Study of Force-Ventilated Fires in Closed Space

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ABSTRACT

Gas analysis and measurements of heat flux and temperature were made using a 50cm cubic model box with methanol as the fuel for grasping a phenomena that occur during force-ventilated fires in closed spaces. The criticality for heavy CO production (1-5 vol.%) can be described as a function of stoichiometric fuel to air ratio, and the CO concentration changes dramatically when the stoichiometric fuel to air ratio is approximately equal to 1.0. The combustion characteristics within the force-ventilated fire enclosure change due to the inlet and outlet conditions even if the other ventilation conditions (air supply rate, tray size) are the same. Further, gas analysis and measurements of temperature were made using a large model box (L=3.6m, W=2.4m, H=2.4m) with methane and propane as heat sources with controllable heat release rate for grasping the characteristics of smoke layer formation within the forced-ventilated fire enclosure which is highly air tight. Smoke layer formation within the force-ventilated fire enclosure is influenced by the air flow within the enclosure and temperature difference between the supply air and exhaust gas.

1. INTRODUCTION

Until now, studies of enclosure fires have been carried out assuming natural ventilation since, openings such as glass windows are usually broken by heat during fires within buildings, and outdoor air (fresh) flows into the enclosure through these openings. The fire characteristics of naturally ventilated fires are predicted by the opening factor $A_p\sqrt{H}$ [1,2,3]. But, in recent years,

rooms have become air tight depending on their intended use (use of computers, air conditioning etc.) and due to spreading use of factory made building components, for example, aluminum window frames [4]. Therefore when the rooms are kept highly air tight without breakage of glass etc., prediction methods for fire characteristics with the opening factor cannot be applied. Although most problems in naturally

Figure 1 Block diagram of instrumentation. (Small Scale experiment.)

All dimensions in millimeters.

Figure 2 Model box setup.

ventilated fires are caused by high temperatures of about 1000°C within the fire enclosure, force-ventilated fires in closed spaces (means highly air tight space) require considerations of the large amounts of carbon monoxide (CO) and soot produced by combustion. exhausting of smoke by positive pressure is not infrequently used in closed spaces. Therefore it can be expected that ventilation is continued when fires break out. These problems pertain to closed spaces such as underground constructions and spaces with few and narrow openings such as nuclear power plants.

Relevant studies have been reported by Tewarson [5], Beyler [6], Morikawa [7], Zukoski, et al [8], Foote, et al [9]. Tewarson [5] and Beyler [6] have described the conditions for CO production as a function of stoichiometric air to fuel ratio for relatively unconfined environment. Dramatic production CO in an under ventilated compartment was reported by Morikawa [7]. These studies have made clear that the conditions for CO production could be evaluated from the ratio of air to fuel generation in fires; however prediction of fuel generation in under ventilated fires is still left unsolved.

From previous studies on modeling of room fires, it is naturally expected that the fuel generation is governed by the heat balance around the fuel surface. This further reveals the need to model the heat transfer in such environment. The only reports available on the heat balance for force-ventilated fires are those by Foote-Pagni-Alvares [9] and Pagni [10]. Especially, Foote et al [9] have correlated the temperature rise in the compartment against heat release rate by fires.

The major purpose of this work are to connect the for CO production and the heat and to the smoke layer formation within a

force-ventilated fire enclosure. To achieve these objectives, gas analysis and measurements of heat flux and temperature were made using a 50cm cubic model box with methanol as the fuel (Small scale experiments), and gas analysis and measurements of temperature were made using a large model box (L=3.6m, W=2.4m, H=2.4m) with methane and propane as heat sources with controllable heat release rate (Large scale experiments).

This report describes the small scale and large scale experiments in progress and discusses the significance of the results obtained.

2. SMALL SCALE EXPERIMENT

2.1 Experimental Description

Small scale experiments were carried out for grasping a phenomena that occur during force-ventilated fires in closed spaces. Figure 1 is a block diagram of the instrumentation for small scale experiments and Figure 2 shows the main features of 50cm cubic model box. The instrumentation consists of a air supply system, a 50cm cubic model box with fuel supplier, fuel weight measuring system, and gas analyzer. Variable Experimental conditions were varied as follows:

1. Air supply rate.
20 l/min, 35 l/min, 50 l/min, 80 l/min, 100 l/min.
2. Fuel tray size.
10cm x 10cm, 15cm x 15cm, 20cm x 20cm.
3. Inlet conditions (position and configuration).
Upper, Middle, Middle with baffle, Lower (see Figure 3).
4. Outlet conditions (position).
Upper, Middle, Lower (see Figure 4).

Figure 3 Air inlet conditions.
(position and configuration.)

2.2 Experimental Results

Figure 5(a)–(d) are examples of the data obtained. This experiment was carried out with middle inlet with baffle, upper outlet. The tray size was 15cm x 15m, and the air supply rate maintained at 80 l/min. Figure 5(a) shows the typical ceiling temperature above the tray within the enclosure and the exhaust gas temperature at the outlet opening. Figure 5(b) shows the consumption and production of combustion gases (O_2 , CO_2 , CO). CO production started at 17 minutes after ignition and achieved the maximum concentration 4 vol.%. Figure 5(c) shows the heat to the fuel surface measured with Gordon type radiometer. Figure 5(d) shows the fuel weight loss rate.

Table 1 arranges the maximum concentration of CO during the experiment and duration of combustion under the different experimental conditions. It was found that the combustion characteristics within the force-ventilated enclosure were strongly influenced by the inlet and outlet conditions.

Figure 4 Air outlet conditions. (position.)

2.3 Conditions for the production of carbon monoxide

As Table 1 shows, under some experimental conditions, combustion did not last long; combustion under such conditions seems to be sustained by the oxygen contained in the enclosure at the beginning of combustion rather the air supply. Also, strong transiency is suspected in the heat transfer under such conditions; only the experiment in which combustion lasted longer than 10 minutes were adopted for the present analysis.

CO production behavior in fires is thought to be controlled by the combustion mode [6,8,11]. Following this assumption, the criticality for heavy CO production (1–5 vol.%) can be described as a function of

Figure 5(a) Example of temperature history in small scale experiment.
($G=80$ l/min, tray size 15cm x 15cm, middle inlet with baffle, upper outlet.)

Figure 5(b) Example of combustion gas (O_2 , CO_2 , CO) history in small scale experiment. ($G=80$ l/min, tray size 15cm x 15cm, middle inlet with baffle, upper outlet.)

Figure 5(c) Example of heat flux to the fuel surface history in small scale experiment.
($G=80$ l/min, tray size 15cm x 15cm, middle inlet with baffle, upper outlet.)

Figure 5(d) Example of fuel weight loss rate history in small scale experiment.
($G=80$ l/min, tray size 15cm x 15cm, middle inlet with baffle, upper outlet.)

Table 1 Duration time and maximum concentration of carbon monoxide (tray size 15cm x 15cm) for various experimental conditions.

(a) $G=20\ell/\text{min}$

[Inlet]	Upper	Middle	Middle with Baffle	Lower
[Outlet]				
Upper	1.03min (0.0vol%)	1.19min (0.0vol%)	1.58min (0.0vol%)	5.54min (0.2vol%)
Middle	0.95min (0.0vol%)	1.27min (0.0vol%)	3.80min (0.0vol%)	1.58min (0.1vol%)
Lower	0.87min (0.0vol%)	1.03min (0.0vol%)	1.27min (0.0vol%)	2.38min (0.0vol%)

(b) $G=50\ell/\text{min}$

[Inlet]	Upper	Middle	Middle with Baffle	Lower
[Outlet]				
Upper	1.58min (0.0vol%)	4.36min (0.0vol%)	30min* (0.5vol%)	30min* (4.9vol%)
Middle	1.43min (0.0vol%)	8.32min (0.0vol%)	30min* (0.6vol%)	30min* (2.7vol%)
Lower	11.72min (0.0vol%)	2.53min (0.0vol%)	2.06min (0.0vol%)	7.92min (0.2vol%)

(c) $G=80\ell/\text{min}$

[Inlet]	Upper	Middle	Middle with Baffle	Lower
[Outlet]				
Upper	30min* (0.0vol%)	9.90min (0.0vol%)	30min* (3.4vol%)	30min* (4.6vol%)
Middle	3.56min (0.0vol%)	8.32min (0.0vol%)	30min* (4.0vol%)	30min* (4.3vol%)
Lower	9.98min (0.0vol%)	2.61min (0.0vol%)	30min* (1.3vol%)	30min* (0.6vol%)

*)Extinguished combustion at 30min after ignition.

stoichiometric fuel to air ratio, which can be written as;

$$\Phi = \frac{A_v \cdot \dot{m}_v'' \cdot x}{M} \quad (1)$$

The numerator of Equation (1) corresponds to the theoretical air volume (kg/s).

Figure 6 shows the relation between maximum CO concentration in the exhaust duct and as defined Equation(1); CO concentration changes dramatically at around $\Phi \approx 1.0$. This shows that Φ is key parameter governing the CO production. Among the

variables in Equation (1), $\dot{m}_v''$ is quantified only after experiments; representation of $\dot{m}_v''$ by known parameters is essential for the evaluation of the criticality for the CO production using Φ .

In Figure 7, $H_v \cdot \dot{m}_v''$ is correlated against heat flux to the fuel surface, $\dot{q}_r''$, as in many previous models on enclosure fires assuming complete transformation of $\dot{q}_r''$ to the vaporization of fuel. Data in relating to conditions under which considerable CO concentration was observed concentrate around the straight line $\dot{q}_r'' = H_v \cdot \dot{m}_v''$, while $\dot{q}_r''$ is much larger than $H_v \cdot \dot{m}_v''$ during the early stages (earlier than 10 minutes after the

Figure 6 Relation between max CO concentration and Φ .

Figure 7 Relation between heat flux to the fuel surface and heat of vaporization.

Figure 8(a) Comparison of combustion gas (O_2 and CO) histories for experiments with different inlet conditions. ($G=80$ l/min, tray size 15cm x 15cm, upper outlet.)

Figure 8(b) Comparison of the theoretical air volume histories for experiments with different inlet conditions. ($G=80$ l/min, tray size 15cm x 15cm, upper outlet.)

ignition, indicated with solid symbols) of combustion. This discrepancy for the early stage is attributed to the adsorption of heat by fuel until its temperature becomes close to the boiling point.

2.4 Influence of inlet and outlet conditions on the combustion characteristics

In the case of naturally ventilated fires, fresh air at ambient is supplied through the lower part of an opening, and high temperature combustion gas is exhausted through the upper part. But when the inlet and outlet conditions can be set artificially, an air flow pattern the fire enclosure would be different from that during naturally ventilated fires in some cases. Influences of inlet and outlet conditions need to be considered.

2.4.1 Influences of inlet conditions on the combustion characteristics

Figure 8(a),(b) are comparisons of some experimental results obtained with different inlet conditions (air supply rate 80 l/min,

tray size 15cm x 15cm, upper outlet). Figure 8(a) shows the consumption and production of combustion gases. Figure 8(b) shows theoretical air volume that was calculated with the fuel weight loss rate and air supply rate. The actual air supply rate is represented by a horizontal straight line.

Significant difference of combustion characteristics for different inlet conditions occurs at 3–10 minutes after the ignition. In case of middle inlet, combustion did not last for 10 minutes. With upper inlet, combustion lasted long without much CO production. In the case of lower inlet, CO production started at an early stage, while for middle inlet with baffle, CO production started about 19 minutes after the ignition.

As Figure 8(a) and (b) show, the combustion characteristics within the force-ventilated fire enclosure change due to the inlet conditions even if the other ventilation conditions (air supply rate, tray size, outlet position) are the same. This can be explained by the effects of inlet condi-

Figure 9 Comparison of the ceiling temperature histories for experiments with different inlet conditions. ($G=80$ l/min, tray size 15cm x 15cm, upper outlet.)

Figure 10(a) Comparison of combustion gas (O_2 and CO) histories for experiments with different outlet conditions. ($G=80$ l/min, tray size 15cm x 15cm, middle inlet with baffle.)

Figure 10(b) Comparison of the theoretical air volume histories for experiments with different outlet conditions. ($G=80$ l/min, tray size 15cm x 15cm, middle inlet with baffle.)

tions as follows;

1 Effect of supporting combustion.

Fresh air is supplied to fuel to support combustion.

2 Cooling effect.

The fuel surface and radiative heat sources to the fuel surface are cooled by the supplied air which has a temperature 100 – 300(K) lower than the room temperature during fires, causing a reduction of fuel generation.

Figure 9 is a comparison of the ceiling temperature under the same experimental conditions as for Figure 8. It is believed that the ceiling above the tray is cooled by the supplied air with upper inlet, and its temperature is lower than the others. In case of middle inlet, a fire plume flow seems to be blown toward the exhaust opening by the supply air flow, and it is thought that the convective heat transfer to fuel is reduced and that the ceiling is not strongly heated by the fire plume. In case of middle inlet with baffle, most of supplied air is appeared

to be introduced below the tray, but some of supplied air flows to the fuel surface and cools it to some extent. With lower inlet, it seems that the ceiling scarcely cooled and that temperature around the tray is kept higher than the other inlet conditions so fuel generation becomes large resulting in heavy CO production at the early stages.

2.4.2 Influences of outlet conditions on the combustion characteristics

Figure 10(a), (b) are comparisons of some experimental results obtained with different outlet conditions (air supply rate 80 l/min, tray size 15cm x 15cm, middle inlet with baffle). Figure 10(a) shows the consumption and production of combustion gases. Figure 10(b) shows the theoretical air volume that was calculated with the fuel weight loss rate and air supply rate. The actual air supply rate is shown by the horizontal straight solid line.

Oxygen consumption with lower outlet has a different pattern compared with the

Figure 11 Combustion gas (O₂ and CO) history for experiments with lower outlet.
(G=80 l/min, tray size 15cm x 15cm.)

other outlet conditions. In the case of lower outlet, CO production started in spite of a greater than 10 vol.% of oxygen in exhaust gas. This phenomena pertains to lower inlet causing the irregular data (heavy CO production occurs when $\Phi < 1.0$) indicated by * and ** in Figure 5 (*: lower inlet $\rightarrow$ lower outlet, **: middle inlet with baffle $\rightarrow$ lower outlet). Figure 11 shows the consumption and production of combustion gases in these experiments.

The above phenomenon is caused by the influence of outlet conditions. That is, since the smoke layer flows down when exhausting along the floor (Lower outlet), the oxygen concentration around the flame becomes low, resulting in heavy CO production in spite of a greater than 10 vol.% of oxygen in exhaust gas.

But since this phenomena did not occur with middle and upper inlet, it can be concluded that outlet conditions are less influential on the combustion characteristics if force-ventilated fire enclosures than inlet conditions.

3. LARGE SCALE EXPERIMENTS

3.1 Experimental Description

Large scale experiments were carried out for grasping the characteristics of smoke

layer formation within the force-ventilated fire enclosure which is highly air tight. Figure 12 is a block diagram of the instrumentation and Figure 13 illustrates the main features of the large model box ($L=3.6\text{m}$, $W=2.4\text{m}$, $H=2.4\text{m}$). The instrumentation consists of a blower, a large model box with diffusion type gas burner as the heat source with controllable heat release rate and lower inlet and upper outlet for ease of formation of a smoke layer, and a gas analyzer. The burner was placed on the center of the floor, 50cm above it. The air supply rate was adjusted so that Φ was nearly 1.0 or less. Methane and propane were used as the fuel.

3.2 Experimental Results

Figure 14(a)–(e) are examples of data obtained in the case of propane gas burner fire with the fire strength set to 150kW and the air supply rate maintained at 150m³/h. In these figures, the blower was started at 0.5 minutes and the fire was initiated at 1.0 minutes. Figure 14(a) shows the inlet air flow measured by a Pitot pipe set located between the blower and the large model box. Figure 14(b) indicated in Figure 13. Figure 14(c)–(e) show the consumption and production of combustion gases measured at

Figure 12 Block diagram of instrumentation. (Large Scale experiment.)

▲: Temperature measuring point with extraction system.

All dimensions in millimeters.

Figure 13 Large model box setup.

Figure 14(a). Example of air inlet flow history in large scale experiment. (propane gas burner set to 150kW)

Figure 14(c). Example of oxygen (O_2) gas history in large scale experiment. (propane gas burner set to 150kW)

Figure 14(b). Example of temperature history in large scale experiment. (propane gas burner set to 150kW)

Figure 14(d). Example of carbon dioxide (CO_2) gas history in large scale experiment. (propane gas burner set to 150kW)

Figure 14(e). Example of carbon monoxide (CO) gas history in large scale experiment. (propane gas burner set to 150kW)

Figure 15(a). Air inlet flow history in large scale experiment. (methane gas burner set to 150kW)

Figure 15(c). O₂ gas history for reduction of air supply rate. (methane gas burner set to 150kW)

Figure 15(b). Temperature history for reduction of air supply rate. (methane gas burner set to 150kW)

Figure 15(d). CO₂ gas history for reduction of air supply rate. (methane gas burner set to 150kW)

Figure 15(e). CO gas history for reduction of air supply rate. (methane gas burner set to 150kW)

the upper part (2151mm above), the lower part (97mm above) of the model box, and in the exhaust duct.

The appearance of a reversal inlet air flow spike in Figure 14(a) is caused by need to reduce the mass in the model box to keep constant energy per unit volume in the approximately constant pressure model box [12].

Figure 15(a)-(e) show the data obtained with reduced from 360m³/h to 150m³/h in Figure 15(a), the temperature measured at C rises remarkably, while that at D dips at reduction of air supply rate. Figure 15(c) shows that the oxygen concentration at the upper part and in the exhaust duct become low when the air supply rate is reduced, while that at the lower part becomes high. This phenomena do not coincide with the general thinking that oxygen concentrations within the fire enclosure would become low following the reduction of the air supply rate.

3.3 Smoke layer formation within the force-ventilated fire enclosure

Conventionally, a two layer zone model, assuming a hot smoke layer formation upper part, and clean air layer formed in lower part of the fire enclosure is used in modeling the early stages of enclosure. But the border between the smoke layer and the air layer becomes unstable when the temperature of the smoke layer is not so high or when significant convective flow occurs within the enclosure, and two layer zone model cannot be applied. Therefore, it is important to consider the smoke layer formation within the force-ventilated fire enclosure from the experimental results.

Figure 16 shows the general idea of the two layer zone model. Assuming the organization of the upper and the lower part of the model box are discussed for condi-

tions similar to those used in the experimental for estimating the smoke layer formation.

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

$$AZ \frac{dY_u}{dt} = GY_1 - Q\epsilon - (G + \frac{Q}{m})Y_u - \Gamma(Y_u - Y_1) \dots\dots\dots (2)$$

$$A(H_r - Z) \frac{dY_1}{dt} = G(Y_o - Y_1) + \Gamma(Y_u - Y_1) \dots\dots\dots (3)$$

Assuming the steady state, Equation (2) and (3) are transformed as follows.

$$Y_1 = \frac{GY_o + \Gamma Y_u}{G + \Gamma}, Y_o - Y_1 = \frac{\Gamma(Y_o - Y_u)}{G + \Gamma}$$

Therefore,

$$\frac{Y_o - Y_1}{Y_o - Y_u} = \frac{\Gamma}{G + \Gamma} \dots\dots\dots (4)$$

When a stable smoke layer is formed, mass transfer through the border of layers must be controlled by eddy diffusion. At this time, mass transfer is negligibly small compared to the fire plume into the smoke layer, so $G \gg \Gamma$, i.e., $(Y_o - Y_1)/(Y_o - Y_u) \ll 0.5$. When the layer becomes unstable because of significant convective air flow, the value of $(Y_o - Y_1)/(Y_o - Y_u)$ must be greater than 0.5. So a value of $(Y_o - Y_1)/(Y_o - Y_u)$ can be used as an parameter for estimating the smoke layer's stability.

Figure 17 shows the relation between the $(Y_o - Y_1)/(Y_o - Y_u)$ and air supply rate with various fire strengths. With the same air supply rate, $(Y_o - Y_1)/(Y_o - Y_u)$ has a tendency to become small at small fire strengths.

Figure 16 A general idea of two layer zone model.

Figure 17 Relation between $(Y_o - Y_l)/(Y_o - Y_u)$ and air supply rate.

Further, $(Y_o - Y_l)/(Y_o - Y_u)$ has a tendency to become small at small supply rate.

From the experimental results, it seems that smoke layer formation within the force-ventilated fire enclosure is influenced by the following:

1. Air flow within the enclosure.

Irregularity of air flow within the enclosure becomes small at small air supply rates, leading the formation of a smoke layer.

2. Temperature difference between the supply air and exhaust gas.

When the heat release rate is high, the

temperature of the supply air remains almost constant (ambient temperature), whereas the exhaust gas temperature rises. So a smoke layer is formed.

4. CONCLUSIONS

The influence of ventilation conditions during fires on the combustion characteristics within force-ventilated fire enclosures, for example CO production and smoke layer formation, are important considerations for human life safety. From these model experiments of force-ventilated fires in closed

spaces, the following conclusions can be drawn;

1. Criticality for heavy CO production (1–5 vol.%) can be represented by specific value of stoichiometric fuel to air ratio, $\Phi = A_x \cdot \dot{m}_v'' \cdot x / M$. In the present experiments, the critical value was 1.0.
2. Fuel volatilization rate $\dot{m}_v''$ can be estimated from the heat flux to the fuel surface.
3. The combustion characteristics within the force-ventilated fire enclosure influenced by the inlet and outlet conditions even at the same air supply rate. Inlet conditions exert more influence than outlet conditions.
4. Smoke layer formation within the force-ventilated fire enclosure is influenced by the air flow within the enclosure and the temperature difference between the supply air and exhaust gas.

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Terminology

A	area of floor (m^2)
A_B	area of opening (m^2)
A_v	tray area (m^2)
G	air supply rate (l/min)
H	height of opening (m)
H_r	height of room (m)
H_v	heat of vaporization (kJ/kg)
M	air supply rate (kg/s)

m	inverse number on heat of combustion (kg/kJ)
$\dot{m}_v''$	fuel weight loss rate per unit area (kg/kJ)
Q	heat release rate (kW)
q_r''	heat flux to fuel surface per unit area (kW/m ²)
t	time (sec)
T_c	ceiling temperature (K)
T_{ex}	exhaust gas temperature (K)
T_o	ambient temperature (K)
x	stoichiometric air to fuel ratio (=6.48(g/g) for methanol)
Y_l	oxygen concentration of the lower part within the model box (vol.%)
Y_o	oxygen concentration of inlet air (vol.%)
Y_u	oxygen concentration of the upper part within 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 (–)

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