Experiments on Smoke Behavior in Cavity Spaces

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ABSTRACT

Reduced scale experiments were conducted to investigate the behavior of smoke in cavity like spaces, which are found in buildings. The cavity space model used in the experiments has a square horizontal section of 0.8mx0.8m, and the height of the floor can be changed from 0 to 3m. This paper presents the results for the case where the cavity has no opening at the bottom and the fire source is located at the center on the floor. The heat release rates in this series of experiments ranged from 0.5 to 4kW. The temperatures were measured by the thermocouples arrayed horizontally over the cavity opening, and vertically along the side walls. The pressure difference between the inside and outside of the cavity along the depth was also measured.

It is found that the temperature rise of plume at the cavity opening is well scaled by the nondimensional temperature defined as $\Theta = (\Delta T / T_\infty) / \dot{Q}^{*2/3}$ where $\dot{Q}^* = \dot{Q} / \rho_\infty C_p T_\infty \sqrt{gD} D^2$, and the temperature is correlated by $\Theta = \alpha (H/D)^\beta$, where β=-5/3, -1 and -1/3 for shallow, intermediate and deep cavity, respectively.

KEYWORDS: smoke behavior, plume, cavity space, heat release rate, reduced scale test

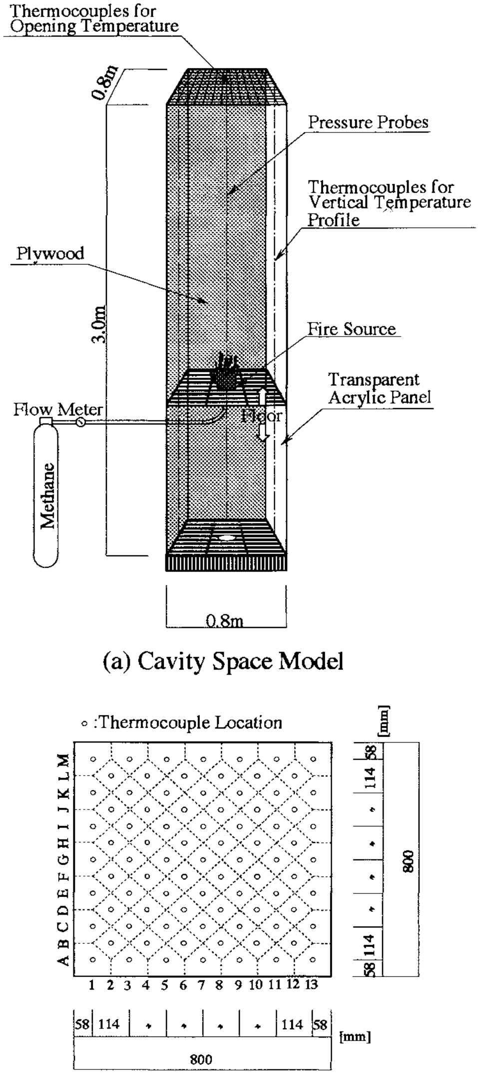
INTRODUCTION

Not a few buildings have cavity like spaces with no roof such as courts, light courts and dry areas. Such a space is usually regarded either as an outdoor equivalent space or a vertical shaft in building fire safety regulations. When the space is regarded as an outdoor equivalent space, not so rigorous safety measures are required, but once regarded as a vertical shaft, very rigid measures such as fire walls and fire doors are often required. However, it is not always easy to classify such spaces into the two extremes since floor area, height and potential fire source are different from one cavity space to another.

One of the major problems associated with a cavity space is that it may become a dominant passage of smoke propagation in a building. When the depth of the space is small relative to its floor area like in the case of a court, the smoke entering into the space will escape freely into the air as if it were ejected from a window in an exterior wall, thus causing no particular hazards concerning internal smoke propagation. But as the area becomes smaller or the depth becomes larger, the space will resemble more like a vertical shaft, so the smoke will behave as if it were in a chimney.

The important factors which control the smoke behavior in such a space are considered to be the floor area and the depth of the space, the heat release rate of the fire source, and the dimensions of the opening at the bottom of the space. The ultimate objective of this study is to clarify the relationship between the smoke behavior and such conditions of cavity spaces. This paper, however, deals with a cavity space having no opening at the bottom. In such a circumstance, all the air entrained into the fire plume is supplied through the opening at the top of the space, which is a major difference from fire plumes in open spaces.

The most conceivable source of smoke to a cavity space in realistic building fire situation will be a fire room on a floor area adjacent to the space, since it is not likely that significant amount of combustible items, which may cause a potential fire, is stored in such an uncovered space. But the fire source in the experiments in this study is placed at the center on the floor of the space considering the fact that even the fundamental nature of smoke behavior has not yet investigated for such cavity spaces.



(a) Cavity Space Model

(b) Thermocouple Array at Opening

FIGURE 1 Experimental Setup

EXPERIMENTS

Cavity Space Model

The cavity space model used in this experiment is illustrated in FIGURE 1(a). It has the square floor of 0.8mx0.8m, whose height can be changed from 0m to 3m using wires and a pulley. The rear wall and the left wall are made of plywood panels of 5mm thickness, and the front wall and the right hand side wall are made of transparent acrylate panels in view of visualization of the flow. Rubber bands are attached to the four sides of the floor to seal the gaps between the floor and the wall, while allowing smooth vertical movement of the floor.

Fire Source

A 7cm diameter diffusion burner filled with small ceramic balls was used as the fire source and methane was supplied at a fixed rate in each test. The heat release rate designated for each of the tests was converted to the volumetric flow rate per minute based on the relationships:
50.1(MJ/kg)x0.722(kg/m³)=36.11(kJ/litter) and 36.11(kJ/litter/sec)=0.602(kW/litter/min).

Measurements

As shown by FIGURE 1(b), 85 thermocouples of ϕ0.3mm were arrayed over the opening to measure the temperatures of the gases flowing out of and the air flowing into the space.

Thermocouples of ϕ0.3mm were arrayed vertically on both of the side walls at every 10cm spacing to measure the inside gas temperatures. The thermocouples were pointed out of the wall surfaces by 8mm to avoid the influence of wall surface temperatures on the measurements. Incidentally, minimum cutoffs were made in the rubber bands where the thermocouples pass so that the vertical movement of the floor is allowed without damaging the thermocouples.

Pressure probes were placed at 10 positions on the rear wall to measure the pressure difference between the inside and the outside of the cavity space; one at the top, another at the bottom and the rest 8 between the top and the bottom with the same spacing, which depends on the depth of the cavity.

About 15 minutes after the depth of the cavity and the heat release rate had been arranged for each test, when the smoke behavior was viewed steady from the monitored temperatures and pressures, the data acquisition was started and the data were recorded for 5 minutes with 5 second interval, namely, 60 times in total.

The Test Conditions

The tests were carried out for every combination of the following depths of the space and heat release rates, except a coupe of conditions in which the flames may touch and damage the thermocouoles at the opening:

Depth of the cavity(m): 0.25, 0.50, 0.75, 1.00, 1.25,1.50, 1.75, 2.00, 2.25, 2.50, 2.75, 3.00
Heat release rate(kW): 0.5, 1.0, 2.0, 3.0, 4.0

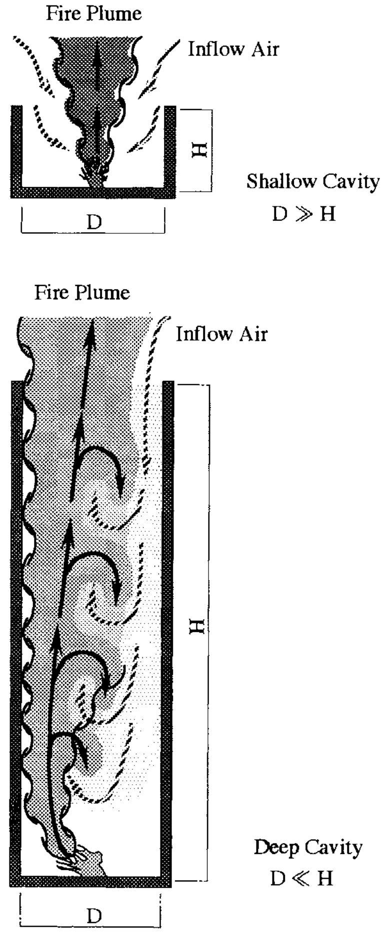


FIGURE 2 Schematic of Smoke Behavior

RESULTS OF EXPERIMENTS

Observation of the Flow in the Cavity

The buoyant plume above the fire source, i.e. fire plume, appears to rise vertically just like a fire plume in an open space when the depth of the space is small, but as the depth increases, the fire plumes, often the flames too, begins to be disturbed by the air which flows into the cavity through the top opening and is entrained into the plume, as illustrated by FIGURE 2.

The axis of the plume no longer stays at the center of the cavity but moves around here and there within the space. The most frequent direction of the axis seems to be towards a wall or a corner.

Vertical Profile of the Temperature and the Pressure

FIGURE 3 shows an example of the vertical profiles of the temperatures and the pressure difference, measured for 3m cavity depth. The measurement of the temperatures may be influenced by the fire plume when its direction happens to be towards the thermocouple arrays along the walls, but otherwise, the temperatures in the cavity seem to be relatively uniform.

The pressure in the cavity drops almost linearly with the depth from the opening, and the pressure difference at the opening is close to zero. This is considered to reflect the fact that the temperature in the cavity is almost vertically uniform and, theoretically, there supposed to be no net flow through the opening.

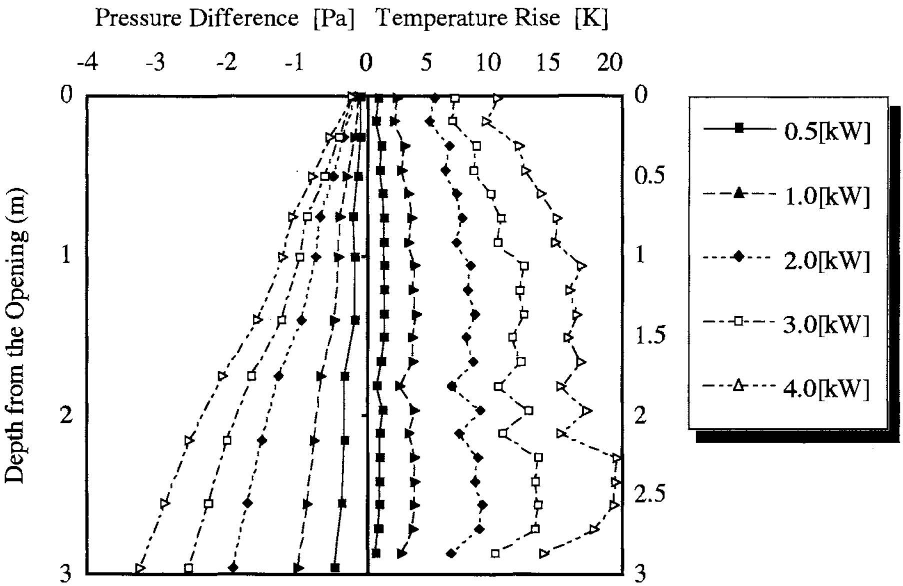


FIGURE 3 Vertical Temperature and Pressure Profile

Fluttering of the Plume Axis

FIGURE 4 shows the frequency that each thermocouple at the opening recorded the highest temperature in the 60 times data recordings during the 5 minutes of the data acquisition period in the case of 2 kW fire. It will be an acceptable assumption that the plume axis exists around the position of the thermocouple which recorded the highest temperature. It is evident from this figure that when the depth is small, the axis stays within relatively narrow area around the center of the cavity, but as the depth increases, the axis becomes to wander over wider area.

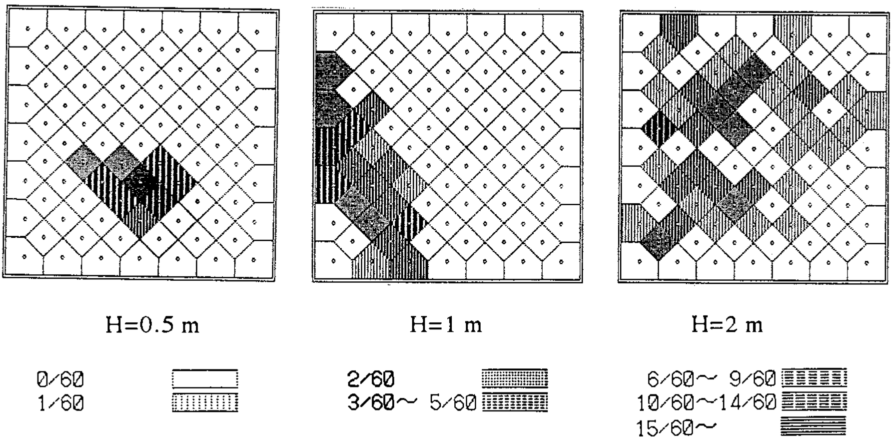


FIGURE 4 Frequency of Plume Axis Location

Temperature of Plume

(1) Definition of plume area

At the cavity opening, upward plume flow and downward air flow exist all the time, and vigorous mixing is occurring around the boundary of the bi-directional flows. The examples of temperature profile at the opening at a given moment shown in FIGURE 5 demonstrate that the effect of mixing more or less reaches up to the edge of the cavity. Hence, it is necessary to define the horizontal section area of the plume in order to discuss the plume temperature. Here the plume area is defined as the area where the temperatures fall in the following condition:

$$\Delta T \geq \left(T_{max} - T_{\infty}\right) \times k \qquad (1)$$

where T_{∞} is the ambient temperature(K), T_{max} is the highest temperature reading of the thermocouples and ΔT is the difference between the temperature at a given position in the opening and the ambient temperature.

Thus defined plume area may vary depending on the value of k, but as shown by FIGURE 6, which is the example for 0.5 kW fire, the area and the temperature are nearly the same for k =0.20~0.30. In this paper, k =0.25 was employed to define the plume area.

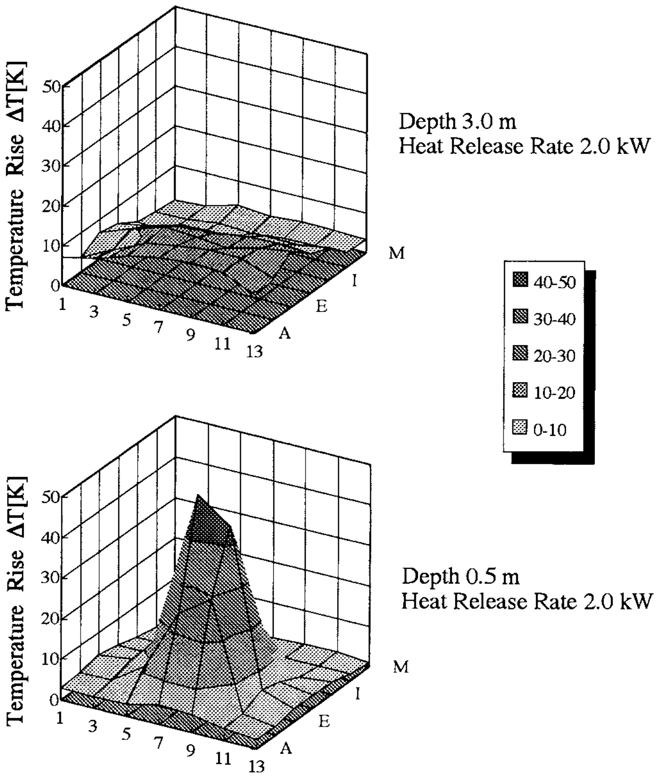


FIGURE 5 Temperature Profile over the Opening

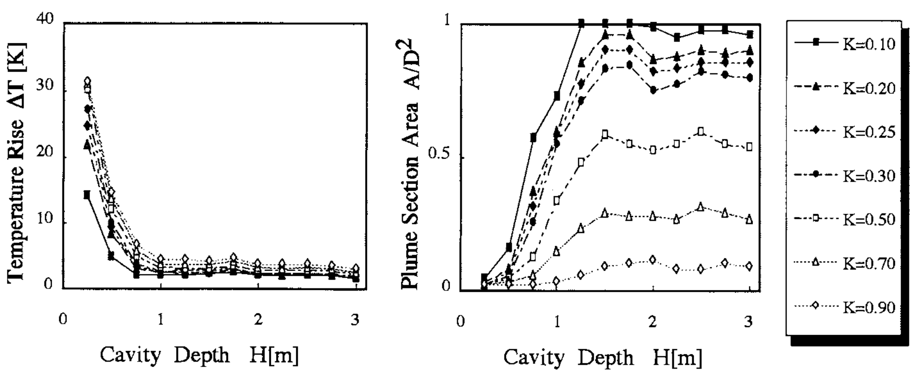


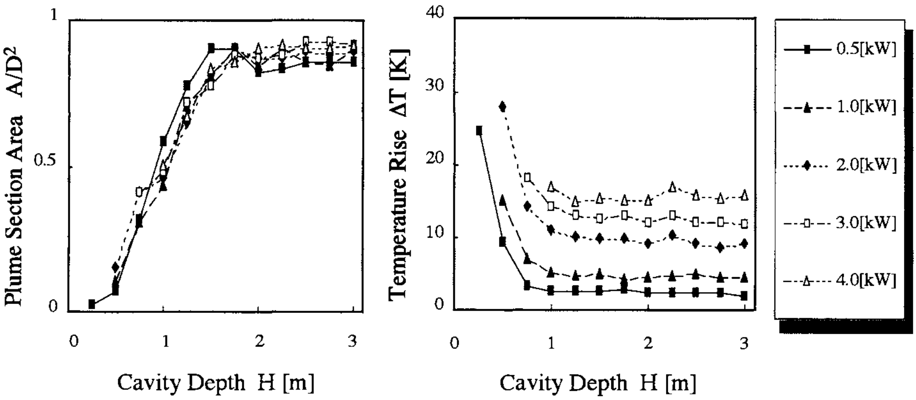
FIGURE 6 Temperature and Area of Plume for Different Values of k

(2) Plume area at the opening

FIGURE 7(a) exhibits the plume areas for different fire sizes at the height of the opening, defined by Eq. (1) with k =0.25, relative to the opening area. The plume area was determined by defining the area at every data recording of 5 second interval and averaged over 5 minutes of data acquisition period. This figure demonstrates that the plume area does not notably depend on heat release rate of the source, which is consistent with fire plumes in open spaces. On the other hand, it is a trend particular to the fire plumes in cavity spaces that the area, while develops proportionally to the square of the depth where the depth is small, becomes nearly constant beyond a certain depth, and develops about proportionally to the depth in the intermediate depth.

(3) Average plume temperature

The average temperature rise over the defined plume area in each test condition is plotted versus the depth of the cavity in FIGURE 7(b). These temperatures are the averages over 5 minutes of the average temperatures of the plume defined at every data recording. It is naturally expected that the larger the heat release rate, the higher the plume temperatures, but it is a remarkable tendency that the plume temperatures do not change significantly beyond a certain depth, while they drops quickly with depth where the depth is small.



(a) Plume area defined for k = 0.25 (b) Average plume temperature rise

FIGURE 7 Area and Average Temperature of the Plume Defined for k = 0.25

THEORETICAL CONSIDERATION

Needless to say, the ultimate goal of this study is to assess the hazard by smoke of fire invading into cavity like spaces of real buildings. In order to predict real scale smoke behavior using the results of the present reduced scale experiments, the relationship among dimensions of the space, heat release rate and temperature rise must be established. Incidentally, the heat release rate mentioned here can be interpreted as the heat that is brought into a cavity space by smoke in realistic fire scenarios.

The heat released from fire source is partly transferred to cavity walls, but if this is neglected, the following relationship is expected to hold for the heat release rate $\dot{Q}$ and the heat transported by the plume convection,

$$\dot{Q} \propto \rho C_p \overline{\Delta T} A \bar{u} \tag{2}$$

where ρ , $\overline{\Delta T}$ and $\bar{u}$ are the average density, the average temperature rise and the average flow velocity of plume at a given height, respectively, A is the plume horizontal section area and C_p is specific heat of gases.

The plume average velocity $\bar{u}$ is caused by the buoyancy due to the temperature rise, so letting the average temperature rise $\overline{\Delta T}$ and the depth of the cavity H be the representative temperature and height, respectively, we would be able to expect the following relationship:

$$\rho \bar{u}^2 \propto \overline{\Delta \rho} g H \tag{3}$$

where $\overline{\Delta \rho}$ is the average difference in density between the ambient air and the plume flow and g is the acceleration due to gravity. Hence we have

$$\bar{u} \propto \sqrt{\frac{\overline{\Delta \rho}}{\rho} g H} \approx \sqrt{\frac{\overline{\Delta T}}{T} g H} \tag{4}$$

Using Eqs.(2) and (4) yields

$$\overline{\Delta T}^{3/2} \propto \frac{\dot{Q} / \rho C_p}{\sqrt{g/T} A H^{1/2}} \tag{5}$$

When the cavity is shallow, that is, where the side length of the cavity D is $D \gg H$, the radius of the plume is expected to increase proportionally to the depth H like a plume in an open space, hence the plume section area A will increase proportionally to the square of H, that is

$$A \propto H^2 \tag{6}$$

Substituting Eq. (6) into Eq. (5), we have

$$\frac{\overline{\Delta T}}{\left(T \dot{Q}^2 / \rho^2 C_p^2 g D^5\right)^{1/3}} \propto \left(\frac{H}{D}\right)^{-5/3} \tag{7}$$

Furthermore, assuming that the plume temperature does not differ significantly from the ambient temperature, that is, $T \approx T_\infty$,

$$\frac{\overline{\Delta T} / T_\infty}{\left(\dot{Q} / \rho_\infty C_p T_\infty \sqrt{gD} D^2\right)^{2/3}} \propto \left(\frac{H}{D}\right)^{-5/3} \tag{8}$$

Hence, it follows that the plume temperature rise is inversely proportional to H/D to 5/3. If use is made of the non-dimensional heat release rate $\dot{Q}^*$ defined as

$$\dot{Q}^* \equiv \dot{Q} / \rho_\infty C_p T_\infty \sqrt{gD} D^2 \tag{9}$$

and the non-dimensional temperature Θ defined as

$$\Theta \equiv \left(\frac{\overline{\Delta T}}{T_\infty}\right) / \dot{Q}^{*2/3} \tag{10}$$

Eq. (8) can be expressed as

$$\Theta \propto \left(\frac{H}{D}\right)^{-5/3} \tag{11}$$

On the other hand, when the cavity is deep, that is, $H \gg D$, the development of the plume area is considered to be restricted by the horizontal section area of the cavity, therefore

$$A \propto D^2 \tag{12}$$

Substituting this into Eq. (5), and following the same procedure as above, we have

$$\Theta \propto \left(\frac{H}{D}\right)^{-1/3} \tag{13}$$

that is, the plume temperature rise is expected to be inversely proportional to H/D to 1/3.

When the cavity depth is intermediate, that is $H \approx D$, it is not evident what dimensions control the plume area. But since $A \propto H^2$ for $D \gg H$, and $A \propto D^2$ for $H \gg D$, it may not be so unreasonable to assume that

$$A \propto DH \tag{14}$$

for $H \approx D$. Then we have the relationship as follows:

$$\Theta \propto \left(\frac{H}{D}\right)^{-1} \tag{15}$$

that is, the plume temperature is inversely proportional to H/D.

COMPARISON BETWEEN THE EXPERIMENTS AND THE THEORY

The Data Reduction of the Experimental Results

According to the theoretical consideration in the above, the plume temperature rise in cavity space is thought to be expressed as

$$\Theta = \alpha\left(\frac{H}{D}\right)^{\beta} \tag{16}$$

Although β in Eq. (16) is predicted to be β=-5/3, -1 and -1/3 for small, intermediate and large depths of cavity, respectively, these predictions have to be validated by the experimental results. In addition, the value of α cannot be derived theoretically but have to be found experimentally. The experimental values of α and β can be obtained by plotting the test data on the logarithmic graph and drawing regression lines as in FIGURE 8. The final results turned out to be as shown in TABLE 1.

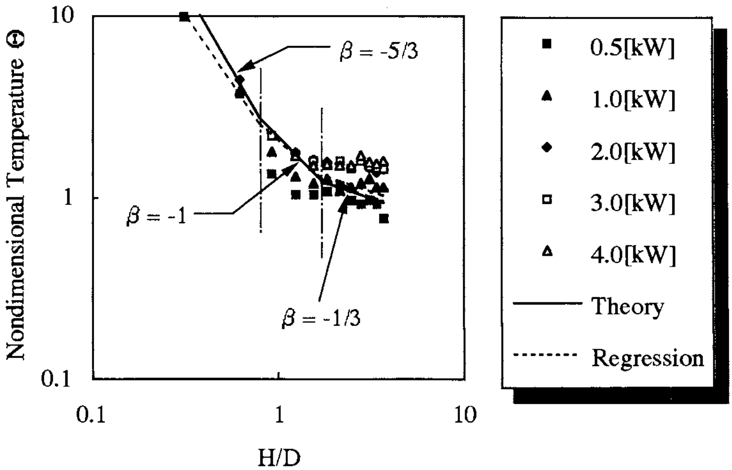


FIGURE 8 Regression of Test Data on Logarithmic Graph

TABLE 1 Values of α and β (*: Adjusted for the theoretical value of β)

Region	Experiments		Theory	
	α	β	α(*)	β
H/D≦0.78	1.74	-1.55	1.86	-5/3
0.78 <H/D≦1.77	2.09	-0.9	2.19	-1
1.77<H/D	1.48	-0.28	1.48	-1/3

Proposed Equations for Plume Temperature

It can be seen in TABLE 1 that although the experimental values of β are somewhat different from the theoretical values, the discrepancies do not seem so significant. Therefore, the theoretical value of β may be used to propose the equations for the plume temperature rise in cavity spaces. The results are as follows:

$$\Theta = \begin{cases} 1.86\left(\dfrac{H}{D}\right)^{-5/3} & (H/D \leq 0.78) \\ 2.19\left(\dfrac{H}{D}\right)^{-1} & (0.78 < H/D \leq 1.77) \\ 1.48\left(\dfrac{H}{D}\right)^{-1/3} & (1.77 < H/D) \end{cases} \tag{17}$$

In FIGURE 9, the non-dimensional temperatures reduced from the experimental data for different conditions of heat release rate and the cavity depths, and the theoretical line generated from Eq. (17) are depicted versus *H/D*.

The excellent convergence of the test data, which have differed considerably in FIGURE 7 depending on the heat release rates, indicates that the non-dimensional temperature in Eq. (10) is an efficient scaling parameter of the smoke behavior in cavity spaces. Also the satisfactory agreement of Eq. (17) and the test data implies that the equation employing the theoretical values of β may be usable for estimating the temperature of cavity smoke flow.

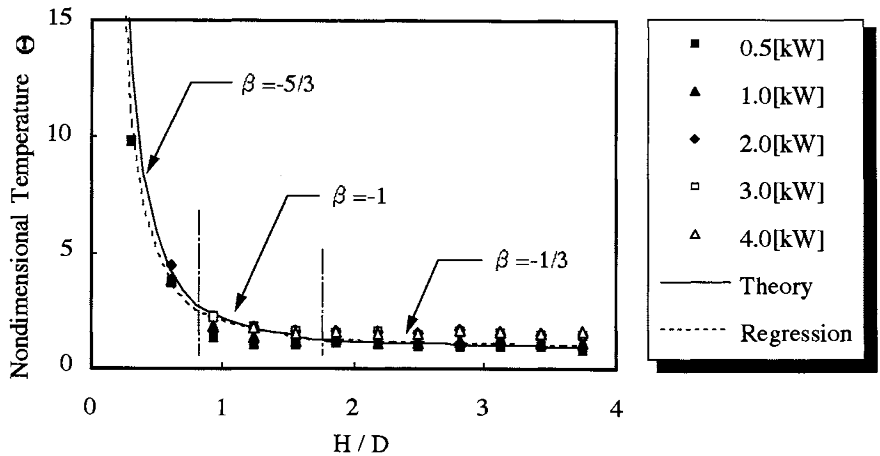


FIGURE 9 Comparison between The Theory and Test Data

CONCLUDING REMARKS

Reduced scale experiments were conducted to investigate the behavior of smoke of fire in cavity like spaces, which are not seldom found in buildings. The experiments in this study were limited to the case where the cavity has no opening at the bottom and the fire source was located on the center of the floor. Some theoretical considerations were also made of such a smoke behavior.

In the case where the fire source is located at the center on the floor, it is found that the temperature rise of the plume at the cavity opening is well scaled by the non-dimensional temperature defined by Eq. (10), and the temperatures are successfully correlated by Eq. (16), where =-5/3, -1, -1/3 for shallow, intermediate and deep cavity, respectively.

Since the possible source of smoke to cavity spaces in most real fires is thought to be fire rooms on floor areas adjacent to the space, the experiments will have to be continued for wall and corner fires located at elevated positions from a cavity floor in order to establish a practical means to predict cavity smoke behavior in realistic fire situations.

NOMENCLATURE

A	Horizontal section area of fire plume (m^2)
C_p	Specific heat of gas (kJ/kgK)
D	Length of the side of cavity space (m)
g	Acceleration due to gravity (m/s^2)
H	Depth of cavity space (m)
$\dot{Q}$	Heat release rate of fire source (kW)
$\dot{Q}^*$	Non-dimensional heat release rate defined by Eq. (9)
T	Temperature (K)
T_∞	Ambient temperature (K)
ΔT	Temperature rise or Temperature difference (K)
$\overline{\Delta T}$	Average temperature rise (K)
$\bar{u}$	Average flow velocity (m/s)
α	Constant in Eq. (16)
β	Constant in Eq. (16)
ρ	Density of plume flow (kg/m^3)
ρ_∞	Density of ambient air (kg/m^3)
$\Delta\rho$	Density difference ($=\rho_\infty-\rho$)
Θ	Non-dimensional temperature defined by Eq. (10)

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