TEMPERATURE PROFILES OF WINDOW JET PLUME

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ABSTRACT

In order to develop a means to assess the effectiveness of some design elements for preventing upper floor fire spread, such as window geometry and arrangement of eaves above windows, possibility of scaling of window jet plume temperature distribution by means of a nondimensional temperature was explored. Experiments were conducted using two geometrically similar setups having different sizes to investigate the applicability of the non-dimensional temperature to various conditions.
It was found that the non-dimensional temperature is independent of size and fire temperature but is uniquely determined only by geometrical conditions, that is, it is possible to predict real scale window jet plume temperatures based on the results of reduced scale experiments.

KEYWORDS: Window jet plume, Upper floor fire spread, Non-dimensional temperature

1. INTRODUCTION

Window flames or window jet plumes are a major cause of upper floor fire spread and perhaps not a negligible cause of fire spread to adjacent buildings in densely built urban area. It is a common practice to assess the hazard of upper floor fire spread based on the estimation of axis temperature of window jet plume. The most complete study on window flames and plumes was conducted by Yokoi. He found the non-dimensional parameter for scaling the axis temperature of the window flames, which gives us a means to predict the axis temperature under various window geometry and fire room temperature[1]. However, the

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temperature which actually affects to fire spread is not exactly the axis temperature but the temperature to which windows on upper floors are directly exposed. Since the window plume temperature is the highest at its axis, it will require excessive, though conservative, fire resistant performance to window panes if the breaking of the window is assessed based on the axis temperature. Generally speaking, the conditions of the usual preventive measures of upper floor fire spread, such as geometry of window, spandrel or balcony differs from one building to another. The only accurate way to investigate the preventive effects of these factors on upper floor fire spread is to conduct the experiments under the conditions reflecting the real situation. However, conducting full-scale experiments are not always affordable. Hence, a practical means to take into account such design features in assessing the hazard of fire spread by window flames may be to use reduced scale experiments provided that an appropriate scaling parameter is established.

2. NON-DIMENSIONAL TEMPERATURE

Yokoi found that the temperature along the axis of window plume can be scaled by the non-dimensional temperature defined by

$$\Theta = \frac{\Delta T_0 r_0^{5/3}}{\left(\dfrac{T_\infty Q_D^2}{C_p^2 \rho^2 g}\right)^{1/3}} \tag{1}$$

where ΔT_0 is the temperature rise at arbitrary position along the plume axis, r_0 is the equivalent radius of the opening jet, T_∞ is the ambient temperature, Q_D is the heat ejected along with the window jet, C_p is the specific heat of air, ρ is the gas density at arbitrary position along the plume axis and g is the acceleration due to gravity.

Yokoi's non-dimensional temperature can be transformed into a form more popular in the current fire research community, i.e.

$$\Theta \equiv \left(\frac{\Delta T/T_\infty}{Q_D^{*\,2/3}}\right) \Bigg/ \left(\frac{T}{T_\infty}\right)^{2/3} \tag{2}$$

where Q_D^* is the non-dimensional heat flow rate of window jet define as

$$Q_D^* = \frac{Q_D}{C_p \rho_\infty T_\infty \sqrt{g}\, r_0^{5/2}} \tag{3}$$

However, here neglecting $(T/T_\infty)^{2/3}$ in Eqn.(2), and the temperature rise ΔT is extended to the rise temperature at not only arbitrary position along the plume axis but arbitrary positions the plume. we employ

$$\Theta(\xi,\psi) \equiv \frac{\Delta T(x,y)/T_\infty}{Q_D^{*\,2/3}} \tag{4}$$

with $(\xi,\psi) = \left(\frac{x}{H}, \frac{y}{H}\right)$

for convenience in practical application of the scaling parameter. Also, in stead of Q_D^* given by Eqn.(2), which uses equivalent radius r_0 as the representative length, we use Q_D^* more conveniently defined using opening height H as the representative length, namely,

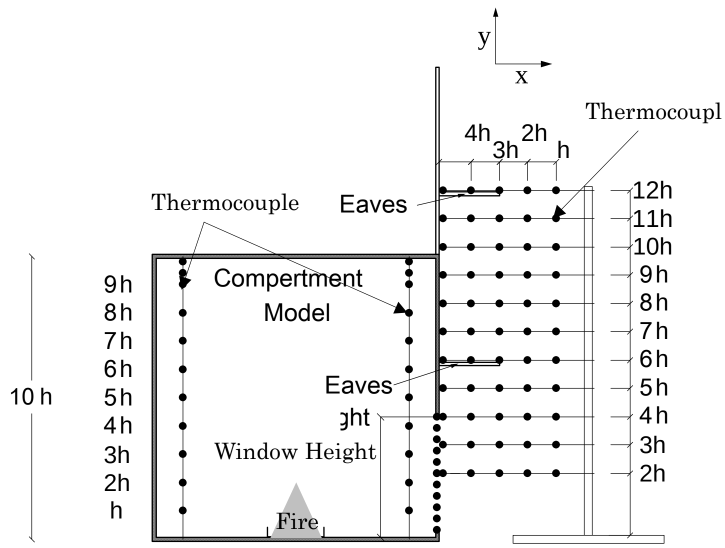
$$Q_D^* = \frac{Q_D}{C_p \rho_\infty T_\infty \sqrt{g} H^{5/2}} \tag{5}$$

since, the characteristic length do not necessarily have to be equivalent window jet radius, as long as similarity among different scale is concerned.

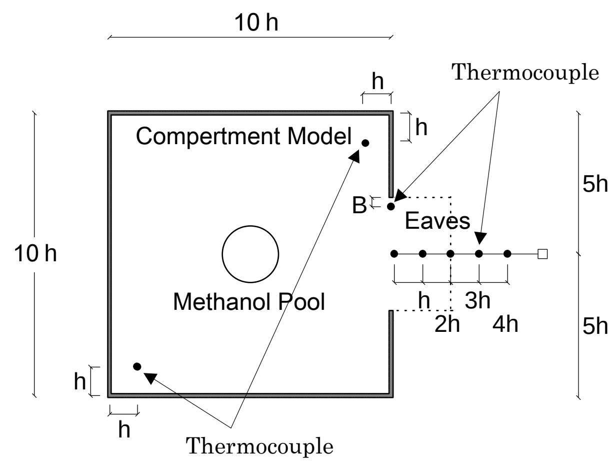
3. EXPERIMENTS

3.1 Model Fire Compartments

The two geometrically similar experimental setups as shown in FIGURE 1 are used in this series of experiments. The temperatures of window jet plumes were measured at geometrically similar positions relative to the opening height under various conditions of opening geometry fire size. The inside measurements of the small scale and the medium scale cubic fire compartments are 0.5m and 1.5m, respectively. The "*h*" in FIGURE1 is the size of thermocouple setup, *h*=0.15m for middle scale experiment and *h*=0.05m for small scale experiment. Methanol in pans of different sizes are placed on the floor of the compartment and burned as the fire source. The size and geometry of the opening of the compartment are changed using panels having different openings.



SECTION (Middle scale experiment : h=0.15m, Small scale experiment : h=0.05m)



PLAN(Middle scale experiment : h=0.15m, Small scale experiment : h=0.05m)

FIGURE1 SCHEMATIC DIAGRAM OF EXPERIMENTAL APPARATUS

3.2 Measurement

The temperatures were measured at the compartment, at the window and outside the window. The locations of the thermocouples for the temperature measurements are shown in FIGURE 2. The temperatures at the compartment were measured by 9 thermocouples arrayed vertically with 15 and 5cm spacing in the middle scale and the small scale setups, respectively. The temperatures at the window were measured by the thermocouples arrayed at 3cm from one of the edges of window with 3cm and 1.5cm spacing in the medium and the small scale setups, respectively. The temperatures outside the window were measured by 55 thermocouples arrayed vertically and horizontally with 15 and 5cm spacing in the middle scale and the small scale setups, respectively.

3.3 Experimental Conditions

The conditions of the opening and fire source in the medium and small scale experiments are shown in Tables 1(a) and (b), respectively. The experiments were conducted for every combination of these conditions.

TABLE 1 EXPERIMENTAL CONDITIONS

(a) Middle Scale Experiment

Opening Shape		Eaves Shape		Fire Source Condition
Width B(m)	Height H(m)	Depth (m)	Length (m)	Diameter (m)
0.30	0.60	non		0.30
0.60	0.60	H/2 (H:Window Height)	B (B:Window Width)	0.40
0.60	0.30	H/2 (H:Window Height)	1.5	0.60

(b) Small Scale Experiment

Window Shape		Eaves Shape		Fire Source Condition
Width B(m)	Height H(m)	Depth (m)	Length (m)	Diameter (m)
0.10	0.20	non		0.10
0.20	0.20	H/2 (H:Window Height)	B (B:Window Width)	0.15
0.20	0.10	H/2 (H:Window Height)	0.5	0.20

4. ANALYSES OF THE EXPERIMENTAL RESULTS

4.1 Temperature of the window jet plume

FIGURE 2(a) shows some examples of the isotherm of the raw measured temperatures of the window jet plumes for different size and heat release rate but similar opening geometry. The difference in density in the isotherm indicates the difference in temperatures, which naturally differ depending on sizes of fire and spaces. On the other hand, FIGURE 2(b) shows the profiles of the non-dimensional temperatures processed by Eqn. (5). Incidentally, the heat flow rate of window jet Q_D in Eqn.(5) was estimated as

$$Q_D = C_p m_D \Delta T \qquad (6)$$

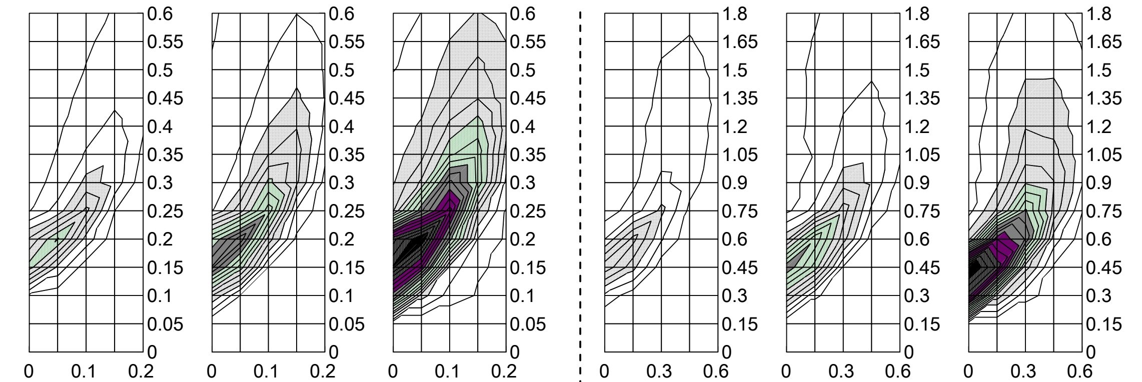
where C_p is specific heat of gas at constant pressure, ΔT is the average temperature rise of window jet and m_D is the mass flow rate of the window jet[2]. m_D was estimated from the compartment temperature and the neutral plane height at the window; calculated by

$$m_D = \frac{2}{3}\alpha B\{2g\rho_s(\rho_\infty - \rho_s)\}^{1/2}(H - Z_n)^{3/2} \qquad (7)$$

where α is window flow coefficient, B is the window width, g is gravitational acceleration, ρ_s is the window jet density, ρ_∞ is the ambient air density, H is the window height and Z_n is the neutral plane height at the window.

FIGURE 2(a) shows examples of the isotherm of the raw measured temperatures of the window jet plume for different size and heat flow rate of but similar window geometry. Difference in density in the isotherm indicates the difference in temperatures, which naturally differ depending on sizes of fire and spaces. On the other hand, FIGURE 2(b) shows the profiles of the non-dimensional temperatures processed by Eqn. (4). It can be seen that all the window jet plume isotherms, which differ in FIGURE 2(a), have become to be almost the same regardless the different size and heat flow rate but similar window geometry in terms of the non-dimensional temperature.
FIGURE 3(a) shows examples of the isotherm of the raw measured temperatures of the window jet plume for different size and window geometry. On the other hand, FIGURE 3(b) shows the profiles of the non-dimensional temperatures processed by Eqn. (4). It is demonstrated that the non-dimensional isotherms agree sufficiently well regardless the difference in size if the geometry is similar.
FIGURE 4(a) and (b) shows examples of measured and non-dimensional temperature profiles of the window jet plume from windows with eaves. It can be seen that all the window jet plume isotherms have become to be almost the same regardless the different size and heat flow rate but similar window and eaves geometry in terms of the non-dimensional temperature.

Judging from the above, it was found that the non-dimensional temperature is independent of size and fire temperature but is uniquely determined only by geometrical conditions, that is, it is possible to predict real scale window jet plume temperatures based on the results of reduced scale experiments.

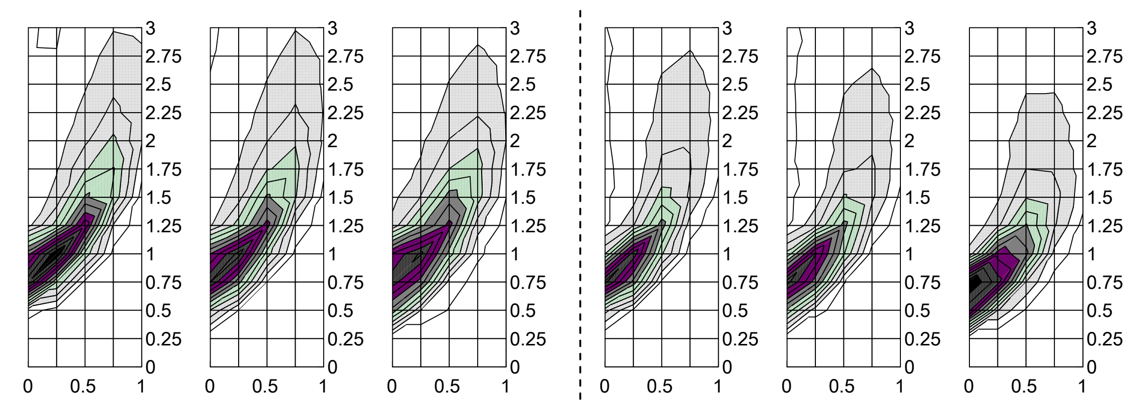


Q_D=0.4(kW) Q_D=1.0(kW) Q_D=2.2(kW) Q_D=5.6(kW) Q_D=12.7(kW) Q_D=26.7(kW)

OPENING SHAPE 0.1(B) : 0.2(H)(m) OPENING SHAPE 0.3(B) : 0.6(H)(m)

SMALL SCALE EXPERIMENT MIDDLE SCALE EXPERIMENT

FIGURE 2(a) RAW ISOTHERMS



Q_D=0.4(kW) Q_D=1.0(kW) Q_D=2.2(kW) Q_D=5.6(kW) Q_D=12.7(kW)
Q_D=26.7(kW)

OPENING SHAPE 0.1(B) : 0.2(H)(m) OPENING SHAPE 0.3(B) : 0.6(H)(m)

SMALL SCALE EXPERIMENT MIDDLE SCALE EXPERIMENT

FIGURE 2(b) NON-DIMENTIONAL ISOTHERMS

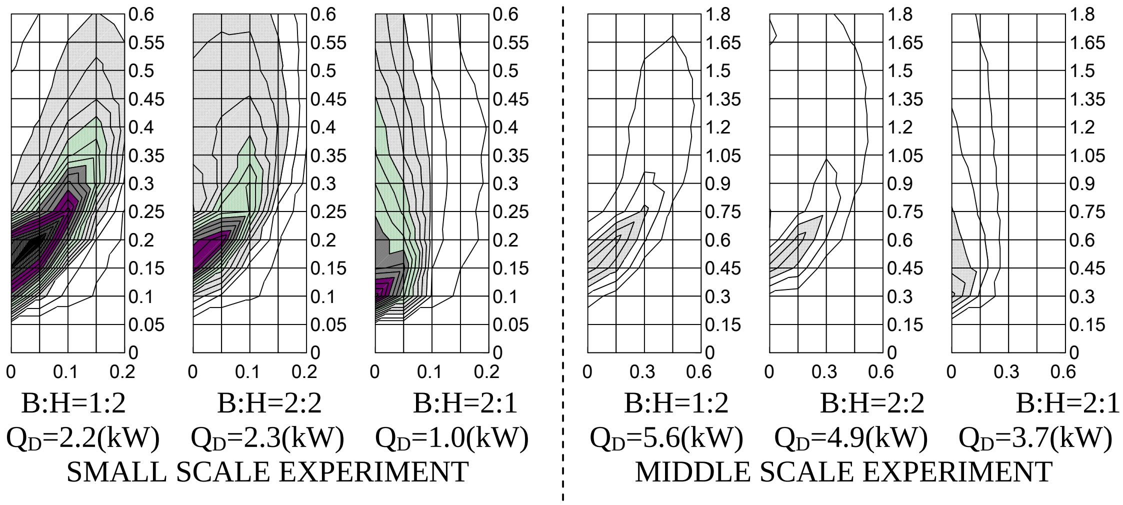


FIGURE 3(a) RAW ISOTHERMS

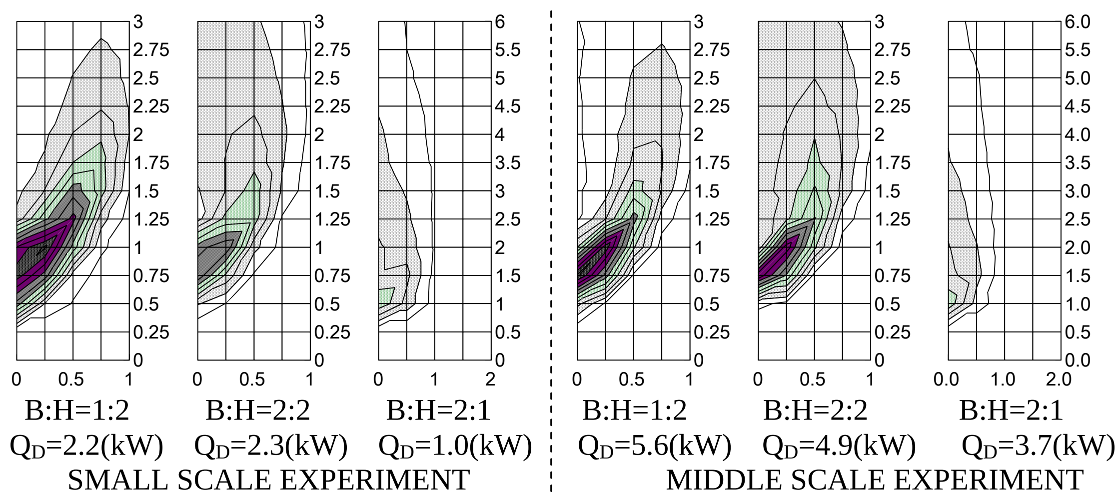
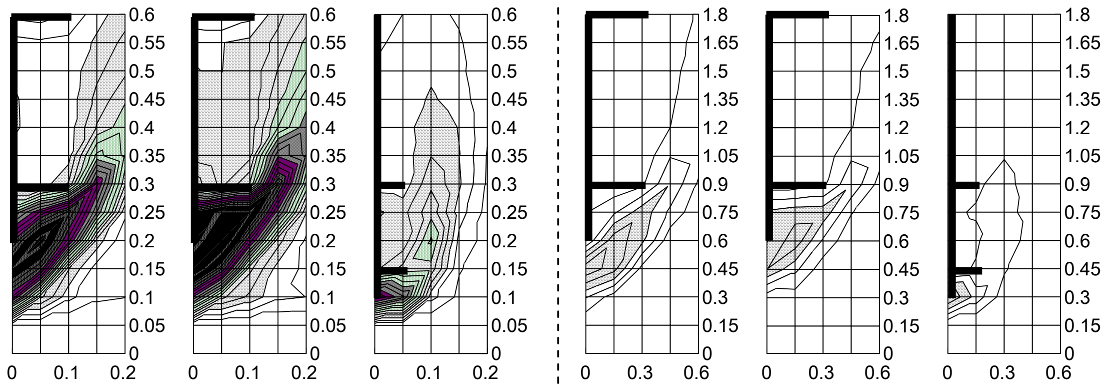


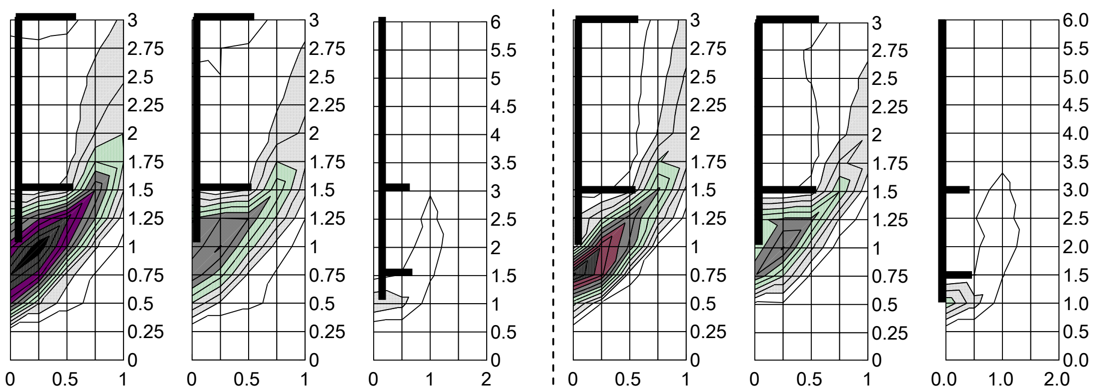
FIGURE 3(b) NON-DIMENTIONAL ISOTHERMS



B:H=1:2 Q_D=2.2(kW) B:H=2:2 Q_D=2.3(kW) B:H=2:1 Q_D=1.0(kW)
SMALL SCALE EXPERIMENT

B:H=1:2 Q_D=5.6(kW) B:H=2:2 Q_D=4.9(kW) B:H=2:1 Q_D=3.7(kW)
MIDDLE SCALE EXPERIMENT

FIGURE 4(a) RAW ISOTHERMS – WITH LONG EAVES -



B:H=1:2 Q_D=2.2(kW) B:H=2:2 Q_D=2.3(kW) B:H=2:1 Q_D=1.0(kW)
SMALL SCALE EXPERIMENT

B:H=1:2 Q_D=5.6(kW) B:H=2:2 Q_D=4.9(kW) B:H=2:1 Q_D=3.7(kW)
MIDDLE SCALE EXPERIMENT

FIGURE 4(b) NON-DIMENTIONAL ISOTHERMS – WITH LONG EAVES -

4.2 Temperature in the vicinity of window panel

If the temperatures at the locations of interest $\Delta T(x,y)$ are measured in a reduced scale experiments, the non-dimensional temperature Θ can be established. Then, the temperatures at geometrically similar locations in real scale building can be obtained by letting Θ be the same between the reduced scale and the real scale as long as the window jet geometry is similar.
FIGURE 5 shows the non-dimensional temperatures defined for in a reduced scale experiments with different conditions without eaves are plotted versus non-dimensional height ψ in the vicinity of window panel[3][4], where n indicates the aspect ratio of the window jet, defined as

$$n \equiv B/(H - Z_n) \tag{8}$$

It can be said that the non-dimensional temperature increase as the aspect ratio became large.

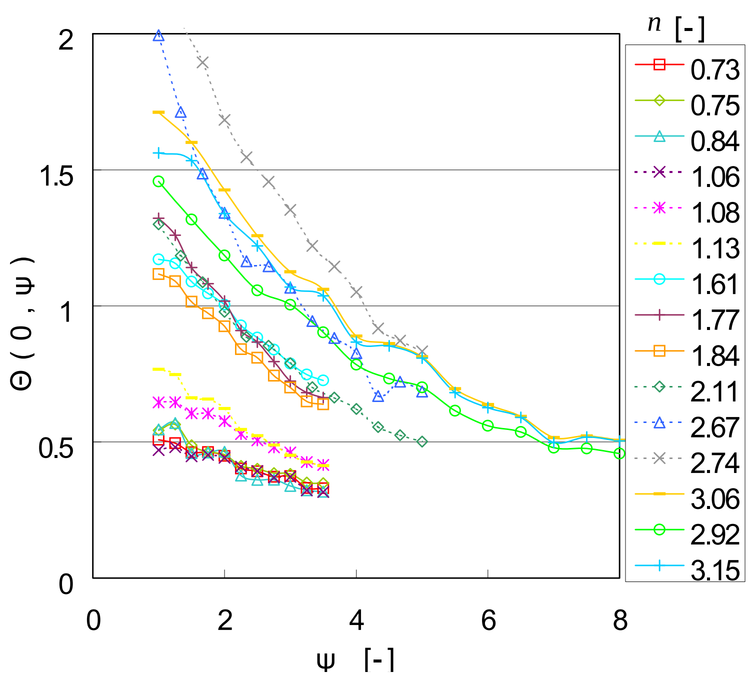


FIGURE 5 NON-DIMENTIONAL TEMPERATURE
IN THE VICINITY OF WINDOW PANEL

Next, the non-dimensional temperatures are inquired by assuming as,

$$\Theta(0,\psi) = \beta \times \psi^{\gamma} \tag{9}$$

so that non-dimensional temperature was proportionate -3/5 to power of non-dimensional height. When β was furthermore computed as the aspect ratio n, it became clear that a tendency as shown in FIGURE 6 is shown. Then the non-dimensional temperature at the vicinity of window panel can be correlated as Eqn. (10).

$$\Theta(0,\psi) = 0.7 n \psi^{-3/5} \tag{10}$$

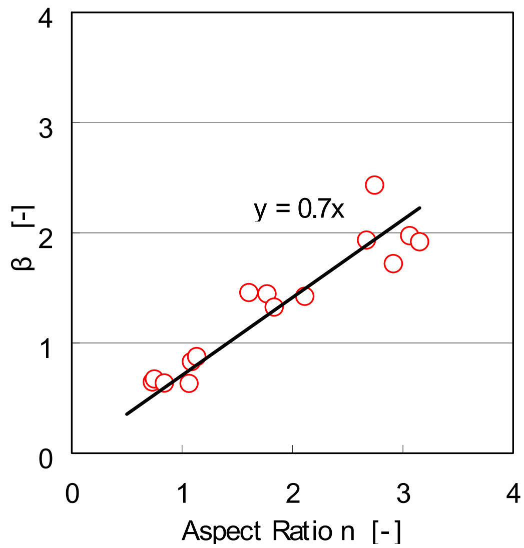


FIGURE 6 α v.s. ASPECT RATIO n

6. CONCLUSION

In this study, experiments were conducted to develop a means to estimate the temperature of window jet plume at the vicinity of upper floor window. From the results obtained through reduced scale and middle scale experiments, the following findings were obtained: ①the profile of non-dimensional temperature depends only on the aspect ratio of window jet section, ②the non-dimensional temperature at the vicinity of upper floor window was proportionate -3/5 to power of non-dimensional height, ③non-dimensional temperature is proportionate to aspect ratio of opening jet section.

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