Influence of Combustible Dimension and Density on Heat Release Rate

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1. INTRODUCTION

Various aspects of the fire safety design of a building, such as the evacuation safety, make it important to understand the burning behavior of flammable materials in the early stages of a fire. Many experimental researches have been conducted, and considerable data concerning the burning behavior of various flammables has been accumulated, especially with respect to the heat release rate.[1] However, it is still unknown how the time history of the heat release rate changes depending on the material and its shape.

Therefore, a burning experiment was conducted by using polyurethane mattresses with different dimensions and densities. From the HRR histories, the fire growth rate and maximum HRR were obtained, and the relation between the dimension, the density of the specimen and the fire growth rate, maximum HRR was related.

2. EXPERIMENTAL SUMMARY

2.1 \textit{Test objects}

The long-side length of the test object used in this experiment was fixed at approximately 900 mm, the thickness was changed from 40 mm to 420 mm, and the short-side length was also changed from 200 mm to 650 mm. Table 1 provides the details of the test objects.
Table 1  List of the test objects used in this experiment

<table>
<thead>
<tr>
<th>No.</th>
<th>Dimension [mm]</th>
<th>Parameters</th>
<th>Density * [kg/m³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exp.1</td>
<td>970 670 40</td>
<td>1.45</td>
<td>0.06</td>
</tr>
<tr>
<td>Exp.2</td>
<td>970 200 200</td>
<td>4.85</td>
<td>1.00</td>
</tr>
<tr>
<td>Exp.3</td>
<td>900 645 60</td>
<td>1.40</td>
<td>0.09</td>
</tr>
<tr>
<td>Exp.4</td>
<td>900 650 60</td>
<td>1.38</td>
<td>0.09</td>
</tr>
<tr>
<td>Exp.5</td>
<td>870 200 40</td>
<td>4.35</td>
<td>0.20</td>
</tr>
<tr>
<td>Exp.6</td>
<td>970 200 180</td>
<td>4.85</td>
<td>0.90</td>
</tr>
<tr>
<td>Exp.7</td>
<td>910 640 180</td>
<td>1.42</td>
<td>0.28</td>
</tr>
<tr>
<td>Exp.8</td>
<td>910 640 180</td>
<td>1.42</td>
<td>0.28</td>
</tr>
<tr>
<td>Exp.9</td>
<td>910 640 425</td>
<td>1.42</td>
<td>0.66</td>
</tr>
</tbody>
</table>

Minimum 1.38  0.06
Maximum 4.85  1.00

* High density (17.8 ~ 19.1 kg/m³)
Low density (12.7 ~ 12.9 kg/m³)

2.2 Measurement parameters

This experiment made use of an oxygen consumption calorimeter in General Building Research Corporation of Japan. The test object was placed below the smoke-collecting hood and a fire was ignited at the center of the upper surface. The flow rate of the combustion gases and the gas concentration ($O_2$, $CO_2$, $CO$) were measured at 3-second intervals, and the heat release rate was calculated with the use of the oxygen consumption. Additional details relating to the measurement parameters can be found in the previous report.[2]

3. EXPERIMENTAL RESULTS AND DISCUSSION

The data relating to the heat release rate of each object and the time history of each burned part are as reported in the previous report.[2] The heat release rate curve can be expressed with variables such as the fire growth rate $\alpha$ and the maximum heat release rate $Q_{max}$. Therefore, understanding the correlation between $\alpha$, $Q_{max}$ and the object’s dimension and density is the main focus of this report.

3.1 Fire growth rate

The heat release rate in the early stages of a fire has been empirically derived, and has been found to be proportional to the square of the time, based on the fire growth rate $\alpha$[3]. Therefore, upon obtaining the time coordinates corresponding to the heat release rate reaching 10% and 90% of its maximum $Q_{max}$, the flame growth rate $\alpha$ was calculated by substituting these coordinates into Equation 1.

$$Q = \alpha(t - t_0)^2$$

Figure 1 shows the fire growth rates $\alpha$ calculated from each experiment. According to Figure 1, although the fire growth rate varies slightly, it generally decreases as the density of the test object increases, except for three cases where the short-side length is short. When the density of the object becomes greater, the quantity of heat $C_p \rho (T_{ig} - T_s)$ required to raise the temperature of the object to the ignition temperature
also increases. Therefore, it is presumed that the fire growth rate becomes lower due to the time spent during the melting phase. This tendency was also confirmed through an experiment using a wood crib.[4]

In Experiments 2, 5 and 6, where the short-side length is short, the fire growth rate becomes as low as only 1/10 of that for the experiments where the longer short-side is longer. This is attributed to the non-concentric spread of the burning area on the surface, which quickly reaches the long side of the upper surface in the case of the short short-side test object. When the burning area reaches the long side of the upper face, it expands downward along the lateral side, which determines the small climb gradient of the heat release rate.

\[ Q = \pi (v_p t)^2 q_0 = (\pi v_p^2 q_0) \times t^2 \] (2)

Here, \( v_p \) is the spreading rate (m/s) of the melted area, and \( q_0 \) is the heat release rate per unit area (kW/m\(^2\)). The fire growth rate is the first term of the right side of Equation 2.

On the other hand, the spreading rate \( v_p \) of the burning area can be theoretically derived from Equation 3, based on the heat transfer from the flame to the non-melted parts[5].

\[ v_p = \frac{V_g (k \rho c)_g (T_f - T_{ig})^2}{k \rho c(T_{ig} - T_0)^2} \alpha \frac{1}{\rho} \] (3)

Here, \( v_o \) is the opposed flow rate (m/s), \( k \) is the thermal conductivity coefficient (kW/m \( \cdot \) K), \( \rho \) is the density (kg/m\(^3\)), \( c \) is the specific heat (kJ/kg \( \cdot \) K), \( T_{ig} \) is the ignition temperature (K), \( T_f \) is the flame temperature (K), \( T_0 \) is the initial temperature (K) and the subscript \( g \) indicates the gas. The fire growth rate can be derived from Equations 2 and 3:

\[ \alpha = \pi q_0 \left( \frac{V_g (k \rho c)_g (T_f - T_{ig})^2}{k \rho c(T_{ig} - T_0)^2} \right)^2 \alpha \frac{1}{\rho^2} \] (4)
Based on that, it is presumed that the fire growth rate is inversely proportional to the square of the object's density. Hence, by calculating the mean value from the product of the square values of the fire growth rate and the object’s density as obtained from the six experiments without short-side length test objects (Experiments 2, 5 and 6), the relational expression (Equation 5) can be written as:

\[ \alpha = \frac{8.54}{\rho^2} \]  

(5)

By plotting the relation of Equation 5 to Figure 1, it can be confirmed that the fire growth rate is inversely proportional to the square value of the density.

### 3.2 Maximum heat release rate

The burned area at the time when the heat release rate reached its maximum in each experiment can be obtained from the video tape recording. According to the recorded images, when the object is thinner, the edge of the burning area reaches the short side of the upper surface and the bottom of the lateral side. On the other hand, when the object is thicker, both the top surface and the lateral side are entirely engulfed in flames. Given this factor, since the burning became planar in the cases where the object was thinner (H=0.04 and 0.06), the burned surface area corresponding to the time of maximum heat release rate was calculated as viewed from above. In the cases where the object was thicker (H=0.18, 0.2 and 0.42), the burned area spread sterically, and therefore the area, when it could be confirmed from the recorded images, was calculated as the burned area that is the total steric surface area as illustrated in Figure 2.

Figure 3 presents a plot of the heat release rate and the burned area at the time when the maximum heat release rate in each experiment was reached. It can be inferred from this figure that the maximum heat release rate with respect to the burned area increases together with the increase of the burning area. In Experiments 7, 8 and 9, where the thickness is greater, the readings from the video-recorded images of the core part became unreliable for the purpose of calculating the burning area. As a consequence, the estimated burning area became smaller than the actual burning area, which resulted in the values of the maximum heat release rate with respect to the burning area being smaller when compared with the other cases.

Figure 4 shows the results of the experiment with a cone calorimeter and the same material. The figure implies that the heat release rate increased drastically immediately after the ignition, it reached 423 kW/m² in 40 seconds, and the burning lasted for 130 seconds. The average heat release rate from the ignition to the complete burning was calculated as 151 kW/m², and the maximum and average heat release rates are represented with a dashed line in Figure 4. According to Figure 4, the heat release rate per unit area at the time when it reaches its maximum is between the cone’s maximum and average heat release rates, and the result of calculating the mean value without the data about the thicker objects was 284 kW/m². This value is approximately the same as
the average heat release rate as calculated for the time until it reaches approximately 90% of the total heat release for the experiment with the cone calorimeter.

**Figure 2** Burned area when reaching the max. heat release rate

**Figure 3** Relation of the max. heat release rate and the burned area
4. CONCLUSION

The burning experiment was conducted with 9 polyurethane mattresses, and the results confirmed the relation between the variables which describe the heat release curve, the dimension and the density of the objects. It is presumable that the fire growth rate is inversely proportional to the square value of the object’s density, and the same tendency was confirmed by the experimental data. The maximum heat release rate can be calculated as the product of the maximum burned area and the average heat release rate until it reaches 90% of the total heat release, as obtained from the experiment with the cone calorimeter.

REFERENCES