BURNING BEHAVIOR IN A POORLY-VENTILATED COMPARTMENT FIRE — Ghosting Fire —

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ABSTRACT

We have investigated fire behavior in a poorly ventilated compartment using a methyl alcohol pool fire of 30cm ϕ as a source in a box of 2m(W) $\times$ 3m(L) $\times$ 0.6m(H). Temperatures, gas concentrations of CO, CO₂, O₂, and methyl alcohol vapor, fuel consumption rate, and air exchange rate were measured simultaneously. The level of the fuel surface was kept constant during the tests by means of automatic fuel supply system. The flame began to detach from the fuel surface as the oxygen concentration decreased to about 6 vol.%, it color then becoming pale blue. The flame later detached from the fuel surface and a "ghosting flame" was observed for 20–40min. In the poorly ventilated burning conditions, it was revealed that the air exchange rate was about 5 liters/sec, oxygen concentration was about 13–14 vol.%, and the burning rate was about 0.3–0.33 g/sec which was almost 1/5 of the normal burning rate. Based on the O₂ and CO₂ concentrations and air exchange rate, the fuel consumption rate was estimated and which corresponded to the consumption rate measured. It was found that three times of the stoichiometrically required ventilation was occurred in the ghosting period and it ensured complete combustion of methyl alcohol.

key words : ghosting fire, poorly ventilation, compartment fire, detached flame, flammability limit.

1. Introduction

We have conducted about 250 model fire tests in a compartment with low natural ventilation conditions. These tests were carried out to improve a model compartment fires to accommodate better the condition of very low natural ventilation which obtains in some recent designed residential/office buildings, under ground structures, ship compartments, and nuclear power plants. To avoid the diffusion of combustion products (hot smoke and gases) in buildings, and to avoid the leakage of radio active particles from atomic power plants, small air exchange openings are provided in these buildings. It is plausible that in an enclosure of

such buildings a fire would become a ghosting fire [1] in the energy rich and poorly ventilated condition [1,2] that obtain. It has been tacitly assumed in the past that flame (combustion reaction zone) stands on a pyrolyzing material (fuel, fuel supplying zone) and leave the compartment together, but for the ghosting fire this is not necessarily so. However, the burning behavior under the poorly ventilated (i.e. fuel rich and oxygen lean condition) and high temperature condition has not been clearly obtained. Therefore, on the fire simulation of the pre-flashover and flashover, and of fire safety view points, the mechanism of the ghosting flame (or ghosting fire) needs further clarification. And the other

view point on the fire fighting. The extinction of the ghosting fire in a poorly ventilated enclosure such as an air-tight compartment, compartment with small openings must be extremely difficult.

2. Experimental

A model compartment with 2m (W) $\times$ 3m (L) $\times$ 0.6m (H) was made by calcium silicate boards used as outer walls and ceramic boards inside of 25mm (T) as is illustrated in Figure 1. Two adjustable slit panels were provided on the upper area of the front wall. An openable service door was also set at the front wall which had a 10cm $\times$ 10cm glass observation window. The door was closed and sealed during tests.

Methyl alcohol in a stainless steel pan of 30cm diameter with 5cm lip was set 30, 35 or 40cm height above the floor in the center of the compartment and was used as a fire source. The fuel was supplied through a copper tube from a reservoir which was set outside so that the fuel level in the pan have been kept constant of 2cm depth during the burning. The fuel consumption rate was estimated based on the change of level by means of the level meter which attached to the reservoir.

Temperatures were measured by 0.3mm ϕ chromel-alumel thermocouples with stainless steel shield cover. We set and monitored 12 thermocouples, five of which were located on a vertical rake with 150mm spacing. Another 5 thermocouples were set vertically above the fire source with 50–75mm spacing to measure the

flame zone temperatures. One thermocouple located in the outside atmosphere and the last was set in the fuel to monitor the fuel temperature.

Concentrations of CO, CO₂ and hydrocarbon gases were measured by gas analyzers of a non-disperse Infra-red detecting type, and oxygen was measured simultaneously by a galvanic battery type detector. Methyl alcohol vapor concentrations were also measured by detecting tube.

Measuring positions of A–G for temperature and gas concentration in the compartment were illustrated in Figure 1, and at each position we set a rake which contained 5 measuring locations of 600mm (corresponding to the ceiling height : point 5), 450mm (point 4), 300mm (point 3), 150mm (point 2), and 5mm (point 1) from the floor. Air exchange rate was estimated by means of time variation of SF₆ gas concentration during the test.

No mechanical ventilation system was employed during the test so that natural ventilation system was employed during the test. Natural ventilation occurred due to the pressure difference given by temperature difference.

The experimental procedure taken was ; the fire source was ignited by a pilot flame and then the service door was closed.

After 4min from the ignition , the total opening area of the both slits was adjusted to 150–160cm² to avoid choking and to keep the limited ventilation.

Fig.1-(a) Outline of the compartment for the ghosting tests. Numbers correspond to the height from floor, as 1 : 600mm, 2 : 450mm, 3 : 300mm, 4 : 150mm and 5 : 5mm.

Fig.1-(b) Measuring positions of A-K in the compartment, length unit is mm.

3. Results and Discussion

(a) Observation

The diffusion flame impinged on the ceiling for the first 6–7 min, and then flame began to detach partly from the circular pan edge. The flame color, initially bright orange became pale purple blue. About 10 min after the ignition, the flame detached from the fuel surface and the very thin blue flame was observed depend on the severity of the ventilation condition. When the fire source was located 40 cm above the floor, the pale blue flame completely detached from the pan and it floated just under the ceiling like an crown shape jellyfish or like an aurora having very thin skin-like flame showing a width of about 5–10 cm and a diameter of about of about 40 cm. We called this "ghosting flame" after Foote [1] and which continued for times varying from 7 to 20 minutes in the different tests. Sometimes it came down to the fuel surface and formed an attached flame again. As the fuel pan located 30 or 35 cm above the floor, the pale blue flame exhibit very thin skin-like flame but its foot did not detach completely from the fuel or pan edge but extended vertically and which continued for about 20–40 minutes. Both of theses pale blue skin-like flames were looked like an aurora. We stopped the fire after 40 min due to the limit of the fuel supply system.

Photo 1 Ghosting flame located under the ceiling and above the 40 cm height fire source pool. The photo was taken by a IR-sensitive film with 1 sec exposure with a fully opened iris.

The ghosting flame from 30 cm or 35 cm height pool was longer than the one from 40 cm height pool.

During the normal burning period (i.e. before the ghosting flame appeared), a flame pulsation frequency of about 3 Hz was estimated from the picture analysis due to the 16 mm movie films and it decreased abruptly to almost zero about 3 sec before the ghosting flame began. Figure 2 shows the outline of the flame shapes during the transition from normal burning flame to the

Fig.2 Outlines of flame shape in the transition from normal burning to ghosting flame.
The last two flame shapes correspond to the starting of the ghosting flame.

ghosting one with the last two figures show the beginning of the ghosting flame. Photo 1 shows the ghosting flame from the 40cm height pool which appeared under the ceiling just above the pool.

(b) Consumption Rate of the Fuel

Figure 3 shows the variation in time of consumption rate of the fuel. In the normal burning period, the con-

sumption rate was about 2 g/sec for the 30 or 35cm height pool used. The fuel consumption rate started to decrease as the ghosting begun and which showed about 0.3–0.33 g/sec (0.94×10^{-2} – 1.03×10^{-2} mol/sec) in the ghosting period. In the ghosting conditions, the consumption rate showed almost quasi-steady state and reduced to about 1/6 of the normal burning rate.

Fig.3 Time history of the consumption rate of the methyl-alcohol as a fuel in case of 35cm height pool was used. The triangle mark indicates the start of ghosting.

(c) Gases Concentrations

Figure 4 shows the typical variation in time of the gas concentrations and a triangle mark in the figure shows the start of the ghosting. Numbers in the Figure 4 refer to the sampling height at each sampling rake. It is very clear that the measured carbon monoxide concentration was very low (almost noise level of the gas analyzer). The oxygen concentration showed about 6

vol.% when the ghosting begun and then increased slowly to 11–14 vol.% varying the heights. The time variation of oxygen concentration showed nearly quasi-steady state in the ghosting period. This concentration level almost corresponds to or little lower than the upper flammability limit [3] of methyl alcohol. When the oxygen concentration decreased under this critical value (about 4.5–5 vol.% of oxygen concentration in

Fig.4 Typical variation in time of CO, CO₂, and O₂ gas concentration in the compartment at measuring position G. The triangle mark indicates the start of ghosting.

Fig.5 Typical CO₂ and O₂ gas concentration distributions for vertical direction in the ghosting period. 30cm height pool was used.

our test) or more dense fuel vapor evolved due to the excess electrical heat added to the pan, spontaneous extinguish was clearly observed. The concentration of carbon dioxide and oxygen, as shown in Figure 5, varied with height and its vertical profile was nearly uniform with some gradient in the upper part during the ghosting period. This profile is quite similar to the one obtained by Foote [1] using methane gas as a fuel. In

the upper layer, the CO₂ concentration was about 6 vol.% and was about 4 vol.% from and below the mid height at point G. Figure 5 also shows the O₂ concentration with vertical direction of 11 vol.% in the upper layer and increased to 12–14 vol.% toward the floor. Based on these gas concentrations measured at points A–K (each point has 5 measuring points), we estimated the time and space averaged gas concentra-

Fig.6 Methyl alcohol vapor concentration variation with time when 35cm height pool was used. The vapor was measured at 0, 300mm, and 600mm high from the floor.

Table 1 Averaged CO₂, O₂ gas concentrations
(in case of 30cm height pool)

Measuring Point	CO ₂ (vol.%)	O ₂ (vol.%)
A	5.33–5.73*	12.11–12.56
B	4.83	12.95
C	5.14–5.47	12.37–12.77
D	4.92–4.99	12.32–12.72
E	4.51–5.08	11.90–13.55
F	5.34–5.55	11.47–12.78
G	5.29	12.04
H	4.97–5.41	12.10–12.81
I	5.24–5.53	11.49–12.40
J	5.06–5.72	11.89–12.70
K	5.62	11.78

(in case of 35cm height pool)

Measuring Point	CO ₂ (vol.%)	O ₂ (vol.%)
A	5.96	11.81
B	5.45	12.88
C	5.95	12.54
D	4.96	11.79
E	4.88	13.11
F	5.91	13.05
G	5.91	12.14
H	4.71	12.29
I	4.91	11.47
J	6.07	12.62
K	5.89	12.21

* The value with variation due to different experiment.

tions in ghosting period and are shown in Table 1.

Hydrocarbon gas was measured simultaneously with CO₂ gas by the gas analyzer but we could not detect it during the test. We measured also the methyl alcohol vapor concentration during the test, as is shown in Figure 6, and which revealed almost 300ppm and nearly constant during the test.

The ambient air which contained about 11 vol.% oxygen in the upper layer was entrained to be fuel rich upward current and then combustion reaction occurred after the fuel concentration reduce to the upper flammability limit at 110–150°C ambient temperature so that the ghosting flame located just under the ceiling in case of the 40cm height pool fire used. On the other case, when 30cm or 35cm height pool was employed, the wider the space between the fuel surface and ceiling the much ambient air which contains more rich oxygen than upper layer can be diffused. Then the ghosting flame extended from fuel surface to the ceiling and showed longer ghosting flame than the one from 40cm height pool.

(d) Temperature

The temperature of the fuel was measured every 10 sec at the mid depth of the fuel during the tests and Figure 7 shows the variation in time of fuel temperature. For both tests, the fuel temperature increased for the first 3–5 min and then the rate of rise dwindled with decreased of oxygen concentration. In the test 21, the ghosting flame continued for only about

Fig.7 Plot of the fuel temperatures, 40cm height pool was used.

Fig.8 Rake thermocouple profiles before and in the ghosting fire period. 30cm height pool was used.

30 sec and then self-extinguished when the oxygen concentration (measured at point B) reached about 4–4.8 %. The experimental conditions of test 24 was the same as the test 21, however, ghosting continued for 20 min more in this case.

Ghosting stopped when the fuel temperature reached about 45°C. The quenching of ghosting flame should be associated both with the high fuel concentration (over the upper flammability limit/lowest concentration of oxygen) and fuel temperature within 1–15°C of the boiling point which accelerated the vaporization. In the ghosting period, the temperature just under the ceiling decreased about 120°C as shown in Figure 7. This decrease of temperature produced less thermal radiation feedback to the fuel surface and might reduce the rate of rise of the fuel temperature. In the normal burning period, average radiation flux to the fuel surface was about 1.05 W/cm² and which reduced to about 0.37W/cm² in the ghosting period.

Figure 8 shows the vertical temperature profiles before and after the ghosting. The less fuel consumption rate in the ghosting gave lower temperature in the upper layer of the compartment, and the vertical profile changed nearly isothermal at each measuring positions. There is a thermal interface for all tests (30, 35 and 40cm height pool fires) at a height of about 300mm.

(e) Air Exchange Rate

In order to estimate the air change rate both in normal burning and in the ghosting period, we put the SF₆ gas as a tracer in the compartment and measured the time variation of which concentration and then the air exchange rate was estimated. It was found that the air ventilated at the rate of 12.3 liters/sec in the normal burning period and at about 4–5 liters/sec during the ghosting appeared.

(f) Burning rate Estimation based on CO₂ Mass Balance

Production of CO₂ gas due to the burning of the fuel in the poorly natural ventilated condition can be described as follows assuming ambient CO₂ concentration is zero.

$$V \cdot dc = M \cdot dt - c \cdot Q \cdot dt, \quad (1)$$

where V = volume of the compartment (3600 liters)

M = CO₂ production rate for time period dt

C = concentration of CO₂ in the compartment (vol.%)

Q = air exchange volume (liters/sec)

Equation(1) can be integrated with time and is expressed as,

$$c = c' \cdot \exp(-Q/V \cdot t) + (M/Q) [1 - \exp(-Q/V \cdot t)] \quad (2)$$

where $c' = \text{CO}_2$ concentration at time $= 0$.

In the ghosting period, CO_2 and O_2 gas concentrations and fuel consumption rate showed quasi-steady state, so that time is regarded as ∞ , we can have equation (3)

$$c = M / Q. \quad (3)$$

From the experimental measurements for ghosting period, we got that the average CO_2 gas concentration was about 4–5 vol.% as shown in Table 1 and air exchange rate was about 5 liters/sec respectively. We could assume neither CO nor hydrocarbon gas was produced in the ghosting period because no hydrocarbon was detected and extremely low concentrations of CO gas measured. The difference pressure between ambient and the compartment was about +0.08mm H_2O at 600mm and -0.02mm H_2O at the floor level so that we neglect the pressure effects on the volume. Thus, based on equation (3), and considering those results with neglecting methyl alcohol vapor of 300 ppm detected during the test, we can estimate the production of CO_2 as $0.89-1.11 \times 10^{-2}$ mol/sec. If the oxidation reaction of vaporized methyl alcohol can be taken as complete, we can estimate the consumption rate of the fuel as about 0.28–0.35 g/sec. This value is nearly equal to the measured one of 0.3–0.33 g/sec. The estimated oxygen concentration based on the mass balance in the quasi-steady state (in ghosting period) is 13.5 vol.% and which is nearly equal to the average value of 12–13 vol.% obtained by measurements. Therefore, it was considered that the almost vaporized methyl alcohol burnt when the combustion appeared ghosting. Foote [1] found the "ghosting fire" using a methane diffusion burner in a full scale compartment under mechanical ventilation of high-inlet-high-outlet condition and at least four times the stoichiometric ventilation rate [4] can sustain the complete combustion. As to be referred he found that the appearance of ghosting flame depended on the positions of the fire source and of the air inlet and outlet. In our case, we found that about three times of the stoichiometrically required ventilation of air was used to ensure almost complete combustion of the fuel independent of the pool height.

4. Conclusion

For no mechanical but low natural ventilated condi-

tion, fires with the ventilation rates of about three times the stoichiometrically required air produced the ghosting fire. In the ghosting fire period, it was formed that almost isothermal vertical profile and almost uniform vertical concentration profiles of CO_2 and O_2 gases with gradient in the upper layer. CO gas concentration and methyl alcohol vapor concentration were negligible small during the test. Combustion of methyl alcohol vapor was completed nearly under the low natural ventilation condition of 12–14 vol.% of oxygen concentration when it was heated up to about 120°C during ghosting period in the compartment.

Ethyl alcohol burnt under the condition of 15 vol.% oxygen concentration and of about 120°C [5] in the same compartment showing the ghosting flame. Methane gas burnt [1] under the condition of about 9 vol.% oxygen in the 127–271°C atmosphere showing sometimes ghosting flame. These experimental results indicate that the upper flammability limit for those combustible materials expand higher (i.e. more fuel rich and lean oxygen concentration condition) depending on the ambient temperature in the compartment. The upper flammability limit varies significantly with ambient temperature [6]. Such condition must appears in the pre-flashover condition and then it leads to the flashover. Oxygen starvation with high ambient temperature in a compartment due to adiabatic walls and ceiling may be obtained in actual fires, some cases have been reported by the fire brigades [7] based on their observations.

In order to advance the understanding of the pre-flashover phenomena, it is essential that the further study of the ghosting fire phenomenon which will be occurred under the poorly ventilated (i.e. oxygen starvation with rich fuel) with high temperature condition in a compartment.

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