are also in line with the model scale tests.

The rate of burning of non-charring fuels, i.e., the majority of synthetic polymers (e.g. thermoplastics
such as polyethylene) is apparently unaffected by the air flow. This conclusion is very important as it explains much of the behaviour of fuels that melt, and thereby create a pool fire on the fuel surface when they burn. This complies with the fact that liquid fire and melted plastic exhibit a lesser tendency to be sensitive to the effects of ventilation.

The rate of burning of charring fuels (e.g. wood and thermosetting plastic) does exhibit a clear dependence on ventilation. The heat released by the oxidation of the char plays an important role in the process of pyrolysis. Harmathy use this as an explanation for why the charring fuel is more affected by the ventilation than the non-charring fuels. This conclusion is central for the work on effects of ventilation rate on heat release rates in tunnel fires. This further explains why wood will show greater effects on the maximum heat release rate or burning rate than thermoplastics or pool fires.

The results can be used by fire safety engineers when considering the effects of ventilation on different fire loads and different geometries of the fuel. The influences of the cabinet of a HGV trailer are of great importance here, as it may affect the results given here. All the results given here are based on tests where the air flow is freely bypassing or going through the fuel.

REFERENCES

