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Characteristics of Fires in Force-Ventilated Enclosures

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ABSTRACT

A series of experiments was conducted to determine the characteristics of smoke layer formation in fires in a force-ventilated and highly airtight enclosure. By using a model box (3.6 m long, 2.4 m wide, 2.4 m high) with a controllable heat source of methane or propane, gas analysis and measurement of temperature were done. Three configurations for the ventilation system were employed: lower inlet/upper outlet, ceiling inlet/ceiling outlet, upper inlet/lower outlet. The combustion lasted for longer than 30 minutes with a lower inlet/upper outlet, but for less than that with ceiling inlet/ceiling outlet and upper inlet/lower outlet. The air supply rate was maintained at 50 m³/h, and the heat release rate was set to 100 kW. The stability of the smoke layer changed with the inlet air velocity in the case of lower inlet/upper outlet. There was hardly any formation of smoke layer with ceiling inlet/ceiling outlet and upper inlet/lower outlet.

INTRODUCTION

Most studies of enclosure fires to date have been carried out assuming natural ventilation. The fire characteristics of naturally ventilated fires are predicted by the ventilation factor $A_B \cdot H^{1/2}$ because the burning rate is controlled by the rate at which air can flow into the enclosure over the limited values of the ventilation factor (Kawagoe and Sekine 1963; Magnusson and Thelandersson 1970; Babrauskas and Williamson 1975). Recent, buildings are more airtight, and unless there is breakage of glass, siding, etc., or open windows or doors, rooms are apt to be highly airtight. In such cases, the ventilation factor theory cannot be applied for predicting fire characteristics. Also, pressurized smoke exhaust is getting popular. Therefore, it can be expected that ventilation would continue even after a fire broke out. These problems pertain to closed spaces, such as underground constructions.

Relevant studies have been reported by Beyler(1990), Zukoski *et al.* (1988), Alvares *et al.*(1984), and Backovsky *et al.*(1988). Experimental studies that focused on the temperature profiles of forced-ventilation enclosures were reported by Alvares *et al.*, and Backovsky *et al.* Zukoski *et al.* have described the combustion processes in two-layer (smoke and air) configuration. Beyler has analyzed the temperature and proposed a unique extinction mechanism observed at fires in enclosures with and without overhead forced ventilation. However, the influences of ventilation on combustion characteristics and smoke layer formation in force-ventilated enclosure fires have been studied only with scale models (Mizuno *et al.* 1991). Conventionally, a two-layer zone model, assuming a hot smoke layer in the upper part and a clean air layer in the lower part of an enclosure, is used in modeling the early stages of fire in an enclosure, but the boundary between the smoke layer and the air layer may become unstable when the temperature of the smoke layer is not so high or when significant convective flow occurs within the enclosure. The two-layer zone model cannot be applied in such situations. Moreover, an increase in the amount of smoke exhausted and a decrease in the concentration of oxygen around the flames could result in heavy production of carbon monoxide. Therefore, it is important to obtain knowledge of the smoke-layer-forming conditions of fires in force-ventilated and highly airtight enclosures.

The major purpose of this work is to estimate conditions for smoke layer formation within a force-ventilated enclosure during a fire. Estimation was done using the oxygen balance method.

DESCRIPTION OF EXPERIMENT

Figure 1 illustrates the main features of the model box. The instrumentation consists of a blower, a model box with a porous gas burner as the source with controllable heat release rate, and a gas analyzer. The wall is covered with 50-mm-thick ceramic fiberboard of thermal conductivity around 0.007 kW/m·K.

The experimental conditions were varied as follow:

1. Fuel:
   methane or propane.
2. Fuel supply rate:
   50 kW, 100 kW, 150 kW, 200 kW (heat release rate assumed perfect combustion)

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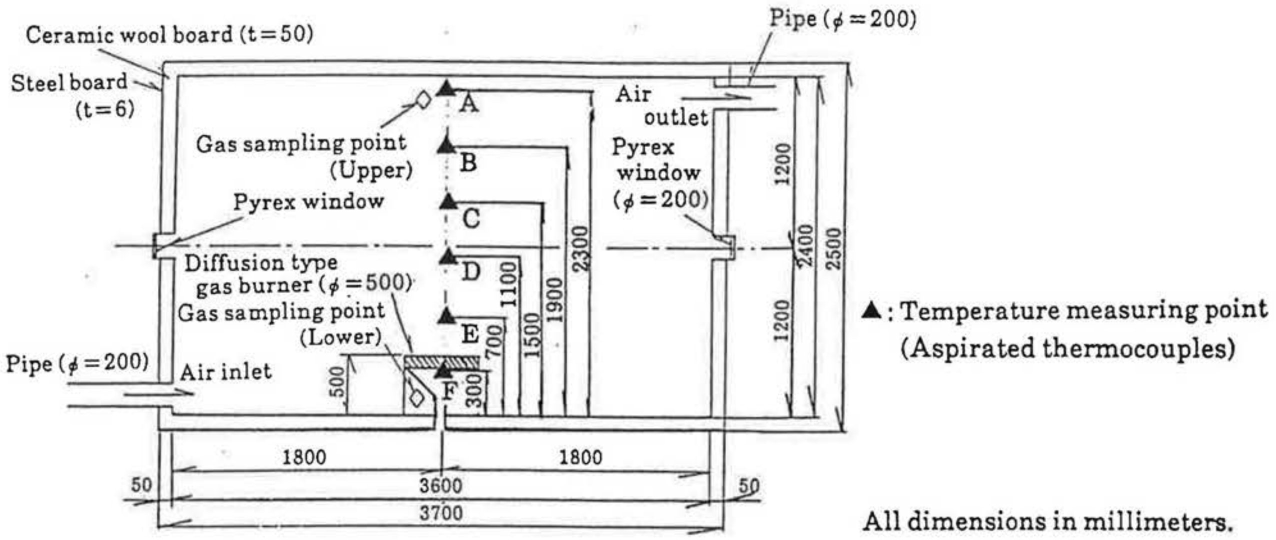
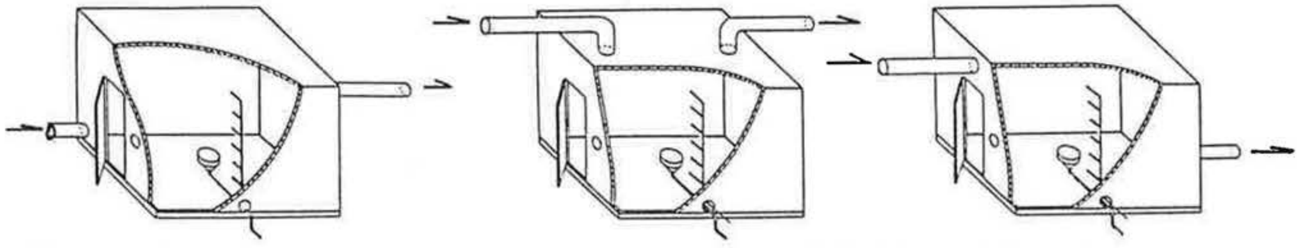


All dimensions in millimeters.

Figure 1 *Model box setup.*



(Lower inlet – Upper outlet) (Ceiling inlet – Ceiling outlet) (Upper inlet – Lower outlet)

Figure 2 *Combinations of ventilation locations.*

3. Air supply rate:
   50 m^3/h~700 m^3/h
4. Inlet air velocity:
   1 m/s~34 m/s (set by the air supply rate and the diameter of the inlet opening)
5. Ventilation inlet-outlet conditions (displayed in Figure 2):

(1)	Lower inlet/Upper outlet
(2)	Ceiling inlet/Ceiling outlet
(3)	Upper inlet/Lower outlet

EXPERIMENTAL RESULTS

Figures 3a-c through 5a-c are examples of data obtained in the case of fire caused by the methane gas burner with a fire strength of 100 kW, an air supply rate of 50 m^3/h, and for various ventilation inlet-outlet locations. Part a of each figure indicates gas temperature measured halfway between the burner and a wall. Parts b and c show the consumption of oxygen and production of carbon monoxide measured at the upper part (2151 mm above floor level.) and lower part (97 mm above floor level.) of the model box and in the exhaust duct. The combustion lasted more than >30 minutes in the case of lower inlet/upper outlet, but in the cases of ceiling inlet/ceiling outlet and upper inlet/lower outlet, the combustion lasted less than 10 minutes. Thus, for given air supply and fuel supply rates, the duration of combustion is dependent on the location of vents.

Figure 6 shows examples of temperature profiles 30 minutes after ignition with various ventilation inlet-outlet locations. In the case of lower inlet/upper outlet, typical two-layer profiles are obtained. But with ceiling inlet/ceiling outlet and upper inlet/lower outlet, there is only weak dependence of temperature on height.

SMOKE LAYER FORMATION IN THE FORCE-VENTILATED ENCLOSURE FIRES

Before beginning this discussion, it is convenient to define a parameter representing the stability of the smoke layer. Figure 7 shows a general idea of the two-layer zone model. Assuming this configuration of a two-layer zone model, the difference of oxygen consumption in the upper and lower parts of the model box is discussed for conditions similar to those used in the experiment for estimating the smoke layer

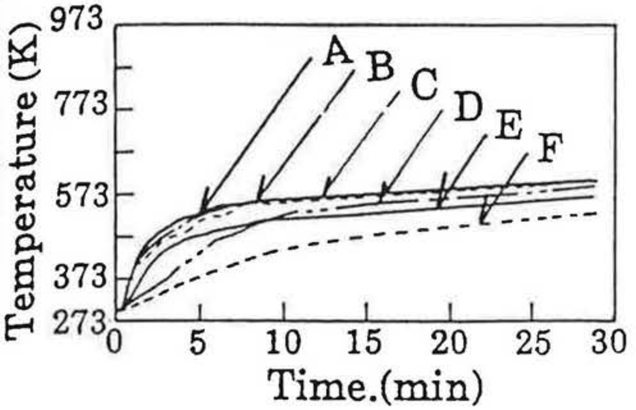


Figure 3(a) *Measured gas temperature history. (lower inlet/upper outlet, ϕ 20 cm, CH_4 100 kW, 50 m^3/h).*

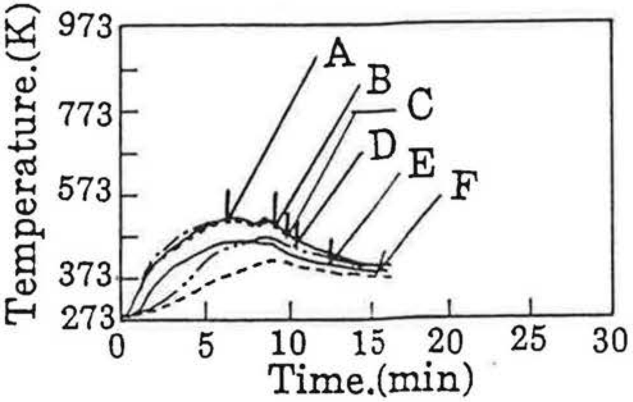


Figure 4(a) *Measured gas temperature history (ceiling inlet/ceiling outlet, 20 cm, CH_4 100 kW, 50 m^3/h).*

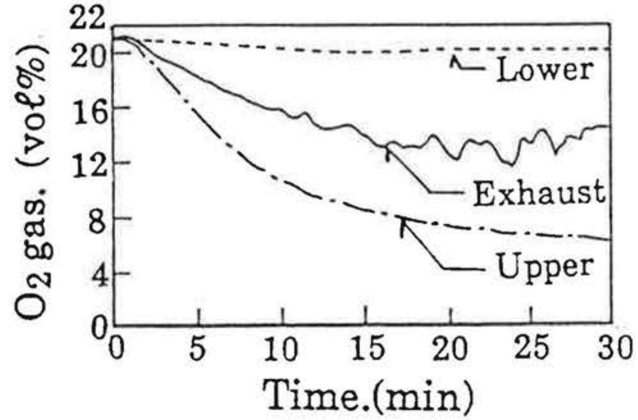


Figure 3(b) *Measured O_2 gas history (lower inlet/upper outlet, 20 cm, CH_4 100 kW, 50 m^3/h).*

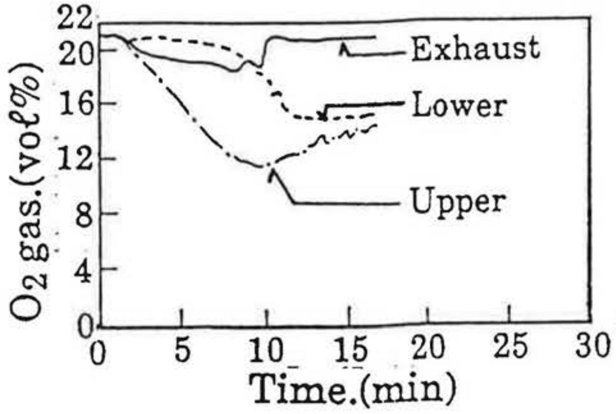


Figure 4(b) *Measured O_2 gas history (ceiling inlet/ceiling outlet, 20 cm, CH_4 100 kW, 50 m^3/h).*

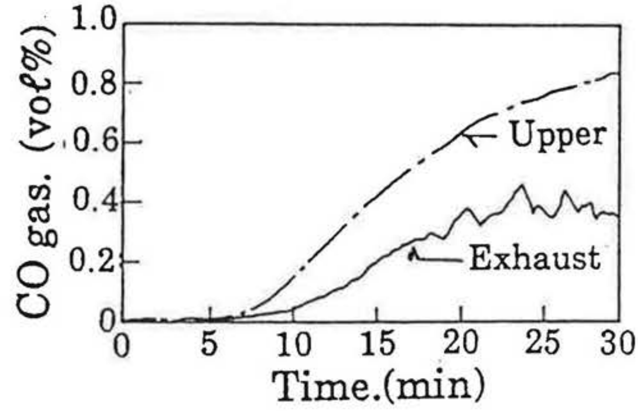


Figure 3(c) *Measured CO gas history (lower inlet/upper outlet, 20 cm, CH_4 100 kW, 50 m^3/h).*

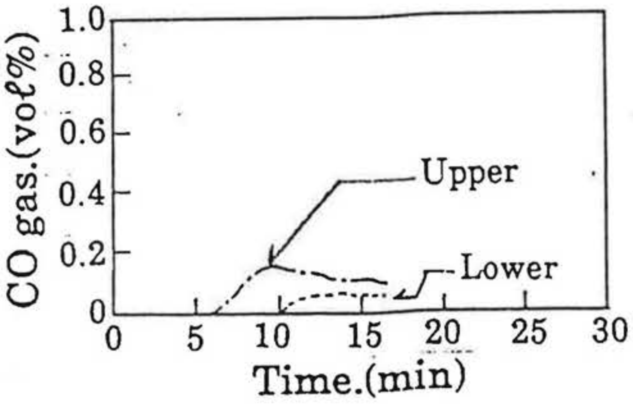


Figure 4(c) *Measured CO gas history (ceiling inlet/ceiling outlet, 20 cm, CH_4 100 kW, 50 m^3/h).*

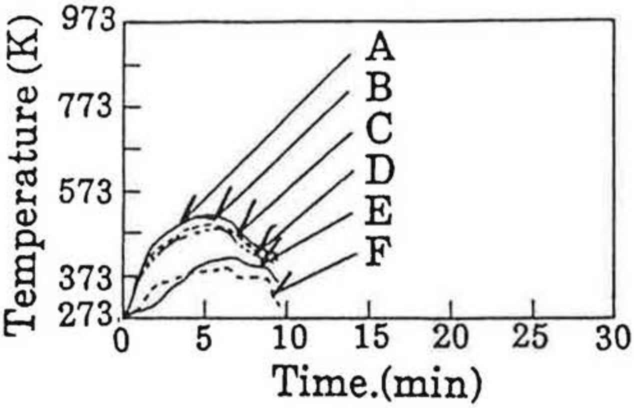


Figure 5(a) *Measured gas temperature history (upper inlet/lower outlet, 20 cm, CH_4 100 kW, 50 m^3/h).*

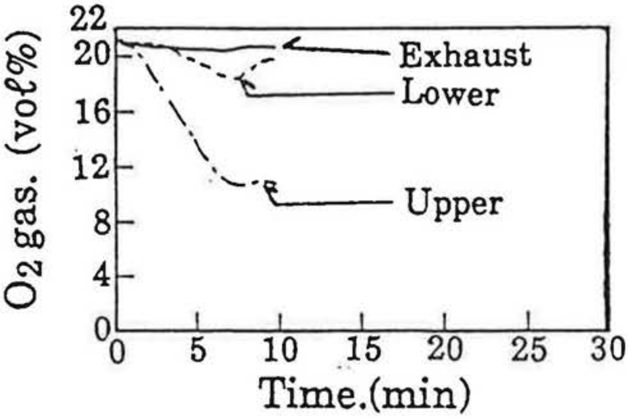


Figure 5(b) *Measured O_2 gas history (upper inlet/lower outlet, 20 cm, CH_4 100 kW, 50 m^3/h).*

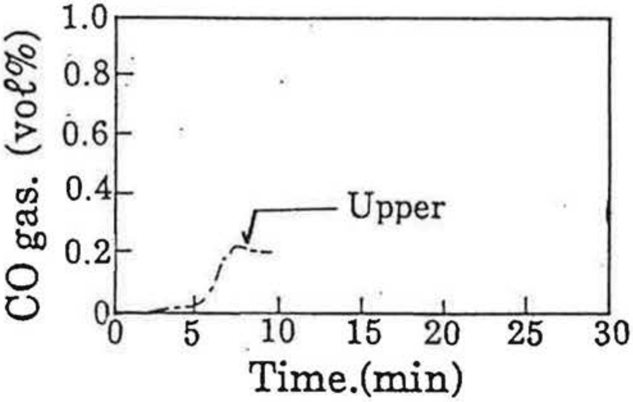


Figure 5(c) *Measured CO gas history (upper inlet/lower outlet, 20 cm, CH_4 100 kW, 50 m^3/h).*

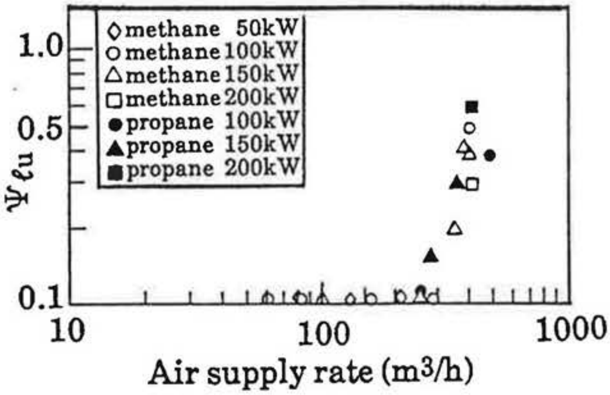


Figure 8(a) *Relation between and air supply rate (lower inlet/upper outlet, 10 cm).*

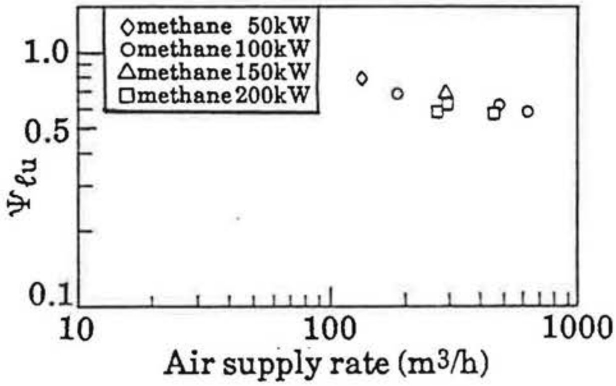


Figure 8(b) *Relation between and air supply rate (ceiling inlet/ ceiling outlet, 20 cm).*

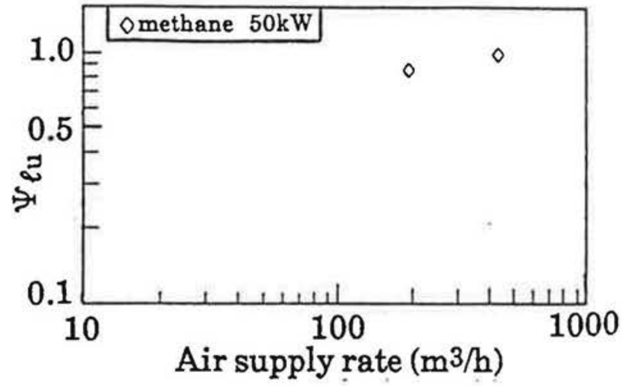


Figure 8(c) *Relation between and air supply rate (upper inlet/lower outlet, 20 cm).*

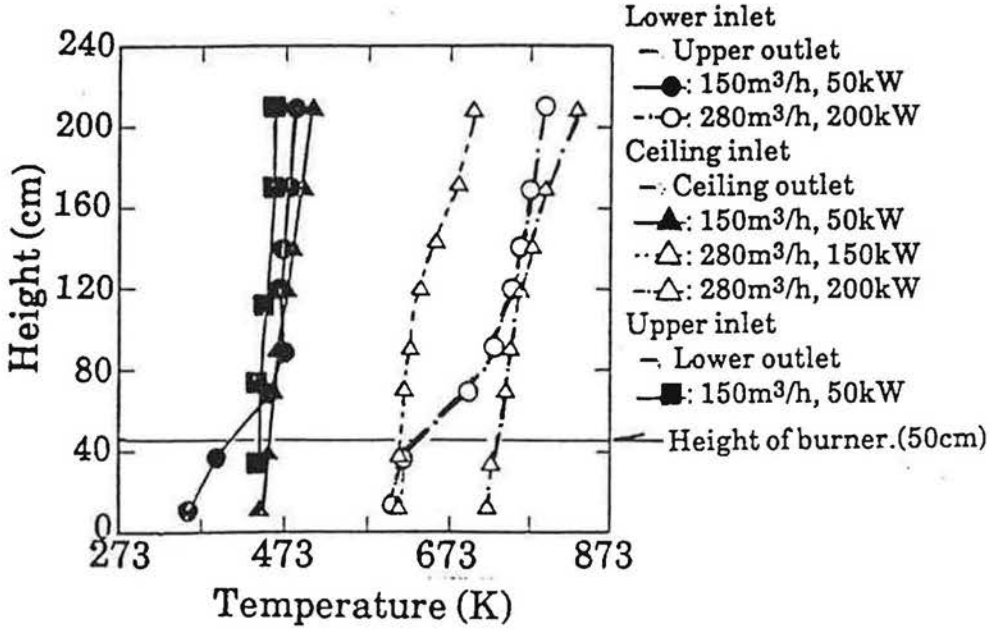


Figure 6 *Temperature profiles (30 minutes after ignition, 20 cm).*

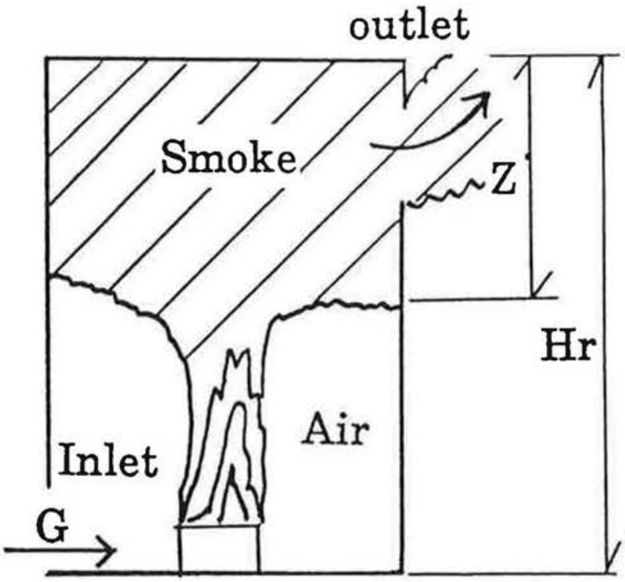


Figure 7 *A general idea of two-layer zone model.*

formation. Oxygen balances in the smoke layer and in the air layer are described as follows:

Upper part:

$$AZ(dY_u/dt) = G\cdot Yl - Q\cdot\varepsilon - (G + Q/m)Y_u - \Gamma(Y_u - Y_l) \quad (1)$$

Lower part:

$$A(H_r - Z)(dY_l/dt) = G(Y_o - Y_l) + \Gamma(Y_u - Y_l) \quad (2)$$

Assuming a steady state, equation (2) is transformed as follows:

$$Y_l = (G\cdot Y_o + \Gamma\cdot Y_u)/(G + \Gamma),\ Y_o - Y_l = \Gamma(Y_o - Y_u)/(G + \Gamma).$$

Therefore,

$$\Psi_{lu} = (Y_o - Y_l)/(Y_o - Y_u) = \Gamma/(G + \Gamma). \quad (3)$$

When a stable smoke layer is formed, mass transfer through the boundary of the layers must be controlled mainly by eddy diffusion. At this time, the mass transfer is negligibly small compared with the fire plume in the smoke layer. Therefore, $G >> \Gamma$, i.e., $\Psi_{lu} << 0.5$. When the smoke layer becomes unstable, the value of Ψ_{lu} must be close to 0.5 or even greater than 0.5. Therefore, the value of Ψ_{lu} can be used as a parameter for evaluating the stability of the smoke layer.

Figure 8a-c shows the relation between Ψ_{lu} and the air supply rate for various fire strengths and three ventilation inlet-outlet locations. The turbulence within an enclosed space when there is no fire is usually controlled by the velocity of the inlet air (Shoda *et al.* 1975) and the distribution of the gas temperature within the space. Applying this effect to force-ventilated enclosure fires, it must be said that the stability of the smoke layer formed depends on the following factors,

1. Turbulence within the enclosure becomes small at small inlet air velocity.

2. The large temperature difference between the smoke layer and the air layer results in stable formation of the smoke layer.

When the heat release rate (fuel supply rate in this experiment) and the diameter of the inlet opening are the same, both factors listed above are satisfied at a small air supply rate. Factor 2 can be achieved by increasing the heat release rate.

Figure 8a shows that Ψ_{lu} has a tendency to become smaller at smaller air supply rates, but for a given air supply rate, Ψ_{lu} does not change with the fuel supply rate in case of lower inlet/upper outlet. Figure 9 shows the relation between Ψ_{lu} and inlet air velocity in the case of lower inlet/upper outlet. When inlet air velocity is less than 6 m/s, Ψ_{lu} is very small. Ψ_{lu} increases dramatically when the inlet air velocity is greater than 6 m/s. At a velocity of about 15 m/s, Ψ_{lu} is nearly 0.4, meaning hardly any smoke layer formation. Therefore, under the current experimental conditions, it is concluded that the stability of the smoke layer is governed by factor 1. This further suggests that the thermal effect on fluid dynamics, including that caused by heat loss from the walls, plays only a negligible role in the stability of smoke layer.

Meanwhile, in case of ceiling inlet/ceiling outlet, Ψ_{lu} fell from 0.8 to 0.6 when the air supply rate rose from 130 m^3/h to 610 m^3/h, as shown in Figure 8b. With upper inlet/lower outlet, Ψ_{lu} remained between 0.9 and 1.0. There was hardly any formation of a smoke layer in both cases. This can be explained by the fact that the airflow within the enclosure during fires is easily disturbed when air whose temperature is much lower than the gas temperature is supplied in the enclosure from its upper part.

CONCLUSIONS

From the experimental results, the following conclusions can be drawn:

1. For given air and fuel supply rates, the duration of combustion is dependent on the ventilation inlet-outlet locations. Combustion lasts longer with a lower inlet/upper outlet than with a ceiling inlet/ceiling outlet and upper inlet/lower outlet.
2. In case of lower inlet/upper outlet, the turbulence within the enclosure becomes small at small inlet air velocity. The smoke layer is formed in the condition of stable airflow.

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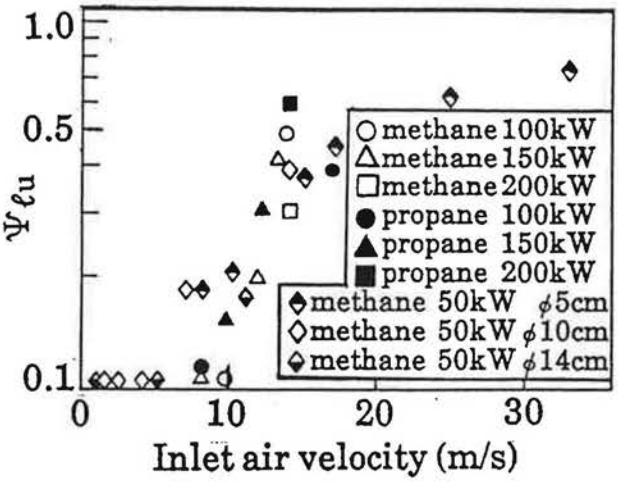

Figure 9 *Relation between and inlet air velocity (lower inlet/upper outlet, 10 cm except for methane 50 kW).*

NOTATION

A = area of floor (m^2)

AB = area of opening (m^2)

G = air supply rate (m^3/s)

H = height of opening (m)

Hr = height of room (m)

m = heat of combustion (kW/m^3)

Q = heat release rate (kW/s)

t = time (s)

Y_l = oxygen concentration of the lower part of the large model box (vol. %)

Y_o = oxygen concentration of inlet air (vol. %)

Y_u = oxygen concentration of the upper part of the large model box (vol. %)

Z = height of smoke layer (m)

ε = oxygen consumption volume per unit heat release (m^3/kW)

Γ = exchange coefficient indicating the mass transfer between the smoke layer and air layer (m^3/s)

Ψ_{lu} = parameter for evaluating the stability of the smoke layer (-)

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