An Experimental Study of Ejected Flames of a High-Rise Buildings
– Effects of Depth of Balcony on Ejected Flame –

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ABSTRACTS

The aim of this study is to investigate the effects of depth of balcony on ejected flames from opening of a fire room. For this aim, an experimental study was done using a 1/7 scale model of seven-storey high-rise apartment building. Variation of temperature in the fire room, that of temperature along trajectories of ejected hot air currents, and that of length and angle of ejected flames were measured and analysed. Temperature in the fire room with balconies was higher than that without balconies. Temperature along trajectory with balconies decreases more rapidly than that without balconies. Horizontal length of ejected flames was independent of depth of a balcony. Vertical length, length, and angle of ejected flame decreased as depth increased.

KEYWORDS: ejected flame, high-rise building, balcony, model experiment

LIST OF SYMBOLS

c_p	specific heat $[J \cdot kg^{-1} \cdot K^{-1}]$
d	depth of a balcony [m]
g	acceleration due to gravity $[m \cdot s^{-2}]$
L	length of ejected flame [m] $=(x^2+y^2)^{1/2}$
Q	heat release rate in the fire room calculated assuming that fuel gas supplied to the fire room through burner undergoes complete combustion [W]
$\dot{Q}$	rate of heat flow ejecting through an opening [W]

r_0 equivalent radius of the upper half of opening [m]
T_∞ ambient temperature in Kelvin [K]
x horizontal length of ejected flame [m]
y vertical length of ejected flame [m]
z distance along trajectory [m]

GREEK

ΔT_0 temperature rise along trajectory at distance z [℃]
$\Delta\theta$ temperature rise in the fire room [℃]
Θ dimensionless temperature [-]
$=\Delta T_0 r_0^{5/3}/(T_\infty \dot{Q}^2/c_p^2\rho^2 g)^{1/3}$
α angle of ejected flame [deg]
$=\arctan(y/x)$
θ temperature in the fire room [℃]
ρ density of air [$kg \cdot m^{-3}$]

INTRODUCTION

Figure 1 shows variation of number of fire incidents with storey of a fire resistive building in Tokyo area[1]. Most of fire incidents occur in high-rise buildings. It is possible that fire spreading to other floors happens in fires of high-rise buildings. Table 1 shows number of fire spreading to other floors in fire resistive buildings in Tokyo area[1]. Fire spreading to other floors is not negligible. Figure 2 shows cause of fire spreading to other floors in fire resistive buildings in Tokyo area[1]. Shaded area shows that fire spreading occurred in apartment houses. Figure 2 tells us following two points.
1) Main cause of fire spreading to other floors in fire resistive buildings is openings of outer wall. That is, ejected flames from openings of outer wall are main cause of fire spreading.
2) Fire spreading by opening of outer wall occurred mainly in apartment houses.

TABLE 1 Number of fires spread to other floors in fire resistive buildings in Tokyo area. Produced from reference 1.

Year	Number of fire spreading to other floor
1990	25
1991	16
1992	21
1993	35
1994	39
1995	32
1996	16
1998	32

Most of apartment houses have balconies. One of the roles that balconies have is prevention of fire spreading to other floors. Committee on fire safety assessment of water front buildings

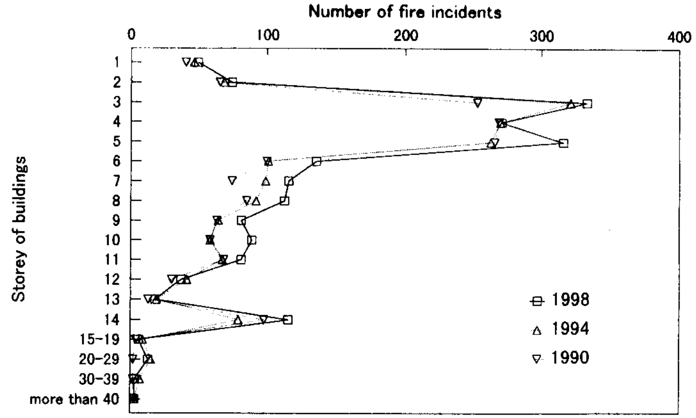

FIGURE 1 Variation of number of fire incidents with storey of fire resistive buildings. Reproduced from reference 1.

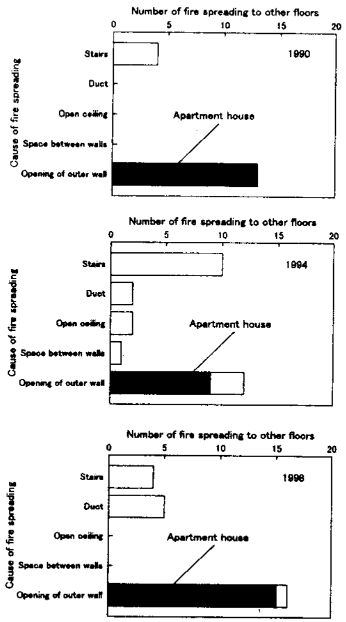

FIGURE 2 Cause of fire spreading to other floors in fire resistive buildings. Reproduced from reference 1. Shaded area shows that fire spreading occurred in apartment house.

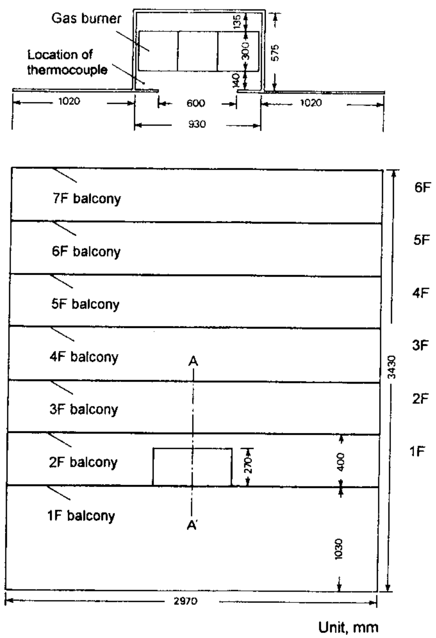

FIGURE 3 Outline of model configuration.

evaluated effects of balcony[2]. They concluded that length of ejected flames for building without balcony is calculated using following equations.

$$\begin{pmatrix}\text{Length of an}\\ \text{ejected flame}\\ \text{without balcony}\end{pmatrix} = (1.64)(\text{Height of opening}) \quad \text{for} \quad \frac{\text{Width of opening}}{\text{Height of opening}} > 2.$$

$$\begin{pmatrix}\text{Length of an}\\ \text{ejected flame}\\ \text{without balcony}\end{pmatrix} = (1.21)(\text{Height of opening}) \quad \text{for} \quad \frac{\text{Width of opening}}{\text{Height of opening}} < 2.$$

For buildings with balcony following equation is used.

$$\begin{pmatrix}\text{Length of an}\\ \text{ejected flame}\\ \text{with balcony}\end{pmatrix} = \begin{pmatrix}\text{Length of an}\\ \text{ejected flame}\\ \text{without balcony}\end{pmatrix} - (\text{Depth of balcony})$$

As an ejected flame becomes longer, radiative heat flux to the upper floor becomes large. Thus possibility of fire spreading to the upper floor increases as an ejected flame becomes longer. According to their equations fire spreading occurs less frequent as depth of balcony increases.

Relation between depth of balcony and hot air current spurting from opening was studied in Yokoi's pioneering work[3]. However knowledge on the relation between deep balcony and ejected flames is limited. Thus in this study varying depth of balcony in wide ranges, relation between balcony and ejected flames is investigated experimentally. For that purpose a 1/7 scale model building was used. Measuring temperature distribution near the opening, trajectories of hot gas ejecting from the opening were obtained. Analysing video images, location of the upper end of an ejected flame was measured to obtain flame length and angle. Relation among the values obtained and depth of balcony was studied.

Studies on hot air ejected from opening of fire room were done by Yokoi[3], Sugawa's group[4-11], Tanaka's group[12-15], and Lin et al.[16]. Though multi-story buildings with continuous-structured balconies are easily found in big cities, model of those buildings were not used in their studies.

Fire experiments using real multi-story buildings with continuous-structured balconies were done by Tokyo Fire Department[17, 18] and Nagoya City Fire Department[19], but experimental conditions in these experiments are limited.

The knowledge obtained through this study is applicable

1)to make fire protection scheme of high-rise buildings, such as suggesting how to use balcony in daily life,

2)to develop fire fighting activity, and

3)to design balcony and window of high-rise buildings.

EXPERIMENTAL

A 1/7 scale model building was used. Outline of model configuration is shown in Figure 3. The model consisted of a 930 mm wide by 575 mm deep by 375 mm high fire room with the front wall extended to 2970 mm in height and 3430 mm in width. Ventilation was provided by the window opening only. A 600 mm wide by 270 mm high opening was used. The fire room was equipped with three 30 cm square LP gas diffusion flame burners whose exits were as high as the floor of the fire room. The LP gas flow was manually controlled. The

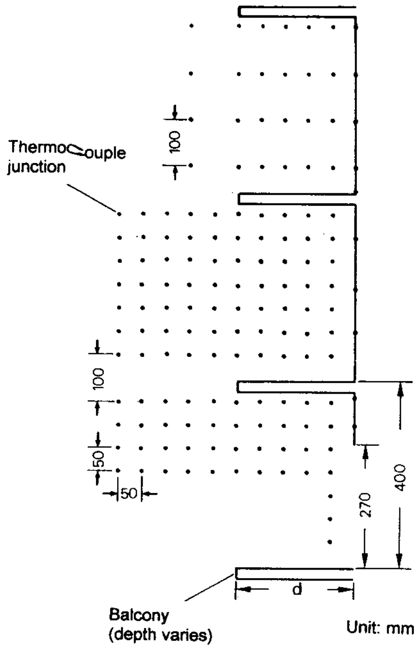

FIGURE 4 Location of thermocouples on the outer wall and near opening.

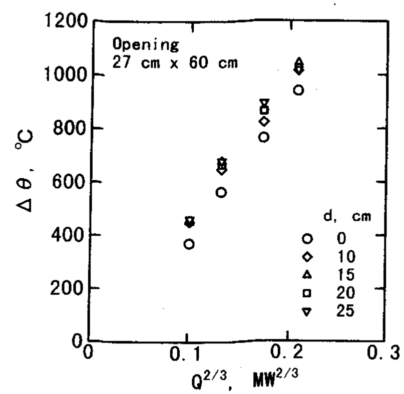

FIGURE 5 Variation of temperature in the fire room with heat release rate.

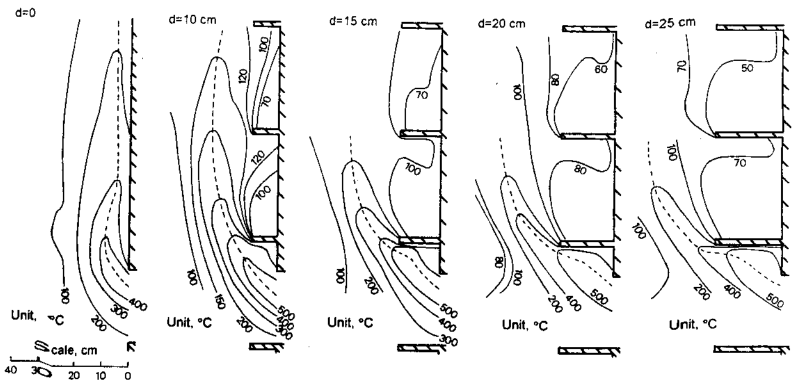

FIGURE 6 Isothermal lines in plain perpendicular to the outside surface passing line A-A' in Figure 2. Q=48 kW. Depth of balcony is 0(no balcony), 10 cm, 15 cm, 20 cm, 25 cm (from left to right). Trajectories are drawn by dashed line.

experimental fires were conducted with four different heat release rates 32 kW, 48 kW, 72 kW, and 95 kW. These values were calculated assuming that LP gas supplied undergoes complete combustion.
Horizontal balconies extended for 2970 mm along the face of the wall. Measurements with and without the presence of balcony were carried out. Balconies of four depths (measured perpendicular to the wall) were used: 10 cm, 15 cm, 20 cm, and 25 cm.
Temperature on the outer wall and near opening was measured with thermocouples. Measurement were taken on the vertical centre line of the wall. The vertical centre line is line A-A' in Figure 3. Location of the thermocouples are shown in Figure 4. Also temperature at the corner of the fire room was measured. Location of thermocouple in fire room is shown in upper part of Figure 3. Temperature 30 cm above the floor at the corner in the fire room is defined as temperature in the fire room in this paper.
Effects of balcony were evaluated by following three measurements.

1. Variation of temperature in the fire room
2. Variation of temperature along trajectories of ejected hot air currents
3. Location of upper end of ejected flames

RESULTS AND DISCUSSION

Variation of Temperature in the Fire Room

Variation of temperature rise in the fire room from ambient temperature is shown in Figure 5. $\Delta\theta$ increased as Q increased. Temperature in the fire room with balconies was higher than that without balconies.

Variation of Temperature along Trajectories of Ejected Hot Air Currents

Isothermal lines were drawn from the results from temperature measurements. Isothermal lines for Q=48 kW are shown in Figure 6. Trajectories are drawn from isothermal lines. They are shown by dotted lines in Figure 6. In case that d=0, trajectory leaves from outer wall and then rises along the wall. In case that d≥10 cm, trajectory rises outside balconies. In case that d=10 cm, trajectory passes near the edge of 2F balcony. In case that d≥15 cm, trajectory proceeds under the 2F balcony. Then it leaves from balcony. As depth of balcony decreases, trajectory approaches the outer wall.
Under the 2F balcony hot area is seen. The area between 2F and 1F balcony plays part of an ancillary room. The hot area under 2F balcony caused air which flows into the fire room through opening to be preheated. Also it decreased heat loss through opening. Thus temperature in the fire room with balconies became higher than that without balconies as mentioned in section 3-1.
Temperature along trajectory is changed into dimensionless number using Yokoi's equation[3]:

$$\Theta=\Delta T_0 r_0^{5/3}/(T_\infty \dot{Q}^2/c_p^2\rho^2 g)^{1/3}.$$

Variation of dimensionless temperature with dimensionless distance is shown in Figure 7.

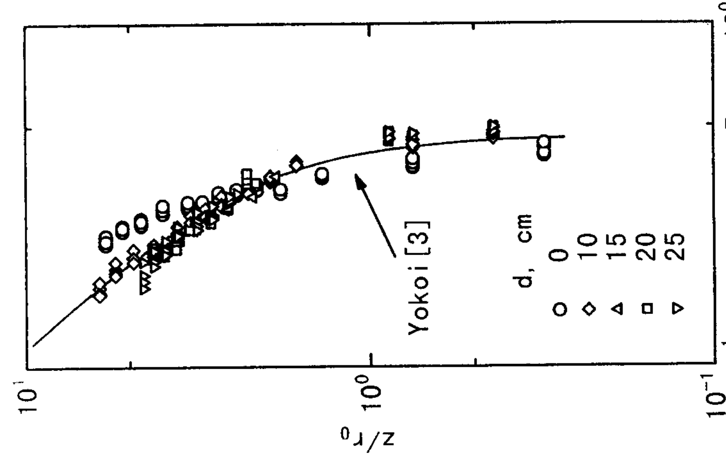

FIGURE 7 Temperature distribution of ejected hot gas along trajectories. Q_1 in Table 2 was used to calculate Θ. Yokoi's results from reference 3 are drawn by solid line

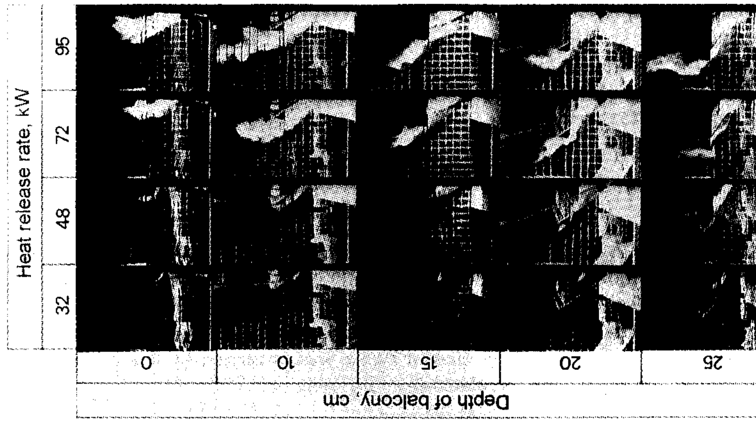

FIGURE 8 Aspects of ejected flames.

Yokoi's results without balcony[3] are shown by solid line in Figure 7. In calculating Θ, value of Q is needed. But value of Q is unknown. Q_1 in Table 2 was used so that our results lie close to Yokoi's results. The ratio of heat flowing out of balcony to heat release rate is close to Q_1/Q in Table 2. Temperature along trajectory with balconies decreases more rapidly than that without balconies. Our results did not agree with those of Yokoi. It is attributed to the difference in shape and size of the model used in experiments.

TABLE 2 Heat release rates used for calculating dimensionless temperature.

Q, kW	Q_1, kW	Q_1/Q
32	23.1	0.72
48	32.2	0.67
72	39.4	0.55
95	42.3	0.45

Location of Upper End of Ejected Flames

In order to obtain length of ejected flames location of upper part of ejected flames was measured from video images of flames.
Aspects of ejected flames are shown in Figure 8. In case that d=0, a flame leaves from outer wall and then rises along the wall. In case that d=10 cm, a flame passes near the edge of 2F balcony. In case that d≥15 cm, a flame proceeds under the 2F balcony. Then it leaves from balcony. Movement of flame observed from video image agrees with trajectory obtained from temperature measurement.
The frequency that a flame ejected from opening increased as heat release rate increased. Since in case that Q=95 kW flames are seen most clearly, video images for Q=95 kW were used for analysis. Four values were defined to characterize the location. Their definitions are shown in Figure 9. Analysing still images taken by video camera location of upper end of ejected flames are measured. Lengths and angle are calculated from the location. Variations of lengths and angle with depth of balcony are shown in Figure 10.
Horizontal length are independent of depth of balcony. Vertical length, length, and angle of ejected flame decreased as depth increased in case that d≥10 cm. This result agrees qualitatively with the prediction by committee on fire safety assessment of water front buildings[2]. Vertical length, length, and angle in case that d=10 cm are the largest. This result does not agree with the prediction.

CONCLUSIONS

To study the effects of depth of balcony on ejected flames, characteristics of a flame ejected from an opening of a fire room was studied experimentally using a 1/7 scale model of seven-storey high-rise building. Isothermal lines were drawn near the opening and trajectories of hot gas ejected from the opening were obtained by measuring temperature distribution near the opening. Location of the upper end of an ejected flame was measured by analysing video images. Flame lengths and angle were calculated from the location.
Following experimental results were obtained.
1)Temperatures in the fire room with balconies were higher than those without balconies.

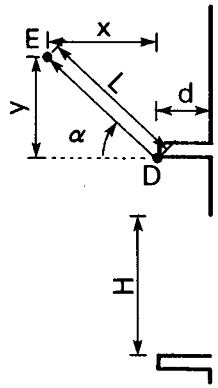

FIGURE 9 Definition of symbols.
D: edge of lower surface of 2F balcony, E: upper end of ejected flame, H: height of opening.

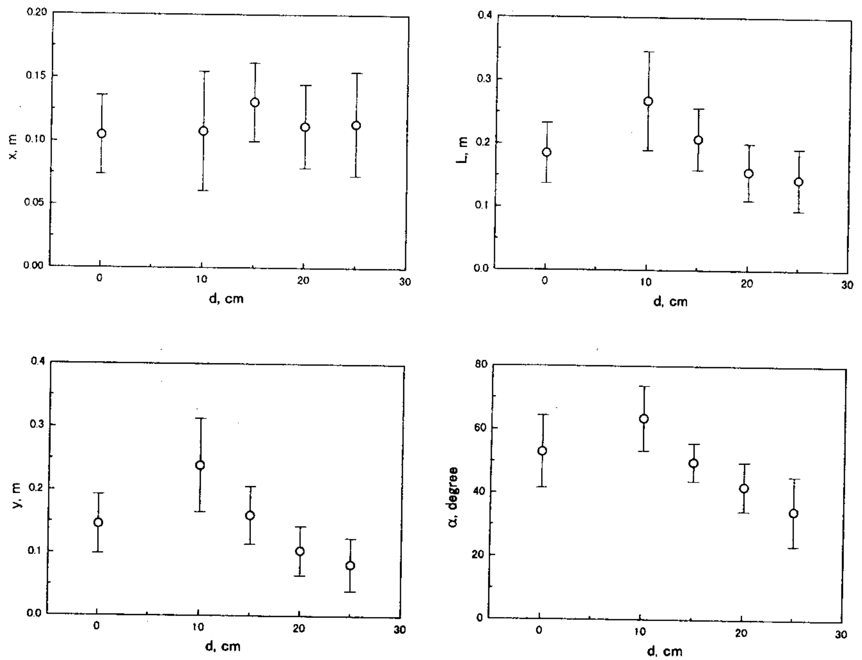

FIGURE 10 Variation of location of upper end of ejected flames with depth of balcony. Q=95 kW. Circle denotes average value. Error bar denotes standard deviation. Horizontal axis represents x(above left), y(blow left), L(above right), α (below right).

2)Trajectory of an ejected flame approaches the outer wall as depth of balcony decreases.
3)Temperature along trajectory with balconies decreases more rapidly than that without balconies.
4)Horizontal length from the edge of a balcony to upper end of an ejected flame was independent of depth of balcony.
5)Vertical length, length, and angle of ejected flame decreased as depth of a balcony increased in case that d≥10 cm. This result agrees qualitatively with the prediction by committee on fire safety assessment of water front buildings.
6)Vertical length, length, and angle in case that d=10 cm are the largest. This result does not agree with the prediction by the committee mentioned above.

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