A Numerical Study of Window-to-Window Propagation in High-Rise Building Fires

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ABSTRACT

This study describes numerical simulations of high-rise building fires extending to upward floors via windows.

Flames and hot gases ejected from openings and flowing along vertical building exterior walls may fracture window glasses and accelerate the fire growth towards upper floors. Particularly, there have been no numerical studies of dynamic fire behavior around windows and along vertical exterior walls, in relation to the fire growth. Here is attempted numerical finite-difference studies of time-dependent flow behavior of fires along external building walls and of the behavior of fires invading into the upper floor windows.

Two-dimensional numerical simulations show that upward flows adhere closely to the wall surface, similarly to the experimental flow patterns. Some large scale vortices are created around the upward fire gases. Almost periodically, "hot" gases enter the room immediately above the fire room via windows. The regular oscillatory motion depends upon the heat release rate in the fire room and is weakly affected by the window configurations.

KEYWORDS : High-rise building fire, Fire simulation, Oscillatory flow,
Wall fire, Fire propagation, Finite difference study,
Turbulent flow

INTRODUCTION

There has been growing concern about high-rise building fires after for example the Hotel New Japan Fire in Tokyo (1982)[1], the MGM Grand Hotel Fire in Las Vegas (1980)[2] and the First Interstate Bank Building Fire in Los Angeles (1988)[3]. It is important to investigate high-rise building fires since they are too severe for fire fighters to control and the number of high-rise buildings constructed in the world is rapidly increasing. In building fires, flames and hot gases ejected from windows and flowing along exterior walls may fracture glasses of upper floor windows and accelerate the fire growth into upward floors.

More than 30 years ago, Yokoi[4] studied the behavior of hot gases spurting out of a window of burning room using small scale models. After that, some experimental studies[5] have been carried out. However, building fires propagating externally via windows are not always fully clarified yet. No numerical studies of externally propagating building fires via windows are existent.

Numerical simulations of building fire propagation via windows are attempted in this study, using a two-dimensional finite-difference code. Not only the dynamic characteristics of fire flows along external walls but also the flow behavior of fires invading into the upper room via windows are investigated. Dynamic turbulent fire flows play a great role in the fire growth. Arbitrary six floors among multi-floors of a high-rise building with balconies are employed as the flow area examined in this numerical study. Video movies of small scale model fires and of a real fire in a building with balconies are used as a reference.

NOMENCLATURE

C_1 : constant ($=\underline{R}_o\underline{T}_o/\underline{U}_o^2$)
C_2 : constant ($=\underline{R}_o\underline{T}_o/\underline{g}\underline{H}_o$)
Fr : Froude number ($=\underline{U}_o^2/\underline{g}\underline{H}_o$)
$\underline{f}$: oscillatory frequency
$\underline{g}$: gravitational acceleration
$\underline{H}_o$, Y : height
p : pressure
Pr : Prandtl number
$\underline{Q}$, q : heat release rate
$\underline{R}_o$: gas constant
Ra : Rayleigh number
Re : local Reynolds number
Re_f : Reynolds number of frequency
$\underline{T}$, T : temperature
$\underline{t}$, t : time
$\underline{U}_o$: reference velocity
u, v : velocity components
x, y : Cartesian coordinates
$\underline{\beta}$: thermal expansion coefficient
$\underline{\lambda}$: thermal conductivity
$\underline{\nu}$: kinematic viscosity
ρ : density

(subscripts)
o : referene value
$\underline{\quad}$: dimensional quantity

MATHEMATICAL MODELING AND NUMERICAL METHOD

It is assumed that the fire gases are the ideal one. Differential equations used in the present 2-D numerical simulations are as follows;

[Continuity equation]

$$\partial\rho/\partial t+\partial(\rho u)/\partial x+\partial(\rho v)/\partial y=0 \tag{1}$$

[Momentum equation - horizontal direction]

$$\partial(\rho u)/\partial t+\partial(\rho u^2)/\partial x+\partial(\rho uv)/\partial y=-\partial p/\partial x +1/Re\cdot[2\partial^2u/\partial x^2+\partial^2v/\partial x\partial y+\partial^2u/\partial y^2] \tag{2}$$

[Momentum equation - gravitational direction]

$$\partial(\rho v)/\partial t+\partial(\rho v^2)/\partial y+\partial(\rho uv)/\partial x=-\partial p/\partial y-(\rho-\rho_o)/Fr +1/Re\cdot[2\partial^2v/\partial y^2+\partial^2u/\partial x\partial y+\partial^2v/\partial y^2] \tag{3}$$

[Energy equation]

$$\partial(\rho T)/\partial t+\partial(\rho uT)/\partial x+\partial(\rho vT)/\partial y=\nabla(1/(Re\cdot Pr)\cdot\nabla T) + q \qquad (4)$$

[Equation of state] [Equation of density at equilibrium state]

$$\rho T=p/C_1 + p_0 \qquad (5) \qquad\qquad \rho_0=\exp(-Y/C_2) \qquad (6)$$

The formulation of the finite difference equation is based on the micro-control volume scheme and the pressure correction algorithm [6]. The details are shown in the references [7 - 8]. Numerical calculations are carried out using the almost same computer code as in the previous studies [9 - 13].

The ceiling height $\underline{H}_0$ is used as the reference length. The dimensions of fire room are 3.43×2.45 m (=$\underline{H}_0$). The two-dimensional flow domain, the inside (6 floors) and outside of the building, is divided into 131×151 (vertical) uniform grids. Dimensions of each grid is 0.098×0.098 m. The thickness of balcony and soffit is set to 0.196 m.

The initial temperature and speed of air are 15℃ and 0 m/s, respectively. Temperatures and velocities at free boundaries are given to be zero gradients. Insulated are all solid boundaries like balconies, soffits,ceilings and walls, where non-slip flow conditions are employed. No particular viscosity model is incorporated, but the laminar viscosity at 15℃ is used.

The heat release in the fire room is given as in the following manner;

$\underline{Q}$: linearly increase [0 sec < $\underline{t}$ < 19.6 sec], $\underline{Q}$: constant [19.6 sec< $\underline{t}$]

This condition is not realistic, but is due to the computational simplicity. The eventual heat release rate, $\underline{Q}$=1500 kW, is employed to produce the temperature rise of more than 700K in the fire room. And the effect of heating rate, ranging from 1MW to 2MW, upon the dynamic motion of upward flow is also investigated. The heat source is distributed uniformly only in the fire room. No radiation and no chemical reactions of combustion are taken into account. These conditions are employed for the simplicity. The dimensionless time step is 10^{-3} or 10^{-4}.

The memory space needed for the computations was about 2 MB. Calculations were performed using a workstation SUN 3-260 (about 60 hrs/run) and a super computer FACOM VP-200 (about 1 hr/run). Computer graphic video animations were produced and used for the analysis of the dynamic flow behavior.

The lengths of soffit above windows and balconies around the exterior walls affect the flow patterns of upward fires along the wall. Nine different cases with various vertical soffit length and horizontal balcony length were examined. The other configurations of the fire room are fixed for all cases. The details of the calculated nine cases are shown in Table 1.

TABLE 1 Details of calculated nine cases

	Horizontal length of balcony (m)	Height of soffit (m)	Height of window (m)	Window conditions in the room immediately above the fire room
Case A	0.0	0.0	1.568	closed
Case B	0.0	0.196	1.372	closed
Case C	0.0	0.196	0.980	closed
Case D	0.098	0.0	1.568	closed
Case E	0.294	0.0	1.568	closed
Case F	0.490	0.0	1.568	closed
Case G	0.686	0.0	1.568	closed
Case H	0.882	0.0	1.568	closed
Case I	0.490	0.0	1.568	open

RESULTS AND DISCUSSION

(1) BEHAVIOR OF FIRE FLOW EJECTED FROM A WINDOW ALONG EXTERIOR BUILDING WALL

First investigated are the flow patterns of fire gas ejected from a window at an early stage. FIGURE 1 shows the isotherms and velocity vectors at $\underline{t}$=9.8 sec, in which only the left half area (about 70 grids out of 131 grids) are shown and velocity vectors are displayed in every two grids. In each case, the released heat is almost half of the eventual input, $\underline{Q}$= 1.5 MW. The other conditions of both the fire room and fire source are the same for the four cases, A, B, C and D.

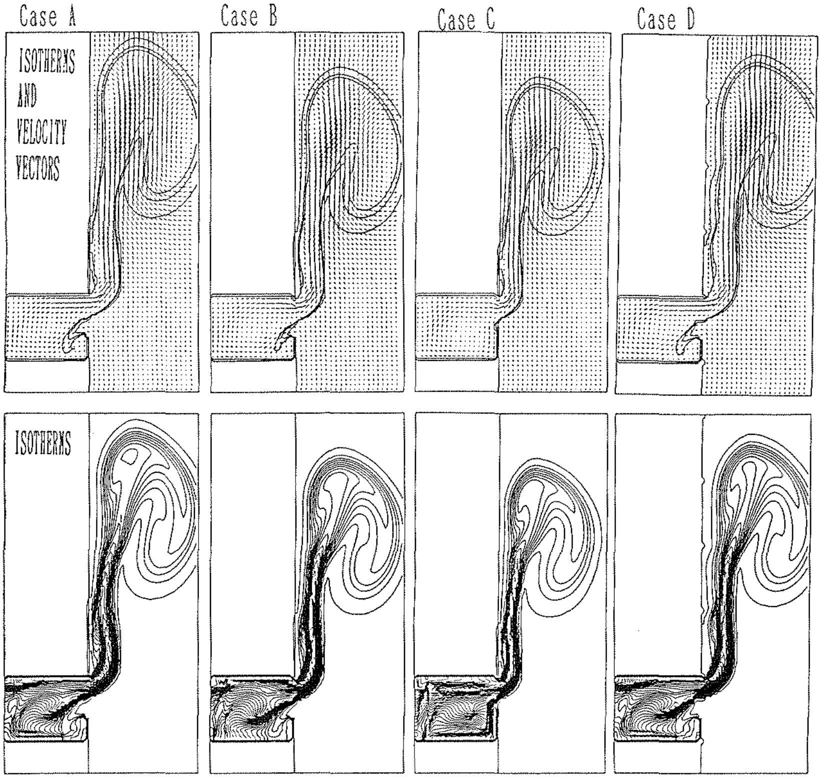

FIG.1 Early stage flow patterns of fire gas ejected from a window. ($\underline{t}$=9.8 sec)

Four flow patterns shown in FIG.1 are almost similar in spite of the discrepancy of each configuration such as window soffit and balcony. The upward flow is attracted toward the exterior wall in all cases. This coincides with the experimental results of Yokoi [4]. It is well-known that the flame of fire ejected from horizontally long windows adheres to the wall. On the other hand, in case of vertically long windows the ejected flames incline and detach from the wall. The two-dimensional window in this calculation corresponds to the case of horizontally long windows.

After this early atage, the upward flow adheres more to the wall as shown in FIG.2. At the fully developed stage the upward flow entrains a plenty of cool air from the bottom and right side boundaries. Moreover, the flow begins to show the periodic behavior as mentioned below.

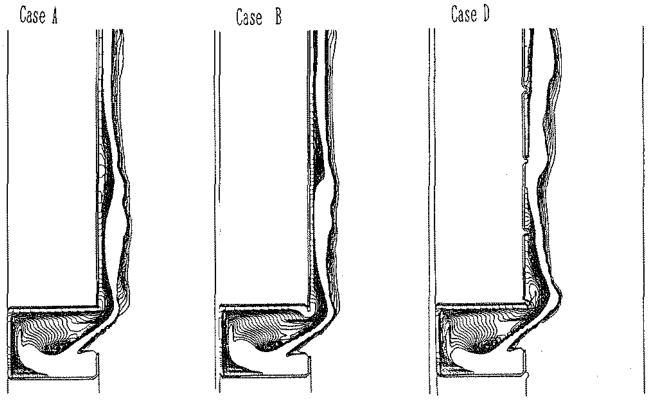

FIG.2 Upward flows of fully developed fires displayed by isotherms. ($\underline{t}$=90 sec) (Intermediary isothermal lines are omitted to clearly visualize the inner structure of fire gase along the exterior wall.)

When the balconies on walls are horizontally much longer, the trajectory of ejected fire gas may incline more and move upward apart from the wall surface. Thus the effect of balcony length is investigated. FIGURE 3 shows the flow patterns at $\underline{t}$=9.8 sec for Cases F and I (where the balcony length is 0. 49 m) displayed by isotherms. Other conditions are the same as those in FIG.1.

At this early stage, the upward flows incline more compared with those in FIG.1. The effect of window condition of the room immediately above the fire room is minor at this stage. However, after this stage, the upward flow adheres to the wall, similarly to the patterns in FIG.2.

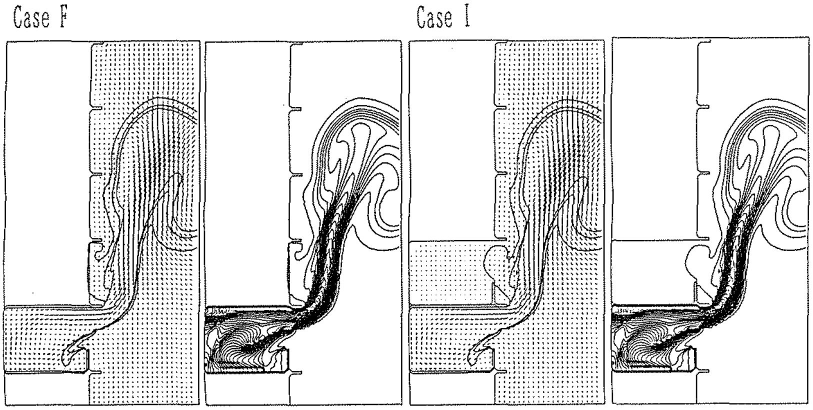

FIG.3 Early stage flow patterns of fire gas ejected from a window. ($\underline{t}$=9.8 sec) (The left figure is displayed by isotherms and velocity vectors and the right figure is by isothrms in each case.)

(2) PERIODIC MOTION OF UPWARD FLOW OF FIRE GAS ALONG EXTERIOR BUILDING WALL

At a fully developed stage of fire, the upward fire flow is time-dependent. Vortices are created around the intersection between the hot gas and cool entrained air. The generation and decay of vortices are repeated with time.

FIGURE 4 shows the time-dependent flow patterns (displayed by isotherms) of upward fire gas of Cases E, F and G. The period of one cycle of oscillatory motion is about 1.8 sec and slightly affected by the balcony length.

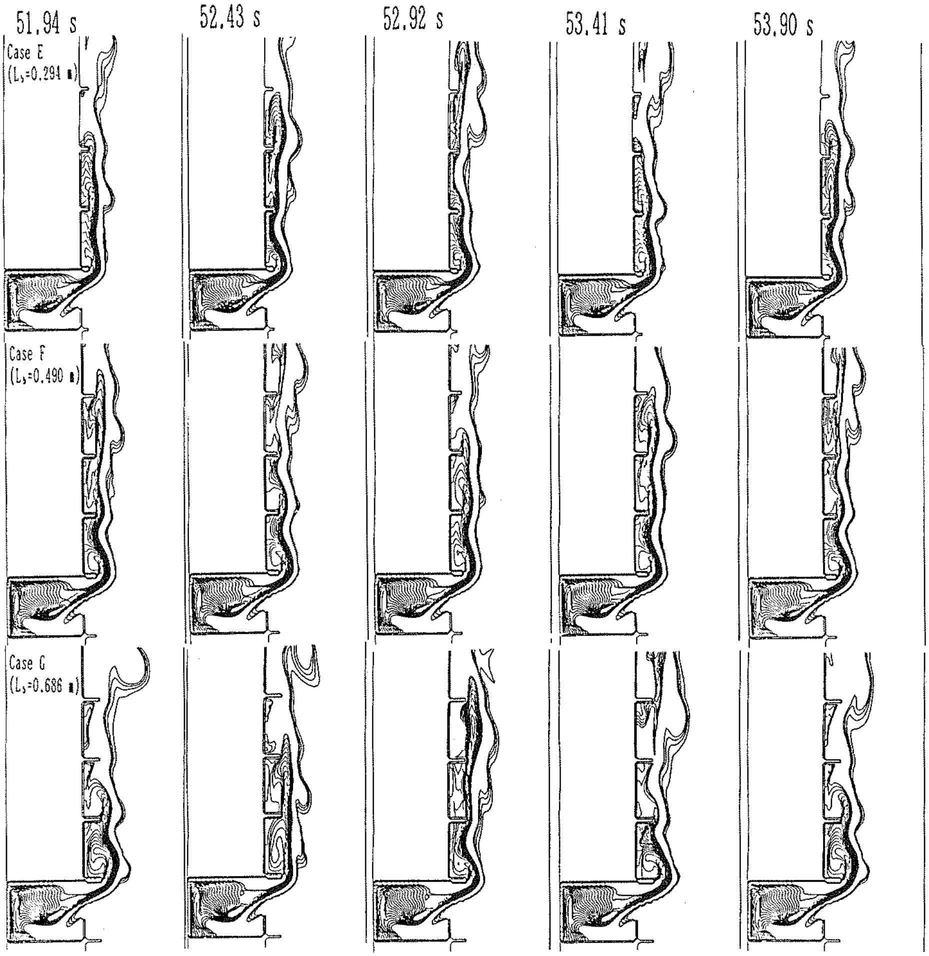

FIG. 4 Time-dependent flow patterns of fire gas along vertical wall with variation of horizontal length of balconies. ($\underline{Q}$=1.5 MW)

In FIG.4, the air in the area between the exterior wall and the upward fire flow is enclosed in a kind of "cavity". The flow behavior and temperatures in the "cavity" depend on the balcony length and the entrained air.

In 1989 a fire occurred in an apartment house (10.7×10.7 m) at the 24th floor of a building, called the Minami-Suna Sky-Mansion, in Tokyo. The fire room was located in one corner of the building and the window of the room was wide. The room burned perfectly, ejecting long flames. The flow along the exterior wall moved upward adhering to the wall surface. Of course the heat released in this fire accident and the structure of the room are different from the present numerical study. However, video movies, taken on a helicopter of fire fighters, of the fire showed clear periodic oscillatory motion of upward flows.

An experiment, using a small scale model ($\underline{H}_0$=0.5 m), of multi-storied building fire was carried out to study the flow pattern and the time-dependent behavior of a fire ejected from a window. (The details of the experiment have already reported [11].) FIG. 5 shows the flame burns adhering to the exterior wall. The flow pattern is qualitatively quite similar to those in this simulation. Large scale vortices are created around the flames. And a periodic motion of the upward flame was observed.

(3) HOT GAS ENTERING THE ROOM IMMEDIATELY ABOVE THE FIRE ROOM VIA WINDOWS

When the window glasses of the room immediately above the fire room are exposed to fires and then broken, the heated gas and smoke may enter the room via windows. The video movies of the high-rise building fires mentioned above showed that the flame tip spurted out of the window was blazing near the upper room balconies. Fortunately the fire did not extend to the upper room. However what happened if the upper room window was open?

Thus, numerical simulations were conducted for the case where the upper room window is open and the horizontal balconies (0.49 m in length) exist at each floor level. FIGURE 6 shows the hot gas entering the upper room and the behavior of upward flow along the exterior wall for the Case I.

FIG.5 Flame ejected from a window and burning along exterior wall. (Fuel : n-heptane burned in a steel tray)

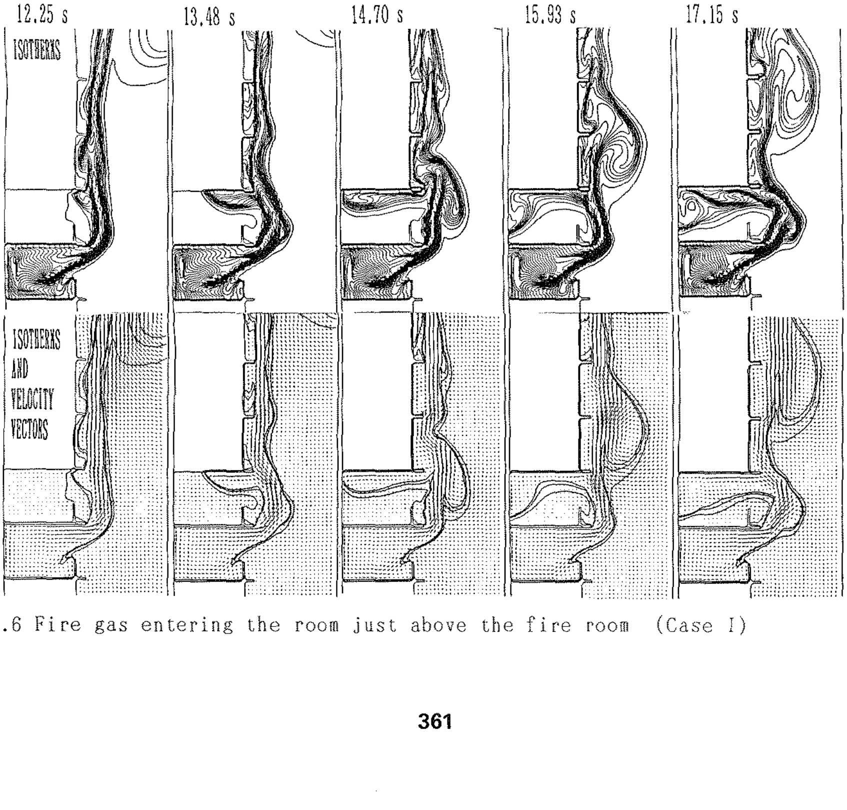

FIG.6 Fire gas entering the room just above the fire room (Case I)

In two-dimensional flows, corresponding to the case of wide windows, the fire gases enter the room immediately above the fire room in spite of the effect of balconies. Hence if the window glasses of the original fire room are widely broken and the flame becomes wide, the fire may propagate into the upper floors.

FIGURE 7 shows the time-dependent motion of Case I at fully developed stage of fire, continuing the flow patterns shown in FIG.6. The oscillatory motion is slightly affected by the space of the room immediately above the fire room.

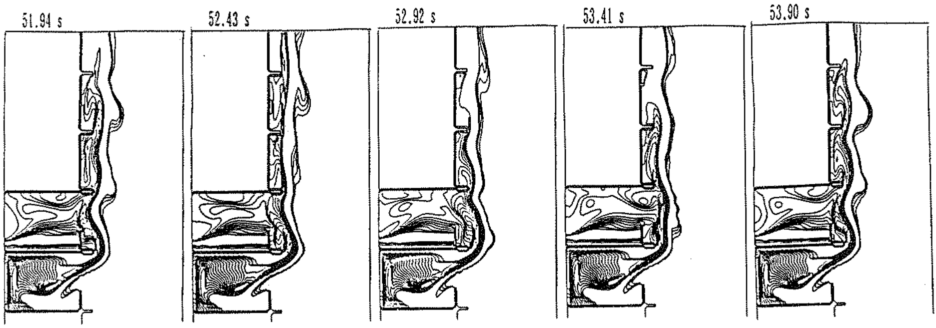

FIG.7 Periodic behavior of upward fire gas along exterior wall (Case I, Q=1.5 MW)

(4) EFFECT OF HEAT RELEASE RATE UPON THE OSCIILATORY MOTION

The energy input of 1.5 MW into the fire room of dimensions of 3.43×3.43×2.45 m (height) produces the temperature increase of about 700 K in the fire room, which is almost reasonable for the fire room temperature. Since the heat release rate depends on the fuel and air supply rates, arbitrary values of heat release rate are not always realistic. However it is important to examine the effect of heat input to the time-dependent flow of fire.

The frequency of the temperature variation at a fixed position for Case F is examined as a function of heat release rate. The position is 0.7 m far from the vertical wall and 6.5 m high from the fire room floor. The heat release rate is varied from 0.5 to 2 MW. FIGURE 8 shows the relationship between the Reynolds number expressing nondimensional frequency of the temperature variation and the Rayleigh number expressing the nondimensional heat release rate.

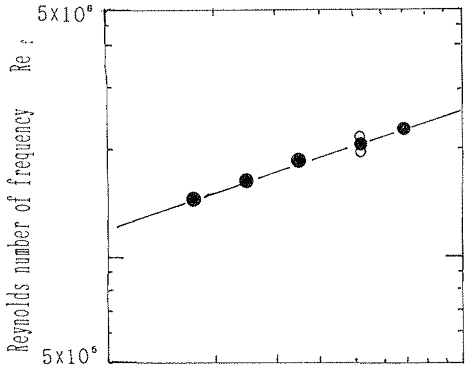

FIG.8 Relationship between Reynolds number and Rayleigh number (Case F)

Here the Reynolds number of frequency and the Rayleigh number are defined by the following equations;

$$Re_f = \underline{f} \cdot \underline{H_0}^2 / \underline{\nu} \qquad Ra = \underline{H_0}^3 \cdot g \cdot \underline{\beta} \cdot Q / \underline{\lambda} / \underline{\nu}^2$$

The relationship shown in FIG.8 can be expressed as $Re_f = 0.57\ Ra^{1/3}$.

It is well-known [14] that the natural swaying motion above a line heat source depends upon the heating rate. Satoh [15] [16] studied the swaying motion above a line heater using the present code and showed that the frequency of the swaying motion depends upon the 1/3rd power of the heat release rate, similarly to the experimental results [17]. The oscillatory phenomena of fire gas near the vertical exterior wall are similar to those of swaying motion above a line heater.

(5) TEMPERATURE DESCENT OF UPWARD FLOW ALONG EXTERIOR WALL

Here investigated is the temperature descent of fire gas along a vertical axis, at 0.4 m apart from the exterior wall surface, for Cases B and D. Their isothermal flow patterns are already shown in FIG.2.

FIGURE 9-(a) shows the time-averaged temperatures for Case B with 0.198 m length upper soffit at the window and FIG.9-(b) for Case D with balconies in length of 0.098 m. Up to the height of 1 m above the upper fringe of the window of the fire room, the temperature is almost constant, but above this height the temperature gradually descends.

Fire gases ejected from a window and moving upward with vortices oscillate with the frequency of about 0.5 Hz and entrain much air into the flow. As a result the temperature of the upward flow of fire descends gradually. The oscillatory phenomena of upward fire flow play a significant role in the heat transfer phenomena of fire gases ejected from a window.

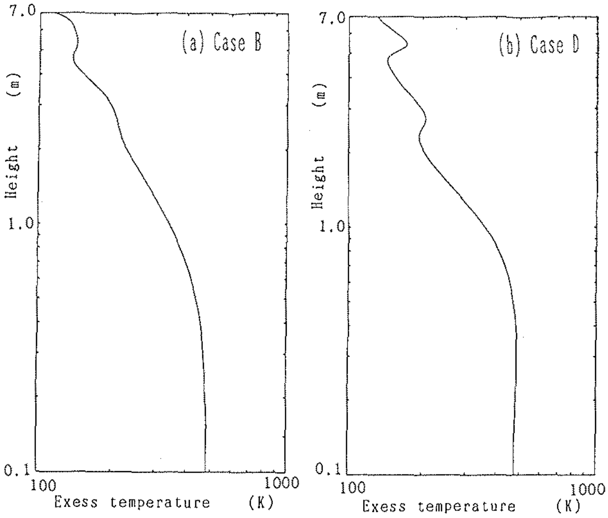

FIG.9 Temperature as a function of height. (Cases B and D, Q=1.5 MW)

CONCLUSION

Flow patterns of fire gas ejected from a window are similar even when the configurations such as window soffit and balcony are different. Two-dimensional fire flows ejected from windows are attracted toward the exterior wall and flow along the surface. This coincides with the case of wide windows in experiments.

Large scale vortices are created around the upward fire flow and generate time-dependent motions. The heat release rate in the fire room accelerates the oscillatory motion. The nondimensional relationship between the oscillatory frequency and the heat release rate is expresed as $Re_f=0.57\ Ra^{1/3}$. This phenomena of upward fire gases are similar to those of swaying motion above a line heater. The time-dependent flow is slightly affected by the configurations of window and balcony. The oscillatory fire gases moving upward entrain much air into the flow. As a result of oscillatory motion the temperatures of the upward flow of fire descends gradually with height.

When the windows of the room immediately above the fire room are widely open, the upward fire flows enter the room with the time-dependent motion.

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