EXPERIMENTAL STUDIES ON FORCED-VENTILATED FIRES

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ABSTRACT

Full scale burning tests were performed to study wood, polymethylmethacrylate (PMMA) and methanol fires in a compartment under forced ventilation conditions. In each fire test, the mass loss rate, the gas temperature, the flame height, carbon monoxide, carbon dioxide and oxygen concentrations were measured. Results illustrated that the burning behaviour of wood will be affected by the ventilation rate. But for PMMA and methanol fires, the burning behaviour and the fire plume properties are not so sensitive to the change in ventilation rates. The hot gas temperatures for wood and PMMA fires within the quasi-steady burning period are expressed in terms of the extraction rates and the average total heat-release rate with empirical constants determined by this experiment. Also the average hot gas temperatures are compared with the values calculated by the simple model due to Deal and Beyler (1990).

1. INTRODUCTION

Knowledge on the compartmental fire is very important in designing fire services systems. For example, the actuation time of a sprinkler head depends on the temperature and speed of the hot gases in the ceiling jet. Many papers have been reported in the literature on compartmental fires under natural ventilation (e.g. Heskestead et al. 1982, Quintiere 1984, SFPE Handbook of Fire Protection Engineering 1988, Deal and Beyler 1990). Although ventilation was identified to be an important factor (e.g. Harmathy 1980), not many reports are on forced-ventilation fires. However, forced-ventilation are commonly provided in commercial buildings in Hong Kong. The design of the ventilation rates depends on the use of the building and the floor area. Usually, smaller the office area, larger is the ventilation rate. For example, large offices might have a ventilation rate of about 10 air changes per hour, but smaller compartments such as a toilet would have higher ventilation rate up to 50 air changes per hour. The kitchen in a restaurant might have 20 air changer per hour. Estimation of the fire environment inside those compartments using the theories for natural ventilated fires will not be good. Studying the effect of inlet air flow rate on the changes of enclosure fire properties is therefore important. Extracted-ventilated compartment fires at a test chamber were studied by Alvares et al. (1984) and Foote et al.(1986) and later theoretically by Mitler (1984). The peak gas temperature was found to be underestimated if forced-ventilation effect is neglected. Studying the fire properties at the same chamber with a suspended ceiling and the extraction changed to an overhead position was reported later by Backovsky et al.(1988). The experimental data was complied and modelled by Deal and Beyler (1990), Beyler (1991). A simple model for estimating the average hot gas temperature in the compartment was derived. The burning behaviour of methanol in a poorly-ventilated compartment was studied by Sugawa et al. (1989). The 'ghosting' fire observed when the burning rate was almost one fifth of the normal burning rate and oxygen concentration was about 13 to 14 percentage by volume. Small-scale compartment fire with polymethylmethacrylate (PMMA) sheet at different ventilation sizes were studied by Takeda (1985). The flashover time was measured
as a function of the ventilation parameter. Crib fires of PMMA were studied later by Yung (1991) with the burning processes observed.

The objective of this paper is to report a study on the preflashover fire in a compartment under forced ventilation conditions with different rates. Materials to be investigated included wood, polymethylmethacrylate (PMMA) and methanol. The forced-ventilated fire tests were similar to those of Alvares et al. (1984), Foote et al. (1986) and the burning behaviour of the above three fuels under different gas extraction rates were studied in a fire chamber at the Department of Building Services Engineering, Hong Kong Polytechnic. The size of the chamber is very similar to a typical office in the commercial building and so the results are very useful in assessing the potential fire risk behind.

2. EXPERIMENTAL SET-UP

The fire chamber used for the burning tests is of length 4 m, width 3 m and height 2.8 m, being shown in Fig. 1. The air inlet is a louvre of width 0.52 m and height 0.41 m. There are six slots in the louvre, each of area of 0.017 m², and height of 0.034 m. The ventilation factor of each slot is 0.003 m⁵/s (i.e. 0.017 m² × (0.034 m)³/²), and the total ventilation factor of the louvre is 0.18 m⁵/s. Hot gases are extracted out of the fire chamber by two axial fans through the air duct of cross sectional area 0.09 m². Butterfly valves are installed in the upstream of axial fans to control the gas extraction rate. Gas velocities are measured by vane-type anemometers inside the air duct in order to calculate the gas extraction rate. The concentrations of different chemical species are measured by probes inserted into the air duct.

The experimental set-up inside the fire chamber is shown in Fig. 2. An electronic balance with a dura-steel load platform was placed at the centre to measure the mass of the fuel. Flame height was measured by a vertical scale with mark of 100 mm

![Diagram](image-url)
located at the left of the load platform. A thermocouple rake with seven thermocouples, labelled as T1 to T7 and spaced at 300 mm interval, was installed at position A at the right of the platform. Another thermocouple T8 was located at position B above the load platform to measure the temperature of the hot gases. All thermocouples were connected to a data acquisition system outside the fire chamber. The data acquisition system was consisted of a data acquisition module and a Laptop computer.

The burning behaviour of wood, polymethylmethacrylate (PMMA) and methanol were investigated at different fuel size and ventilation rates. Those materials are chosen because wood and PMMA are commonly used in furnitures, and the burning process of methanol can be controlled easily. There were twenty-five tests performed at the fire chamber with gas extraction rates up to 60 air changes per hour or 556 l/s as labelled in Table 1. The fuel sizes were fixed for all the materials in the natural-ventilated and forced-ventilated fire tests, but different fuel sizes were used for studying methanol fires without ventilation when all the openings and leakage area were sealed. The wood crib had four layers, each layer had three sticks of length 310 mm, width 25 mm and thickness 25 mm as shown in Fig. 3. The moisture content of the sticks was kept in the range of 7% to 9%. For PMMA fires, two cribs were put side by side. Each PMMA crib had five layers, each layer had four sticks of length 140 mm, width 20 mm and thickness 3 mm as shown in Fig. 4a and 4b.

For methanol fire tests, the fuel was burnt in a pan of depth 70 mm. The fire size was determined by the diameter of the pan and the mass of the fuel. A circular burning pan of diameter 150 mm containing 250 g of methanol was used for all natural-ventilated and forced-ventilated tests. But for the 'no' ventilation tests, the mass of methanol
was increased to 600 g. The number and the diameter of the pans used in each under-ventilation test were different for obtaining various fuel sizes. In the four 'no' ventilation methanol fire tests, there were two test (i.e. tests 22 and 23) with a single pan of diameter 180 mm and 220 mm respectively, and one test (i.e. test 24) with two pans of diameter 180 mm and another test (i.e. test 25) with two pans of diameter 180 mm and 220 mm.

Carbon monoxide, carbon dioxide and oxygen concentrations were measured by gas analyzers which were calibrated before use. The data acquisition system was kept running for ten minutes. The butterfly valves were adjusted before each forced-ventilated fire test and readjusted at 2 minutes after ignition to maintain the required gas extraction rate. For the 'no' ventilation fire tests, the intake air louvre and the gaps of the fire chamber were sealed. The wood and PMMA cribs were soaked with 30 g of methanol for easier ignition (e.g. Mizuno and Kawagoe 1984). Once the fuel ignited, temperature, gases concentrations and mass of fuel were recorded at an interval of one minute.

3. RESULTS

The average mass loss rate, peak value of total heat-release rate, gas temperature, maximum concentration of carbon monoxide and maximum flame height for the twenty-five tests performed at the fire chamber are summarized in Table 1 and described followings:

3.1 Mass Loss Rate \( M_t \)

Transient fuel mass was measured for all the tests. For example the mass of the three materials at a gas extraction rate of 20 air changes per hour or 185 l/s (i.e. tests 3, 10 and 17) are plotted against time in Fig. 5, their mass loss rates are plotted in Fig. 6. From the graphs, the mass of wood and PMMA changed exponentially with time. The mass of methanol changed in a linear manner with a fairly constant rate. The variations of the mass of wood cribs at different extraction rates (i.e. tests 1 to 7) are plotted in Fig. 7. Increasing the gas extraction rate would increase the burning period from 10 to 17 minutes. But for PMMA and methanol fires, the burning periods were not extended while varying the extraction rates.

![Figure 5. Variation of mass at 20 air changes per hour](image-url)
Table 1. Summary of the twenty-five fire tests

<table>
<thead>
<tr>
<th>Test no.</th>
<th>Fuel</th>
<th>Ventilation condition</th>
<th>Gas Extraction Rate 1/s</th>
<th>Air changes per hour</th>
<th>Peak total heat-release rate Q&lt;sub&gt;r&lt;/sub&gt; (kW)</th>
<th>Peak gas temperature (°C)</th>
<th>Max. [CO] (ppm)</th>
<th>Max. flame height (mm)</th>
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<tr>
<td>1</td>
<td>Wood</td>
<td>Natural ventilated</td>
<td>0</td>
<td>0</td>
<td>34.2</td>
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<tr>
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<td>Wood</td>
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<td>10</td>
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<td>920</td>
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<td>520</td>
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<td>195</td>
<td>520</td>
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<td>371</td>
<td>40</td>
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<td>181</td>
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<td>520</td>
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<tr>
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<td>14.3</td>
<td>50.43</td>
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<td>48.52</td>
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<td>45.13</td>
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<td>9</td>
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<td>20</td>
<td>7.6</td>
<td>43.47</td>
<td>9</td>
<td>220</td>
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<tr>
<td>18</td>
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<td>Methanol(150)*</td>
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<td>36.65</td>
<td>9</td>
<td>220</td>
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<td>Methanol(150)*</td>
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<td>60</td>
<td>7.3</td>
<td>35.92</td>
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<td>0</td>
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<td>320</td>
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<td>Methanol(220)*</td>
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<td>0</td>
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<td>66.84</td>
<td>17</td>
<td>520</td>
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<tr>
<td>24</td>
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<td>0</td>
<td>22.1</td>
<td>79.74</td>
<td>20</td>
<td>520</td>
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<tr>
<td>25</td>
<td>Methanol (180&amp;220)*</td>
<td>'No' ventilation</td>
<td>0</td>
<td>0</td>
<td>28.8</td>
<td>89.78</td>
<td>22</td>
<td>620</td>
</tr>
</tbody>
</table>

Remark:
* The numbers inside the bracket are the diameter of the burning pan in mm.
# Two burning pans are used in those tests.

For the under-ventilated methanol fires, the burning rate increased with the pan area. As the size of the fire chamber is large, the mass of air remained inside the fire chamber (about 19 kg, which can burn a maximum mass of 4.67 kg of methanol if 4.07 kg of air is required to burn 1 kg of methanol completely) is sufficient to burn all the fuel. Therefore, the methanol fire is not extinguished even under the 'no' ventilation conditions.
3.2 Estimation of Heat Release Rate

In this study, the heat-release rate, $Q_t$, is estimated by mass loss rate $M_t$:

$$Q_t = M_t H_c$$

(1)

The heat of combustion $H_c$ for PMMA is 25.3 kJ/g (e.g. Tewarson 1976) and 19.83 kJ/g for methanol (e.g. Drysdale 1985). For wood cribs, $H_c$ is taken to be 12.83 kJ/g as calculated from the regression equation suggested by Janssens (1991).

The heat-release rate of methanol is fairly constant but there is a peak value $Q_p$ for PMMA and wood fires. The peak value of the heat-release rate is calculated from the maximum mass loss rate and is shown in Table 1. Values of $Q_p$ are nearly constant for PMMA fires under natural-ventilations and forced-ventilations. For the ‘no’ ventilation methanol fire tests, $Q_p$ increases with the burning rate. In all the wood fire tests, the variations of $Q_p$ is small when the gas extraction rate is greater than 20 air changes per hour or 185 l/s.

A growing fire can be described by the ‘power-law’ model (e.g. Heskestad and Delichatsios 1982, 1990):

$$Q_t = \alpha (t-t_0)^p$$

(2)

Applying this equation to PMMA and wood fires and assuming the virtual ignition time $t_0$ is zero, the fire growth coefficient $\alpha$ and the fire growth exponent $p$ can be determined by plotting log $(Q_t)$ against log $(t)$ in the fire growth period. Taking the natural ventilated PMMA fire (test 8) as an example and plotting log $(Q_t)$ versus log $(t)$ as in Fig. 8, log $\alpha$ is found to be -1.8 and $p$ is 1.3. Similarly, values of $\alpha$ and $p$ for the other tests are determined. For wood, $p$ is found to be roughly equal to 1, and is about 1.3 for PMMA in all the
tests. Values of $\alpha$ are tabulated in Table 2. It is observed that the value of $\alpha$ ranged from 0.012 kW/s$^{1.3}$ to 0.017 kW/s$^{1.3}$ for PMMA, and can be treated as a constant for all the gas extraction rates. But for wood, it decreased from 0.38 kW/s to 0.03 kW/s when the gas extraction rate was changed from 93 l/s to 556 l/s. Therefore, the growth of a wood fire will be slowed down by large gas extraction rates, leading to a longer burning period as shown before in Fig. 7.

### 3.3 Gas Temperature

The hot gas temperature is taken to be the average values measured by the thermocouples T7 and T8. Results of the gas temperature for wood fires at different ventilation rates, i.e. tests 1 to 7 are plotted in Fig. 9. To have a better understanding on the gas temperature, the ‘quasi-steady burning period’ is used. This is defined as a four-minute time interval in which the gas temperature reached its peak value in the middle of this interval. For example, the gas temperature for wood fires under natural ventilation (i.e. test 1) reached its peak value at 5 minutes after ignition.

<table>
<thead>
<tr>
<th>Test no.</th>
<th>Fuel</th>
<th>$V$ (l/s)</th>
<th>$V$ Air changes per hour</th>
<th>$Q_0$ (kW)</th>
<th>Measured $\delta T_g$ ($^\circ$C)</th>
<th>Calculated $\delta T_g$ ($^\circ$C)</th>
<th>$\alpha$ ($\times 10^{-3}$ kW/s$^\alpha$)</th>
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<td>1</td>
<td>Wood</td>
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<td>19.44</td>
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</table>

Remark:

* $p$ is equal to 1 for wood and 1.3 for PMMA
The quasi-steady burning period is then the time interval from 3 to 7 minutes after ignition. Variations of gas temperature within this period would be the smallest and this period is taken as a steady burning period. Increasing the gas extraction rate would reduce the peak gas temperature and increase the time to reach this peak value. The gas temperature for a natural-ventilated fire is higher than a forced-ventilated fire. Similar profiles are found for PMMA and methanol fires and their peak gas temperatures are tabulated in Table 1.

The gas temperature of the methanol fires for natural ventilation with different fuel sizes, i.e. tests 15, 22, 23, 24 and 25 and the forced ventilation of fuel size 150 mm diameter, 30 air changes per hour or 278 l/s i.e. test 18 are plotted against time in Fig. 10. The gas temperature increased during the burning period for under-ventilated and natural-ventilated conditions. But it increased to a peak value and then remained constant for forced-ventilated fires. The gas temperature of ‘no’ ventilation methanol fire tests increased with the area of the burning pan.

The average values of the total heat-release rate $Q_I^*$ within the quasi-steady burning period for wood and PMMA fires are tabulated in Table 2. Values of $Q_I^*$ are not reduced significantly in large gas extraction rate. A reason why the peak gas temperature decreases within the quasi-steady burning period for large gas extraction rate is because of the large ventilation heat loss by the gases extracted out.

The average gas temperature rise above ambient $\delta T_g$ within the quasi-steady burning period is a function of the gas extraction rate $\dot{V}$ (in l/s) and $Q_I^*$ (in kW). It can be written in a non-linear form as (e.g. Foote et al. 1986):

$$\delta T_g = a (Q_I^*)^b \dot{V}^c$$

(3)

giving,

$$\log (\delta T_g) = \log a + b \log (Q_I^*) + c \log (\dot{V})$$

(4)

By performing a bivariate regression analysis of $\log \delta T_g$ on $\log (\dot{V})$ and $\log (Q_I^*)$ respectively using the method of least squares, coefficients $a$, $b$ and $c$ can be determined.

For wood fire:

$$\delta T_g \big|_{\mathrm{wood}} = 12.7 (Q_I^*)^{0.28} \dot{V}^{-0.29}$$

(5)

or

$$\delta T_g \big|_{\mathrm{wood}} = 12.7 \left( \frac{Q_I^* \dot{V}^{0.96}}{\dot{V}} \right)^{0.29}$$
For a PMMA fire:

\[ \delta T_g \text{ PMMA } = 10.8 \left( \frac{Q_f^*}{V} \right)^{0.24} V^{-0.1} \]

or

\[ \delta T_g \text{ PMMA } = 10.8 \left( \frac{Q_f^{2.4}}{V} \right)^{0.1} \] (6)

No correlation relation is obtained for the methanol fires because the changes of \( Q_f^* \) within the quasi-steady burning period did not follow such a general pattern given by (3) for all the gas extraction rates.

The experimental data of \( \delta T_g \) for wood and PMMA fires are well fitted by equations (5) and (6) as plotted in Figs. 11 and 12. The measured \( \delta T_g \) and the values of \( \delta T_g \) calculated by equations (5) and (6) are also tabulated in Table 2. The exponents of \( Q_f^* \) for wood and PMMA fires are 0.28 and 0.24 respectively. In comparing to the exponent value 0.72 for methane gas found by Foote et al. (1986), this is much smaller. But \( \delta T_g \) here is the hot gas temperature closed to the ceiling, not the average temperature of the whole compartment.

### 3.4 Vertical Temperature Profiles

The vertical variation of the temperatures was measured by the seven thermocouples located at point A in Fig. 1. The temperature profile for the wood fire an extraction rate of 30 air changes per hour, i.e. test 4 is shown as an example in Fig. 13. The temperatures along the rake increased to

![Figure 11. Data and correlation of hot gas temperature (wood fire, forced ventilation)]
roughly the same value and an isothermal region was found at height from 1.9 m to 2.5 m above the ground. The temperature gradient above the height of 2.5 m was steep.

The variation of temperature profiles for steady burning of wood fires at the different extraction rate, i.e. tests 1 to 7 are plotted in Fig. 14. Results for PMMA and methanol fires at natural ventilation and extraction rates of 30 and 60 air changes per hour, i.e. tests 8, 11, 14, 15, 18, 21 are shown in Fig. 15. As shown in Fig. 14, the thermal stratified layer became unstabled at large gas extraction rates. When the gas extraction rate was greater than 20 air changes per hour or 185 l/s, a
bigger drop in temperature was resulted. But from Fig. 15, the temperature profiles of PMMA and methanol fires did not change with the gas extraction rates. There were no thermal stratified layers for PMMA and methanol fires under these ventilation conditions.

3.5 Flame Height

In this study, the flame height is taken to be the height at which a flame can be observed at or above that height for 50% of the observing time. The flame heights measured for wood, PMMA and methanol of fuel size 150 mm diameter under
different gas extraction rates are shown in Fig. 16. The maximum flame heights obtained for the natural-ventilated wood fire and the forced-ventilated wood fire with gas extraction rate of 10 air changes per hour or 93 l/s were the same. When the gas extraction rate was greater than 20 air changes per hour or 185 l/s, the flame height became quite steady. At gas extraction rate of 60 air changes per hour or 556 l/s, the flame height decreased to about one third of the height for the natural-ventilated fire. For PMMA and methanol fires, the flame heights were quite steady and became constant at large gas extraction rates.

3.6 Chemical Species Concentration

Concentration of oxygen, carbon dioxide and carbon monoxide were measured (e.t. Pitts 1989). Carbon monoxide concentration will be very high for underventilated fire. In all the tests performed, oxygen concentration was high enough to support combustion. For natural-ventilated fires, the reduction in oxygen concentration is 2% for wood, 1.1% for PMMA and 0.6% for methanol. When the gas extraction rate increases from 10 air changes per hour or 93 l/s to 60 air changes per hour or 556 l/s, the reduction in oxygen concentration decreases from 0.9% to 0.4% for wood fires, 0.5% to 0.2% for PMMA fires and 0.3% to 0.1% for methanol fires. For the ‘no’ ventilation methanol fires, oxygen concentration was still decreasing at the end of the fire and a maximum reduction of 1.9% in oxygen concentration was recorded for the all under-ventilated methanol fires.

The concentration of carbon monoxide was increased at the end of a wood crib fire due to smouldering combustion. For PMMA and methanol fires, the carbon monoxide concentration decreased at the end of fire. The maximum carbon monoxide concentration for all wood fire tests at different gas extraction rates are plotted in Fig. 17, for the other two fuels are shown in Fig. 18. It is clearly shown that the maximum carbon monoxide concentration of wood fire decreased with the gas extraction rates. For PMMA fires, the maximum carbon monoxide concentration obtained for natural-ventilated fire was greater than that of the forced-ventilated fire. The relationship between maximum carbon monoxide concentration and gas extraction rate for forced-ventilated PMMA fire is not obvious. Maximum carbon monoxide concentration obtained for natural-ven-
The concentration of carbon monoxide for wood fires is shown in Figure 17. For PMMA and methanol fires, the concentration of carbon monoxide is shown in Figure 18. For the 'no' ventilation methanol fires, the maximum carbon monoxide concentration increased with the burning rate.

For wood fires, the maximum values of the ratio of the carbon monoxide concentration to carbon dioxide concentration $[\text{CO}] / [\text{CO}_2]$ increased with the gas extraction rate. The $[\text{CO}] / [\text{CO}_2]$ ratio increased from 0.04 to 0.13 when the gas extraction rate increased from 93 l/s to 556 l/s. For a PMMA fire, the maximum ratio of $[\text{CO}] / [\text{CO}_2]$ lied in the range of 0.2% to 0.6%. This value was approximately 0.03 for all methanol fires.

4. PREDICTION OF THE HOT GAS TEMPERATURE

A forced-ventilated fire is very different from a natural ventilated fire. At higher ventilation rates (e.g. in Fig. 14), no clear thermal stratified layer was formed. A simplified model for calculating the average temperature in a force-ventilated compartment was proposed by Deal and Beyler (1990). There, the average gas temperature rise in the compartment above the ambient $\delta T$ can be calculated by:

$$\delta T = \frac{Q^*}{V \rho C_p + h_k A_T}$$

(7)

where $\rho$ and $C_p$ are density and specific heat capacity of air, $\rho C_p$ is about 1188 Jm$^{-3}$K$^{-1}$, $h_k$ is the heat loss coefficient of the compartment and $A_T$ is the total surface area of the compartment. As proposed by McCaffrey et al. (1981) for natural ventilated fires and modified by Deal and Beyler (1990), Beyler (1991) for a forced-ventilated fire, the heat loss coefficient $h_k$ can be written as:
\[ h_k = 0.4 \max \left\{ \sqrt[4]{\frac{k_w \rho_w c_w}{t}}, \frac{k_w}{\delta_w} \right\} \] (8)

Here, \( t \) is the time, \( k_w, \rho_w, c_w \) and \( \delta_w \) are the thermal conductivity, density, specific heat capacity and thickness of the wall respectively. For this fire chamber, \( \sqrt[4]{k_w \rho_w c_w} \) is about 1213 W m\(^{-2}\)K\(^{-1}\)s\(^{1/2}\) and \( A_T \) is 63.2 m\(^2\). Values of \( \delta T \) at maximum heat release rate (note there are more than one values for several methanol fire tests) are calculated and plotted against the measured values in Fig. 19. The measured temperature rise of the hot gas inside the compartment was calculated by a weighted average of the temperature measured by the seven thermocouples at \( T_1 \) to \( T_7 \), minus the initial value \( T_0 \):

\[ \delta T = \frac{1.15 T_1 + 0.3 (T_2 + T_3 + T_4 + T_5 + T_6) + 0.15 T_7}{2.8} - T_0 \] (9)

In views of Fig. 19, the calculated temperatures were smaller than the measured values. There might be some problem on calculating the heat loss coefficient and perhaps it was higher. A smaller value of \( h_k \) given by \( \frac{200}{\sqrt{t}} \) Wm\(^{-2}\)K\(^{-1}\) (i.e. changing the constant in equation (8) from 0.4 to 0.165) was used. Results using this values are plotted in Fig. 20 and good agreement with the measured temperature was found. Since the power law correlations by McCaffrey et al. (1981) will give nonphysical behaviour in limiting cases, an exponential correlation on the average hot gas temperature rise \( \delta T \) has been found by Foote et al. as reported by Deal and Beyler (1990):

\[ \delta T |_{\text{Foote}} = \left( \frac{Q_i}{V \rho C_p} \right) \exp \left[ -0.53 \left( \frac{h_k A_T}{V \rho C_p} \right)^{0.43} \right] \] (10)

This is also calculated at the peak values of heat release and plotted against the measured hot gas temperatures in Fig. 21. Quite a good correlation is obtained.

5. CONCLUSIONS

Experimental studies of forced-ventilated fire tests on wood, PMMA and methanol before flashover are reported in this paper. From the results, it is found that the average burning rates for PMMA and methanol are not affected significantly by the gas extraction rate. Relatively,
the burning of wood is more sensitive to the change in ventilation rate. For large extraction rates, the fire burning period was longer, the maximum flame height and carbon monoxide concentration were smaller, the gradient of the temperature profile decreased and the thermal stratified layer became unstable. For PMMA fires, the burning period did not change with the gas extraction rate. The methanol fire had a peak release rate after ignition for all ventilation rates and there were several peaks for some tests. The maximum flame height and concentration of carbon monoxide remained constant at large gas extraction rates. The gradient of temperature profile did not vary with the extraction rates.

The gas temperatures of the forced-ventilated
fires decreased when the gas extraction rate increased. From the statistical analysis performed, it is found that the gas temperature closed to the ceiling is proportional to the 0.28 power of $Q$, for wood and 0.24 power of $Q$ for PMMA. These exponent values are smaller than the one found by Foote et al. (1985). The average temperature rise in the compartment is also compared with the values calculated by a simple model of Deal and Beyler (1990). Good agreement was found when the heat loss coefficient was smaller. The data can also be fitted by the exponential correlation proposed by Foote et al reported in Deal and Beyler (1990).

Finally, the tests performed in this paper were at the preflashover stage of a fire. Here, only convective heat transfer is considered. However, thermal radiation effects should be included for bigger fires (e.g. Mizuno et al. 1991) and would be studied later.

REFERENCES


NOMENCLATURE

\( H_c \) heat of combustion (kJ/g)
\( M_f \) mass burning rate (g/s)
\( p \) fire-growth exponent
\( Q_p \) peak value of total heat-release rate (kW)
\( Q_t \) total heat-release rate (kW)
\( Q_t^* \) average total heat-release rate within quasi-steady burning period (kW)
\( \delta T_g \) average gas temperature rise above ambient within quasi-steady burning period (°C)
\( t \) time (s)
\( t_o \) virtual ignition time (s)
\( V \) gas extraction rate (litres/s)
\( a \) fire growth coefficient (kW/s²)

\([CO]\) volume concentration of carbon monoxide (ppm)

\([CO_2]\) volume concentration of carbon dioxide (ppm)

\([O_2]\) volume concentration of oxygen (%)