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Decrease of carbon dioxide concentration and entrainment of horizontally spreading ceiling jet

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ABSTRACT

Knowledge about the mass flow rate of a ceiling jet in a large space is important for predicting smoke behavior, determining suitable smoke control equipment, and designing the operating conditions in the early stages of a fire. Here, full-scale ceiling jet tests with a flat unconfined ceiling were conducted. The mass flow rate of a ceiling jet spreading in the radial direction was estimated based on measurement of carbon dioxide concentration. The relation between the entrainment properties of the ceiling jet and radial distance was experimentally investigated. Empirical formulae representing the dependence of the carbon dioxide concentration decrease with radial distance was developed. The entrainment coefficient characteristic by ceiling jet was also described.

1. Introduction

In the majority of the conventional models for predicting smoke flow behavior in a building (e.g., the two layers zone model, BRI2002 [1]), the entrainment process in the plume region is primarily considered. In a space having a high ceiling in comparison to its width, such as an atrium, the amount of mass flow rate in the plume region dominate the flow behavior of the ceiling jet.

However, in wide spaces, such as large offices with floor space of about 3000 m^2, shopping malls, warehouse, and airports, which have a wide length compared with the ceiling height, there is a possibility that the increment of mass flow rate entrained through the lower surface of the ceiling jet, which spreads in the radial direction under the ceiling from the plume impingement point, influences the smoke movement and its characteristic.

Therefore, to predict smoke movement accurately in the early stages of fire and to apply appropriate smoke control, an estimation is necessary of the amount of mass flow rate carried by the ceiling jet that is spread in the radial direction over a large space.

The objective of the current work is to make clear the entrainment properties of a ceiling jet by measuring the gas concentration in a ceiling jet spreading under an unconfined ceiling. Attempts have also been made to develop empirical models that predict and describe not only the carbon dioxide concentration but also the characteristic of entrainment coefficient of a ceiling jet.

2. Experimental procedures

A series of pool fire tests were conducted as listed in Table 1. An unconfined full-scale model ceiling having dimensions of 14.0 m × 7.0 m and constructed of 9.5 mm thick plasterboards with a smooth finish was employed in these tests. The ceiling height, the length of the vertical line from the midpoint at the bottom of the fuel pan to the point where it intercepts the ceiling, was changed by adjusting the distance between the floor of the fire facility and the fuel pan.

Three stainless steel fuel pans having diameters of 0.3, 0.4 and 0.6 m were used. Methanol was employed as a fuel, the fuel pool was sat on an electric balance (LP34001S, Sartorius; accuracy: 0.1 g) to measure the mass loss. The heat release rates were estimated from the mass loss and the heat of combustion of methanol (assumed to be 19.1 MJ/kg [2]), and corresponded to values calculated by assuming complete combustion.

Carbon dioxide concentrations were measured with portable carbon dioxide measuring sensors (GMT221, Viasala; 0–5 vol%, 0–2 vol%, 0–1 vol%) set in the radial direction at five points (r=3.5, 4.9, 6.3, 7.7 and 9.1 m) 25 mm below the ceiling surface, as shown in Fig. 1. It is hard to set gas sensors at the position of 25 mm or less from the ceiling because of the physical size of gas sensor head. Therefore, the concentrations reported are representative concentrations in the vicinity of each sensor installed.

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Nomenclature

C_m	coefficient of mass flow rate [kg s^{-1} kW$^{-1/3}$ m$^{-5/3}$]
E	entrainment coefficient [dimensionless]
H	ceiling clearance [m]
F_{CO_2}	mass fraction of CO_2 to the fuel [dimensionless]
$\dot{m}_c$	mass flow rate of ceiling jet [kg/s]
$\dot{m}_f$	mass loss rate of the fuel [kg/s]
$\dot{m}_i$	mass flows rate to be carried by ceiling jet passing through the sub-region i [kg/s]
$\dot{m}_p$	mass flow rate of plume [kg/s]
Q	heat release rate [kW]
r	radial distance from the point of fire plume on the ceiling [m]
v_{ent}	entrainment velocity
X_{CO_2}	volume fraction of CO_2 [dimensionless]
X_{O_2}	volume fraction of O_2 [dimensionless]
Y_{CO_2}	mass fraction of CO_2 [dimensionless]
z	height from the fire source [m]
Δm_i	increment of mass flows rate to be carried by ceiling jet passing through the sub-region i
ΔT	temperature rise [K]
Δx	length of sub-region, = 0.1 m
ΔX_{CO_2}	volume fraction rise of CO_2 from initial condition [vol.%]
ΔY_{CO_2}	mass fraction rise of CO_2 from initial condition [dimensionless]
θ	inclination angle of ceiling from the horizontal

Subscripts and superscripts

∞	atmosphere
c	ceiling jet
max	maximum
mean	mean
p	plume
up	upward

3. Estimation of entrainment coefficient

The mass flow rate of the ceiling jet passing over each measuring point was estimated from the carbon dioxide concentration in both ceiling jet and fresh air entrained, mass fraction of carbon dioxide to the fuel and mass loss rate of the fuel as follows [3,4]:

$$\dot{m}_c = \left(\frac{F_{CO_2} - Y^{\infty}_{CO_2}}{Y^{C}_{CO_2} - Y^{\infty}_{CO_2}} \right) \dot{m}_f \quad (1)$$

where $\dot{m}_c$ is mass flow rate of the ceiling jet passing at a measured position, $\dot{m}_f$ is the mass loss rate of the fuel, F_{CO_2} is the mass fraction of carbon dioxide to the fuel (methanol = 44/32), $Y^{C}_{CO_2}$ is the mass fraction of the carbon dioxide in the ceiling jet at a measured position, and $Y^{\infty}_{CO_2}$ is the mass fraction of carbon dioxide in the fresh air.

Since the carbon dioxide concentration is measured in terms of the volume fraction, a conversion must be made from volume fraction to mass fraction. When employing methanol as a fuel, the relationships between the mass fraction and the volume fraction of carbon dioxide in the ceiling jet and in the fresh air, respectively, can be expressed as follows:

$$Y^{C}_{CO_2} = \frac{22X^{C}_{CO_2}}{2X^{\infty}_{O_2} - 5X^{C}_{CO_2} + 13X^{\infty}_{CO_2} - 5X^{\infty}_{H_2O} + 14} \quad (2)$$

$$Y^{\infty}_{CO_2} = \frac{22X^{\infty}_{CO_2}}{2X^{\infty}_{O_2} + 8X^{\infty}_{CO_2} - 5X^{\infty}_{H_2O} + 14} \quad (3)$$

where $X^{C}_{CO_2}$ is the volume fraction of carbon dioxide in the ceiling jet at the measured position which is radially apart from the point of fire plume impingement on the unconfined ceiling, $X^{\infty}_{O_2}$ is the volume fraction of oxygen in the fresh air, and $X^{\infty}_{CO_2}$ is the volume fraction of carbon dioxide in the fresh air.

It is reported that the error is approximately 1% when compared the mass fraction of carbon dioxide under the condition at 20 °C and 20% relative humidity with that at 20 °C and 98% relative humidity [4]. Then the volume fraction of water vapor in the fresh air, $X^{\infty}_{H_2O}$, is assumed to be neglected.

Table 1
Experimental conditions.

No.	H [m]	Diameter of fuel pan [m]	Q [kW]
1	2.80	0.4	38.5
2	2.80	0.6	85.8
3	1.56	0.6	90.0
4	1.56	0.4	38.5
5	1.56	0.3	20.5
6	0.94	0.3	20.5
7	0.94	0.4	39.6

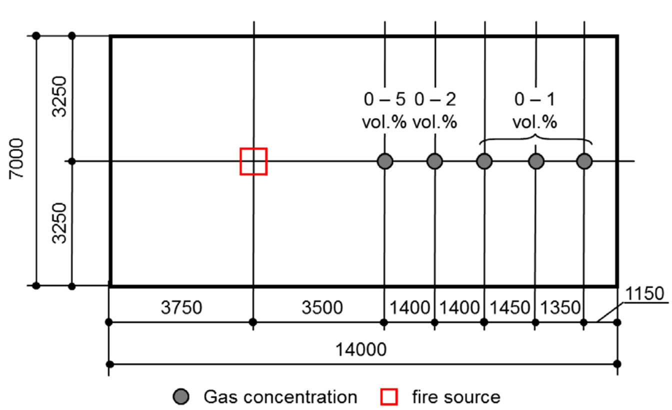

Fig. 1. Outline of experimental rig and positions of CO_2 concentration measurement (plan view).

4. Results and discussions

4.1. Time history of heat release rate and carbon dioxide concentration

Fig. 2 shows the time history of carbon dioxide concentration at each measured positions with changing ceiling height. Because the carbon dioxide concentration rises an almost constant value 3 min after ignition, the data averaged during 240–540 s were used, and the mass flow rate of ceiling jet and the entrainment coefficient were estimated by using these averaged values. The results of mass fraction of carbon dioxide calculated in each test are shown in Table 2, and it is confirmed that the mass fraction of carbon