BURNING RATE OF FUELS AND GENERATION LIMIT OF THE EXTERNAL FLAMES IN COMPARTMENT FIRE

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ABSTRACT

The generation of external flames from windows, which plays a important role in upper floor fire spread, depends on the fire behavior in the compartment. Small scale fire tests using methanol, PMMA and wood as the fuels were conducted to investigate into the effect of fuel conditions on burning rate and generation of external flames. The measurement of the temperature, the burning rate and the heat release rate, and the observation of emergence of the external flames were conducted for different fuel and ventilation conditions. It is found that the burning rate obtained by Kawagoe et al. for ventilation controlled period of crib fire holds regardless of the type of the fuels tested in this study and that the criteria established based on stoichiometric air/fuel ratio and ventilation factor may be used for assessing the emergence of the external flames.

KEYWORDS: *Small scale tests, External flames, Compartment fire, Burning rate, Ventilation factor*

1. INTRODUCTION

It is beneficial for effective prevention of fire spread in buildings to have a means to predict the behavior of the external flames ejecting from windows of a room under fully developed stage of fire, since the flames are the major cause of the fire spread to adjacent upper floors.

The behavior of the hot gases ejecting to outdoor through openings of fire compartments was studied most extensively by Yokoi [1]. Based on his work, it is possible to predict the temperature profile of the window plume if the heat associated with the flow through the opening is properly given. As an application of this work to practical problems, Yokoi proposed an engineering method for the assessment of the hazard of upper floor fire spread, in which the heat of the opening flow was calculated only from the compartment fire temperature predicted using the method by Kawagoe et al. [2], in other words, the heat release due to the combustion of the excess fuel in external flames was ignored.

It will be important to take into account the heat release due to the combustion of excess fuels because it can have significant effect on the opening flames and plume. In order to assess the heat release of excess fuels, it is first necessary to predict the rate of the excess fuel ejecting out from the fire compartment. This is considered as the difference of the rate of generation of combustible fuels by the thermal decomposition from the rate of consumption of the fuels by the combustion within the compartment. The maximum value of the latter can be estimated rather easily from that the maximum heat release rate is controlled by the rate of air supply to the compartment. The former, which is usually called as mass burning rate m , has often been calculated by the empirical formula: $m = 6AH^{1/2} \text{ (kg/min)} = 0.1AH^{1/2} \text{ (kg/s)}$, where $AH^{1/2}$ is called as ventilation factor [3][4].

However, it is somewhat hard to believe that mass burning rate is simply determined only by ventilation factor. It must depend on heat transfer to fuels [5]. It is suspected that the existing formula for the

mass burning rate may hold only for the limited conditions under which the experiments by Kawagoe and others were conducted.

In this study, room fire experiments are carried out for different kinds and surface areas of fuels and opening conditions to investigate into the effects of these conditions on the mass burning rate and the emergence of external flames.

2.TEST METHOD

2.1 Model Fire Room

The setup of the experiments consists of a model fire room and a capture hood as shown in Figure 1. The dimensions of the room are 110cm (width) $\times$ 180cm (depth) $\times$ 110cm (height). The walls are made of 5cm thick parlite boards. A fuel bed is arranged on the floor of the model room and the load cells are placed below the legs of the fuel bed to measure the mass loss rate. The capture hood is connected with an exhaust fan through an exhaust duct in which a thermocouple, multiple pressure probes and gas sampling probe are equipped.

Figure 1: Schematic diagram of experimental apparatus

2.2 Kinds and Arrangement of Fuels

In this series of experiments, three kinds of fuels: a)methanol, b)PMMA and c)wood are used as the fuel. The unit size is set for each of the fuels as follows:

a)methanol ; rectangular container of $45\text{cm} \times 45\text{cm} \times 5\text{cm}$ (depth)

b)PMMA ; piece of board of $22.5\text{cm} \times 22.5\text{cm} \times 0.5\text{cm}$ and $45\text{cm} \times 45\text{cm} \times 0.5\text{cm}$

c)wood ; piece of cedar board of $45\text{cm} \times 30\text{cm} \times 6\text{cm}$ and $45\text{cm} \times 30\text{cm} \times 3\text{cm}$, and pine wood crib stick of $2\text{cm} \times 2\text{cm} \times 60\text{cm}$

Different number of the units are arranged in each test as shown in Figure 2 to realize different fuel surface area condition. The conditions of the fuels in this series of tests are summarized in Table 1. Note that the total quantity of methanol for each of A(1), A(2) and A(4) cases is the same over through the surface area is different. Likewise, the total weight of PMMA for each of P(1), P(2) and P(4) , and P*(1), P*(2) and P*(4) are the same, respectively. But the weight of the wood fuel is the same only for W(1) and W(2). Incidentally, the values of fuel properties in the table are quoted from references [6]~[8].

Table 1: Conditions of fuel

Type	Methanol			PMMA						Wood		
	A(1)	A(2)	A(4)	P(1)	P(2)	P(4)	P*(1)	P*(2)	P*(4)	W(1)	W(2)	W(4)
Surface area(m^2)	0.2	0.41	0.81	0.13	0.22	0.42	0.24	0.43	0.83	1.33	2.41	2.62
Weight(kg)	3.17			2.4			4.8			13	13	8
Volume(L)	4			—			—			—		
Latent heat of gasification(kJ/kg)	1170			1630			1700			1700		
Heat of combustion(kJ/kg)	22300			25200			18400			18400		
Stoichiometric air/fuel ratio	6.47			8.28			5.7			5.7		

a) Methanol

b) PMMA

c) Wood

Unit : cm

Figure 2: Schematic diagram of fuel arrangement

2.3 Ignition

The fuels are ignited somewhat differently depending on the type of fuel: Methanol is ignited simply by gas lighter. The gas burner with the 50 liter/min.(78.2kW) supply rate of propane is provided for PMMA and wood panels until they catch fire. The burner is turned off as soon as the fuel has started to burn by themselves. The crib fuel are started to burn by igniting the methanol saturated textile board sticks placed under the cribs.

2.4 Opening condition

The opening conditions in this series of experiments are shown in Table 2. In case of methanol and wood crib fuel, the tests were conducted for all the opening conditions listed in Table 2. On the other hand, the PMMA and the wood panel fuels were tested for the ventilation factors smaller than 0.8 and 0.5, respectively, for it was too harder to ignite these fuel by the propane burner when the opening factor is larger than these values. The PMMA fuels with the total weight of 4.8kg (P*(1), P*(2) and P*(4)) are tested only for the three conditions in which the opening width is 0.3m.

2.5 Measurement

(1) Burning rate

The mass burning rate is measured by the four

(Opening height 0.3m×width 0.4m)

(Opening height 0.3m×width 0.8m)

a) Methanol

(Opening height 0.3m×width 0.4m)

(Opening height 0.3m×width 0.8m)

b) PMMA

(Opening height 0.3m×width 0.4m)

(Opening height 1.0m×width 0.2m)

c) Wood

Figure 3: Temperature for different opening conditions

load cells (full scale: 50kg, accuracy: $\pm 0.05\text{kg}$) installed under the fuel table (see Fig.1).

(2) Heat release rate

The total heat release rate of fire is measured by applying the oxygen consumption calorimetry to the burning product gases captured by the hood installed outside of the opening [9].

(3) Temperature

The room temperature is measured by C.A. thermocouples of $\phi 0.65\text{mm}$ arrayed vertically by 10cm spacing on the thermocouple trees which are positioned in the vicinity of the two corners in the model room (A, B in Fig. 1).

The temperature at the opening is measured by the four thermocouples arrayed vertically along the central axis of the opening.

(4) Incident heat flux

The incident heat fluxes to the ceiling and the floor in the room are measured by the total heat flux meters [10][11].

(5) External flames

The emergence of the external flames from the opening is observed by eye, and the time of appearance and disappearance of the flames is recorded. The emergence of external flames is judged not by instantaneous appearance but by a degree of continuous ejection of flames.

Table 2: Conditions of opening

Height(m)	Width(m)	Ventilation factor
0.3	0.4	0.066
	0.6	0.099
	0.8	0.131
1	0.2	0.2
	0.3	0.3
	0.4	0.4
	0.5	0.5
	0.6	0.6
	0.7	0.7
	0.8	0.8
	0.9	0.9

3. TEST RESULTS AND DISCUSSIONS

3.1 Room Temperature

Figure 3 shows the examples of the fire room average temperatures. The temperature rise due to the initial burner source, which is before the ignition of

the fuels, is disregarded for PMMA and wood panel to avoid confusion.

In case of methanol fuel, a notable difference can be observed between the cases of $0.3 \times 0.4\text{m}$ and $0.3 \times 0.8\text{m}$ openings: In the former, only slight difference is observed in the tendency of temperature regardless the different fuel surface area, while in the latter, the temperature rise and the duration of high temperature vary to a large degree depending on the difference of fuel surface area. However, fuel type A(1) is not affected by the difference of the opening size.

In case of PMMA, the rise and duration of the temperature are different between the two opening conditions, but for each opening condition, the tendency of the temperature is similar regardless the difference of the fuel surface area.

In case of wood, the difference in the room temperature due to the opening condition is not apparent. The temperature seems to be rather affected by the conditions of fuel in this particular cases.

3.2 Mass Burning Rate

(1) Mass burning rate and heat release rate

Figure 4 a), b) and c) show the examples of the transient changes of the mass burning rates and the heat release rates of methanol, PMMA panels and wood panels, respectively. Two mass burning rates are shown in each figure: Burning rate(load cell) denotes the mass burning rate obtained from the mass loss measurement using load cells, and Burning rate(HRR) denotes the mass burning rate obtained by dividing the measured heat release rate(HRR) by the heat of combustion of the corresponding fuel.

While all the heat release in a) is produced by the combustion of the methanol, the heat release rates until about 7min. in b) and until about 10min. in c) are generated by the gas burner before the ignition of PMMA and wood, respectively, so the data during this time periods are omitted for the purpose of the present study. The two mass burning rates, i.e.: one derived from direct measurement of the fuel weight loss using the load cell and the other calculated from the heat release rate, are in good agreement for a) methanol and b) PMMA. On the other hand, the agreement of the two mass burning rates is poor for c) wood. This discrepancy is considered to be induced by the moisture vaporization from wood, which is included in the measurement of the mass loss rate by the load cells.

Henceforth the mass burning rate calculated from the heat release measurement is used since this seems more accurate than that measured by the load cell.

Figure 4: Transient rate of burning and heat release from ignition of fuels

(2) Mass burning rate and ventilation condition

In Figure 5 a) - c), the average burning rate during the vigorous fire stage reduced from each test versus the ventilation factor of corresponding opening condition. A black symbol indicates the test is plotted case where external flames was observed, which

implies that the fire is approximately under ventilation controlled stage, and an open symbol indicates the case with no external flames, which implies that the fire is approximately under fuel controlled stage. The broken line in each figure shows the burning rate empirically derived by Kawagoe et al.:

$$m_{bk} = 0.1A\sqrt{H} \quad (1)$$

The solid line indicates the maximum burning rate of the fuel that can be burned by the stoichiometric combustion with the air supplied into compartment through opening mps, i.e.:

Figure 5: Ventilation factor and burning rate

$$m_{b,s} = m_a/\gamma \quad (2)$$

where m_a is the rate of air inflow and γ is the stoichiometric air/fuel ratio.

Here, m_a is estimated by

$$m_a = 0.5A\sqrt{H} \quad (3)$$

and the value of the stoichiometric air/fuel ratio given in Table 1 is used for γ of each fuel, yielding:

$$m_{b,s} = \begin{cases} 0.077 \\ 0.061 \\ 0.089 \end{cases} A\sqrt{H} \quad \text{for } \begin{cases} \text{Methanol} \\ \text{PMMA} \\ \text{Wood} \end{cases} \quad (4)$$

The burning rate given by Eqn.(4) can be said as the theoretically maximum rate of fuel that can be combusted within the compartment, which imply that if the rate of production of fuel volatiles due to the thermal decomposition in the fire room exceeds this value, excess fuel will be ejected out to the outdoor to produce external flames.

It can be seen from Figure 5 a) - c) that the maximum value of the burning rates at ventilation controlled stage almost agree with Eqn.(1) regardless the kind and the surface area of fuel. In other words, the burning rate empirically derived by Kawagoe et al. for wood crib seems to hold for a variety of fuel conditions, type and surface area, which is quite interesting.

(3) External flames

The solid lines in Figure 5 a) - c) , i.e. Eqn.(4), seems to be reasonably appropriate as the criteria for the emergence of external flames when the value of ventilation factor is small. However, it is not indisputably a good criteria when the ventilation factor is large. This is thought to be because the inside compartment air becomes to be more stratified than uniform as the opening becomes larger so Eqn.(3) becomes to overestimate the rate of air inflow through the opening.

(4) Mass burning rate per unit surface area of fuels

The burning rate per unit surface area of each fuel is shown in Figure 6 a) - c), respectively. The abscissa means the theoretically maximum rate of fuel that can be combusted within the compartment per unit fuel surface area. The coordinate is the measured mass burning rate per unit fuel surface area. The broken lines indicate

$$\frac{m_{bk}}{A_F} = \frac{0.1A\sqrt{H}}{A_F} \quad (5)$$

that is, the mass burning rate empirically derived by Kawagoe et al. divided by fuel surface area A_F . The horizontal chain lines indicate the free burning rates

per unit fuel surface area which were measured in open space.

Figure 6: Stoichiometric and measured burning rate per unit fuel surface

As can be seen in the figures, the measured mass burning rates per unit surface area for each fuel almost

lies along the same curve regardless the fuel surface area, with only exception of the case of P(1). They increase along the broken lines of Eqn.(5) where the value of the abscissa is small, which imply the burning rates in this region are also independent of the fuel type and only dependent on the ventilation factor. The point where the measured burning rates and the diagonal solid line merge may be approximately regarded as the threshold of the emergence of external flames for each fuel. The value of abscissa of this point can be identified as 0.025, 0.06 and 0.006 for methanol, PMMA and wood, respectively. Based on these values, the criteria of external flames emergence can be written as

$$\frac{A\sqrt{H}}{A_F} = \begin{cases} 0.324 \\ 0.994 \\ 0.068 \end{cases} A\sqrt{H} \quad \text{for} \begin{cases} \text{Methanol} \\ \text{PMMA} \\ \text{Wood} \end{cases} \quad (6)$$

The peak values of the measured burning rates differ depending on fuel type. The peak of methanol is not much different from its free burning rate, while the peaks of PMMA and wood are about 6 ~ 7 times and twice larger than their free burning rates, respectively. As the value of the abscissa increases after the peaks, the measured burning rates gradually come down to reach to the respective free burning rates.

3.3 Heat Flux and Mass Burning Rate

(1) Incident heat flux and mass burning rate

Figure 7 shows the examples of the incident heat fluxes to the ceiling and the floor measured by total heat flux meters. The period before the ignition of the fuels are omitted from the figure for the case of PMMA and wood panels. While the heat fluxes to the ceiling and the floor are close in case of PMMA, the floor heat flux is considerably lower than the ceiling heat flux in case of methanol and wood. The reason is considered to be because the room was fully filled with flames in the case of PMMA so both of the ceiling and the floor heat flux meters were exposed to the flames. On the other hand, in the other cases, although the ceiling was covered by the flames, the floor was under the influence of inflow air even in the fully developed stage so the heat flux meter might be cooled down by the air flow.

If the net heat flux to fuel q_F is known, the mass burning rate at nearly steady state fire period can be calculated as

$$m_b = \frac{q_F A_F}{L_V} \quad (7)$$

where L_V is the latent heat of fuel gasification.

a) Methanol

b) PMMA

c) Wood

Figure 7: Incident heat flux to ceiling and floor

In view of speculating the heat flux to the fuels, which are covered by flames, it will be more adequate to use the ceiling heat flux than the floor heat flux. Figure 8 shows the comparison of the measured and calculated burning rates. The latter is calculated using Eqn.(7) and the ceiling heat flux averaged over the period of vigorous burning stage.

Figure 8: Incident heat flux to ceiling and burning rate

Figure 9: Incident heat flux to ceiling of compartment

As can be seen in Figure 8, the measured and calculated mass burning rates are close for methanol and PMMA fuels, although the data scatter somewhat, as is often inevitable in this kind of experiments. On the other hand, the measured burning rate is much smaller

than the calculated burning rate in case of wood fuel. The former is only 1/4 of the latter. This is considered to be by the effect of char forming on the surface of wood.

As we look at the data more closely, the regression

lines of the data for the cases with external flames seem to pass through the origin, while those for the cases without flames seem to reach a bit above the origin. This is suspected to be because the burning rates of the latter cases are more controlled by the heat flux from the flames above the fuels than the heat flux from the compartment at elevated temperature.

(2) Heat flux and ventilation factor

It has been shown that the mass burning rate of the fuels for ventilation controlled stage can be well predicted by Eqn.(1), i.e. the relationship empirically derived by Kawagoe et al.. Substituting Eqn.(1) into Eqn.(7), we have

$$q_F = 0.1L_V \frac{A\sqrt{H}}{A_F} \left(\propto \frac{A\sqrt{H}}{A_F} \right) \quad (8)$$

that is, it follows that the heat flux to fuel in ventilation controlled stage is proportional to the ventilation factor divided by the fuel surface area. Figure 9 shows the relationship of the ceiling heat flux with this parameter. The solid line represents Eqn.(8). If we disregard the cases without external flames and only focus on the cases with external flames, i.e. ventilation controlled cases, the data seem to be approximately proportional to the value of abscissa. Although the measured heat flux is far larger than that deduced from the relationship of Eqn.(8) in the case of wood, the agreement seems to be fair for methanol and PMMA.

4. CONCLUSIONS

The compartment fire experiments were conducted to investigate the effect of the fuel conditions on the burning rate. The major findings from the results of the this experiments are as follows:

(1) Mass burning rate

- (a) the mass burning rate increases proportionally to the ventilation factor and well agrees with the relationship given by Kawagoe et al. regardless the kind and the surface area of the fuels when the factor is small,
- (b) the mass burning rates gradually decreases as the ventilation factor increases beyond a certain value and asymptotically approaches to the free burning rate of the fuel, and
- (c) the maximum value of the mass burning rate in the test enclosure is about 1.5, 4-5 and 2 times larger than the free burning rate for methanol, PMMA and wood, respectively.

(2) External flames

- (a) external flames always emerge under ventilation controlled conditions,
- (b) a fairly good threshold condition can be deduced from the opening flow rate and the stoichiometric air fuel ratio.

(3) Incident heat flux and mass burning rate

- (a) the heat flux to fuel in the ventilation controlled stage is considered to be proportional to the ventilation factor divided by the fuel surface area under ventilation controlled conditions,
- (b) the mass burning rate of methanol and PMMA can be estimated from the incident heat flux and the latent heat of gasification.
- (c) the measured burning rate of wood fuel is about 1/4 of the burning rate estimated from the incident heat flux.

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NOMENCLATURE

A	:Area of opening (m^2)
A_F	:Area of fuel surface (m^2)
H	:Height of opening (m)
L_V	:Latent heat of fuel gasification (kJ/kg)
m_a	:Rate of air inflow (kg/s)
m_b	:Mass burning rate (kg/s) (Experiment)
m_{bk}	:Mass burning rate (kg/s) (Kawagoe's formula)
$m_{b,s}$	:maximum burning rate of the fuel that can be burned by the stoichiometric combustion with the air supplied through the compartment opening (kg/s)
q_F	:Intensity of radiant heat (kW/m^2)
γ	:Stoichiometric air/fuel ratio Subscripts
m	:Methanol
p	:PMMA
w	:Wood