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Some Improvement of Smoke Movement Predictions Using BRI2002

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Abstract

In revising BRI2 to construct BRI2002, consideration was made on the improvement of the physics, numerics and convenience of use. As to 1) Physics sub-models: a) Generation of chemical species, b) Convective heat transfer and c) Smoke extraction efficiency, 2) Numerics: a) Convergence criterion and b) Heat release rate around equivalence ratio equals one and 3) Improvements for convenience in practical application: a) Change of opening, b) Horizontal opening and c) Simple output files. Sample predictions using BRI2002 were also conducted.

1. Introduction

A new variety of smoke control methods, which are not prescribed in the building codes, have been introduced into actual buildings in Japan since the Ministry of Construction's 5 year research project: Development of Fire Safety Design System of Buildings, 1982-1986. The enhanced transparency of the fire safety verification procedure provided by the 5 year project, particularly, through the introduction of the standardized design fires and safety criteria, has fostered noble practices of smoke control methods such as atria smoke managements, vestibule pressurization and so on.

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In performance-based smoke control designs, some engineering tools are indispensable to predict the smoke behavior with a reasonable accuracy, under a prescribed design fire condition. For this purpose, a multi-story, multi-room smoke transport model: BRI2 [1-5] (or its revised version BRI2T [6-8]), has been extensively used. On the other hand, more than 15 years have already passed since BRI2 was first made available for practical uses. Understanding of several aspects of fire has significantly progressed since then. So it is decided to revise the model taking into account new research results. Although a number of improvement items were discussed, not a few items had to be given up due to the limitation of time and work resources. The revised version is named as BRI2002 taken after BRI2.

The improvements made in the revision of BRI2 are summarized as follows:

1.1 Physics

The main structure of BRI2002 [9] is never different from BRI2, the preceding model: The coupled zone equations constitute the heart of BRI2002, and the component physics sub-models are incorporated into the equations. The program BRI2002, is structured so as to enable incorporation of the sub-models for various component physics comprising a building fire behavior, as was BRI2. Of such physics sub-models, the improved or newly introduced in the course of the revision are as follows:

(1) Generation of chemical species

While generation rate of CO was given as the prescribed rate per unit mass burning rate, in BRI2002, a sub-model was developed and introduced for the prediction of the generation rates of chemical species due to incomplete combustion including CO.

(2) Convective heat transfer

While BRI2 used to use a convective heat transfer coefficient, in BRI2002, a convective heat transfer coefficient as a function of non-dimensional heat release rate Q* is introduced [10].

(3) Smoke extraction efficiency

While BRI2 used to assume that a mechanical smoke vent in a ceiling only extracts smoke from the upper layer, in BRI2002, a model for smoke extraction efficiency is introduced.

1.2 Numerics

Under certain conditions, unstable calculation results due to convergence failure of room pressure were experienced by BRI2. The primary causes of the conver-gence failures are considered to be (1) inadequate convergence criterion and (2) an extremely rapid change of heat release rate. Although the problem has not yet been completely solved, certain mitigation measures are introduced as follows:

(1) Convergence criterion

In BRI2002, the convergence criterion is slightly modified to ease the problems due to different opening sizes.

(2) Heat release rate around equivalence ratio equals one

A convergence failure of room pressure calculation is most likely to occur at such a stage due to the assumption that inflow air is instantaneously consumed for combustion. BRI2002 uses a smoothing treatment of the burning rate to ease the problem.

1.3 Improvements for convenience in practical application

The improvements made for the convenience in application to design practice are as follows:

(1) Change of opening

In BRI2002, not only the change of width, but the change of height of an opening is also allowed.

(2) Horizontal opening

While BRI2 did not allow a horizontal vent, in BRI2002, input horizontal vents are automatically converted to tilt vents retaining the same area so to allow bi-directional flows.

(3) Simple output files

In addition to the files for detail outputs, several simple output files are added in BRI2002 so to meet the needs of most of practical applications.

2. Outline of The Model

Only a summary of the formulation of BRI2002 is given here. For more detailed description, reader should refer to Ref. [9].

2.1 Concept of The Model

BRI2002 model is constructed based on two layer zone concept. The concept of the model is illustrated in Figure1, and assumptions made for this model are as follows:

(a) any space in a building is filled with an upper and a lower gas layer;
(b) the upper and the lower layers are distinctly divided by a horizontal boundary plane (discontinuity);
(c) each layer is uniform with respect to physical properties by virtue of vigorous mixing;
(d) mass transfer across the boundary of a layer occurs only through a fire plume, doorjets and doorjet plumes;
(e) heat transfer across a layer boundary occurs by radiative heat exchange among the layers and the boundary surfaces and by convective heat transfer between a layer and the wall surface contacting with the layer, as well as that associated with the mass transfer referred in (d)
(f) all the heat released by a fire source is transported by the fire plume, in other words, the flame radiation loss is neglected.
(g) radiative heat transfer between rooms is neglected.

2.2 Mathematical Description of The Model

Consideration on the conservations of mass, species, heat for the layers and state of gas yields the zone equations for the temperature, species mass fractions, layer volume and the room pressure as follows [9]:

(1) Temperature

$$c_p \rho V \frac{dT}{dt} = Q + Q_h + c_p \sum_j m_{ji} \left(T_j - T\right) \quad (1)$$

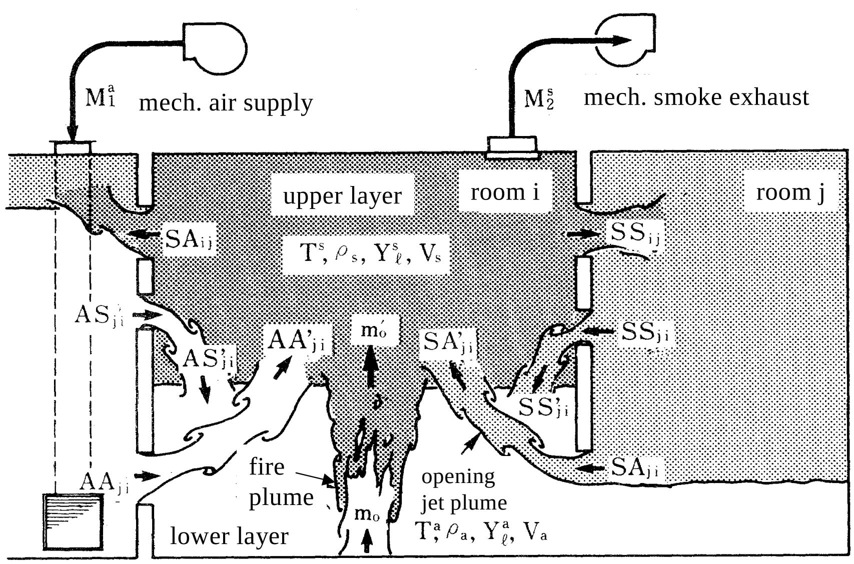


Figure 1. Schematic of Two layer zone Model [4,5,9]

(2) Mass fraction of chemical species

$$\rho V \frac{dY_l}{dt} = \sum_j \left(Y_{l,j} - Y_l\right) m_{ji} + \Gamma_l \qquad (2)$$

where

$$\Gamma_l = \frac{\left(\nu_l'' - \nu_l'\right) M_l}{\nu_f' M_f} m_b$$

(3) Layer volume

$$c_p \rho_\infty T_\infty \frac{dV}{dt} = Q + Q_h + \sum_j c_p \left(-m_{ij} T + m_{ji} T_j\right) \quad (3)$$

(4) Room pressure

$$\sum_{1,2} \left\{ Q + Q_h + \sum_j c_p \left(-m_{ij} T + m_{ji} T_j\right) \right\} = 0 \quad (4)$$

where $\Sigma_{1,2}$ denotes the summation with respect to the two zones in the same space.
These zone equations are further complimented with component physics models including the models for combustion, fire plume, heat transfer and door jet as elaborated in Ref. [9]. The coupled zone equations, combined with the component physics models, are solved numerically by the use of a Runge-Kutta method for the ordinary differential equations (1) - (3) and a Newton-Raphson method for the non-linear algebraic equation (4).

3. Improvement of The model

In revising BRI2 to construct BRI2002, consideration was made on the improvement of the physics, numerics and convenience of use. Although many issues had to be disregarded due to the lack of resources and the constraint of time, a certain degree of refinements have been accomplished as summarized as follows:

3.1 Physics

BRI2 series models are structured so as to enable incorporation of the sub-models for various component physics comprising a building fire behavior, such as combustion heat release, generation of chemical species, fire plume entrainment, opening flow, radiative and convective heat transfer among zones and across room boundaries, heat conduction. Of the physics sub-models, the models for species generation and convective heat transfer are revised and the model for smoke extraction efficiency is newly introduced in BRI2002.

(1) Generation of chemical species

In BRI2, generation or consumption rates of dominant species, i.e. CO_2, H_2O, O_2 and fuel were calculated based on the chemical composition and the rate of burning of the gasified fuel but the generation rate of CO, which is generated mostly due to the incomplete combustion, was given by the prescribed rate per unit mass burning rate. On the other hand, it has been gradually recognized that CO yield is more dependent on the environment of combustion rather than the nature of a fuel, on which the experimental findings have been increasingly made available owing primarily to U.S researchers. Based on the results of such work, a sub-model was developed and introduced into BRI2002 to predict the generation rates of chemical species including CO as a function of upper gas layer equivalence ratio Φ. The concept of the combustion model of gasified fuel is shown in Figure 2. According to this model, a gasified fuel undergoes complete and incomplete combustion in general, and the latter produces unburned fuel, CO_2, CO, C (carbon particle), H_2O and H_2. The ratio factors r, s, p and q are calibrated with the existing experiments [11-13].

(2) Convective heat transfer

The convective heat transfer coefficient, given as a function of the average temperature of zone and its boundary surface, was used in BRI2. This was derived based on the consideration on the formulas of Nusselt number for natural convection, well established in the area of heat transfer engineering. On the other hand, the influence of buoyancy flow due to heat release of the fire source is considered to play a more important role than temperature difference between zone and boundary surface, at least for convective heat transfer in the room of origin. The convective heat transfer coefficient as a function of non-dimensional heat release rate Q*, which is defined using heat release rate and room characteristic length as follows:

$$h_c = \begin{cases} 8.3\times10^{-3} & \left(Q^* < 2\times10^{-3}\right) \\ 0.1Q^* & \left(2\times10^{-3} \le Q^* < 0.1\right) \\ 40\times10^{-3} & \left(0.1 \le Q^*\right) \end{cases} \tag{5}$$

is used in BRI2002 based on the scale experiments by Yamada et al [10].

(3) Smoke extraction efficiency

BRI2 assumed that a mechanical smoke vent in a ceiling only extracts smoke from the upper layer. However, the vent may also extract air from the lower layer, particularly when the rate of extraction is large relative to the thickness of the upper layer, thereby the efficiency of the smoke extraction is reduced. In BRI2002, a model for smoke extraction efficiency (=actual smoke extraction rate/nominal extraction rate) is introduced based on the experimental formula by Spratt et. al for critical smoke layer thickness for non-air extraction. The critical smoke layer thickness by Spratt et al, $Z_{s,\min}$ is given by [14]

$$Z_{s,\min} = \left\{ \frac{\left(m_{ex}T_s/1.33\rho_a\right)^2}{gT_a\left(T_s - T_a\right)} \right\}^{1/5} \tag{6}$$

The smoke extraction efficiency R_{eff} in BRI2002 is simply given by

$$R_{eff} = \begin{cases} Z_s/Z_{s,\min} & \left(0 < Z_s < Z_{s,\min}\right) \\ 1 & \left(Z_{s,\min} < Z_s\right) \end{cases} \tag{7}$$

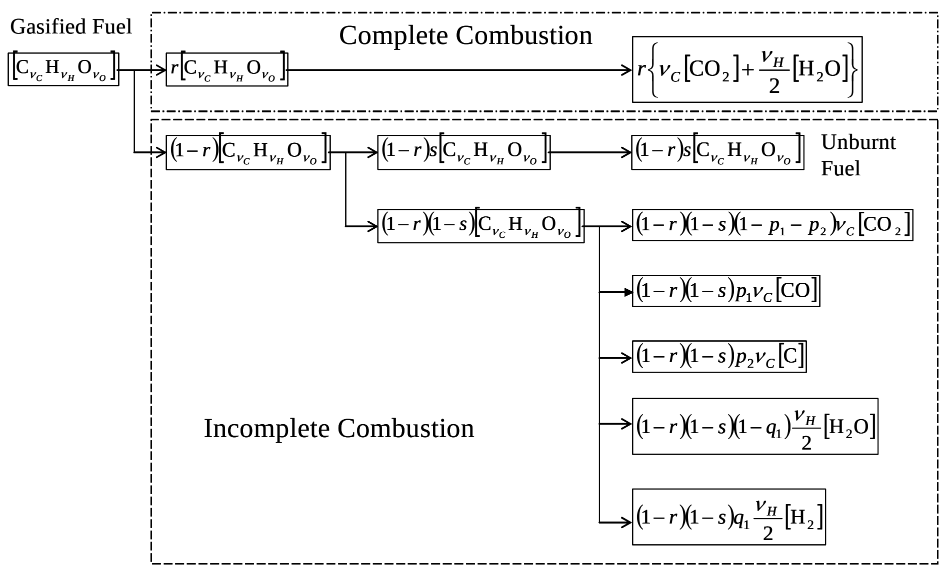


Figure 2. Schematic Combustion Model of Gasified Fuel

Incidentally, Eqn.(7) can be proved to be reasonably adequate for spot type vents by the experiments by Nii and Harada.[15]

3.2 Numerics

Under certain conditions, unstable calculation results, due primarily to the convergence failure of room pressures, were experienced by BRI2. The primary reasons of the convergence failures are considered to be (1) inadequate conver-gence criterion and (2) an extremely rapid change of heat release rate. Although it is not easy to completely solve these problems, certain measures are introduced to alleviate them as follows:

(1) Convergence criterion

To obtain the pressures in multiple rooms, the coupled non-linear algebraic equations are numerically solved using Newton-Raphson method. In BRI2, the convergence criterion for arbitrary room i was

$$Q_i + c_p \sum_j \left(T_j m_{ji} - T_i m_{ij} \right) < \delta \qquad (8)$$

The convergence criterion δ was set empirically at a constant value regardless the opening sizes. The smaller the value of δ, the more difficult is convergence. Conversely, the larger the value the less accurate is the convergence. Since the condition of opening size may vary widely from one case to another, it was difficult to find a universally adequate value. In BRI2002, the convergence criterion for arbitrary room i is slightly changed as follows:

$$Q_i + c_p \sum_j \left(T_j m_{ji} - T_i m_{ij} \right) < \delta \sum_j A_{ij} \qquad (9)$$

It is considered this criterion can contribute to mitigate the problems due to different opening sizes.

(2) Heat release rate around equivalence ratio equals one

If a large fuel burning rate continues, oxygen concentration in a room may drop to zero so the fire turns into ventilation control regime. When this occurs in a room with limited opening, a sudden change of burning rate and numerical oscillation may appear since the burning rate of gasified fuel at this stage depends heavily on air inflow: If the heat release rate happens to be large, a high pressure is quickly built up, which reduces the air inflow rate and thereby reduces the heat release rate. Then, before long, the room pressure quickly drops allowing an increase in the air inflow and corresponding increase in the heat release rate. So again a pressure buildup occurs in the room. This process repeats to bring oscillation. Convergence failure of room pressure calculation is likely to occur at such a stage partly because of the assumption that the inflow air is instantaneously consumed for combustion. So in BRI2002, a smoothing of the burning rate over a specified time (tentatively set at 4 seconds) is used, since it is considered that a certain time is needed in actual case for the inflow air to mix and be consumed by combustion.

3.3 Improvements for convenience in practical application

The improvements made for the convenience in application to design practice are as follows:

(1) Change of opening

In BRI2, only the change of width was allowed for the openings that change in area according to the scenarios of evacuation et al. In BRI2002, change of the opening height is also allowed so that the gradual closing of fire shutter etc, can be dealt with.

(2) Horizontal opening

If an orifice flow scheme is simply applied to a horizontal opening, only one-directional flow is predicted. But in reality a bi-directional flow may appear when the pressure difference at the opening is small. For this reason, BRI2 did not allow a horizontal opening. In BRI2002, instead, when a horizontal opening is input it is automatically converted to an opening having a certain slope but retaining the same area so that a bi-directional flow can be predicted. Incidentally, when the pressure difference is large enough one-directional flow is realized despite this treatment.

(3) Simple output files

In addition to the files for detail outputs, a simple output file was provided in BRI2 for the predicted results most often used in practical application. When some other results were needed the program had to be changed to a certain extent and re-compiled. In BRI2002, the idea of simple output, employed in BRI2, was extended to more extensive data so that necessary results can be more easily obtained without change of the program.

4. Sample Predictions Using BRI2002

4.1 Comparison with Small-scale Experiments for Gas concentration

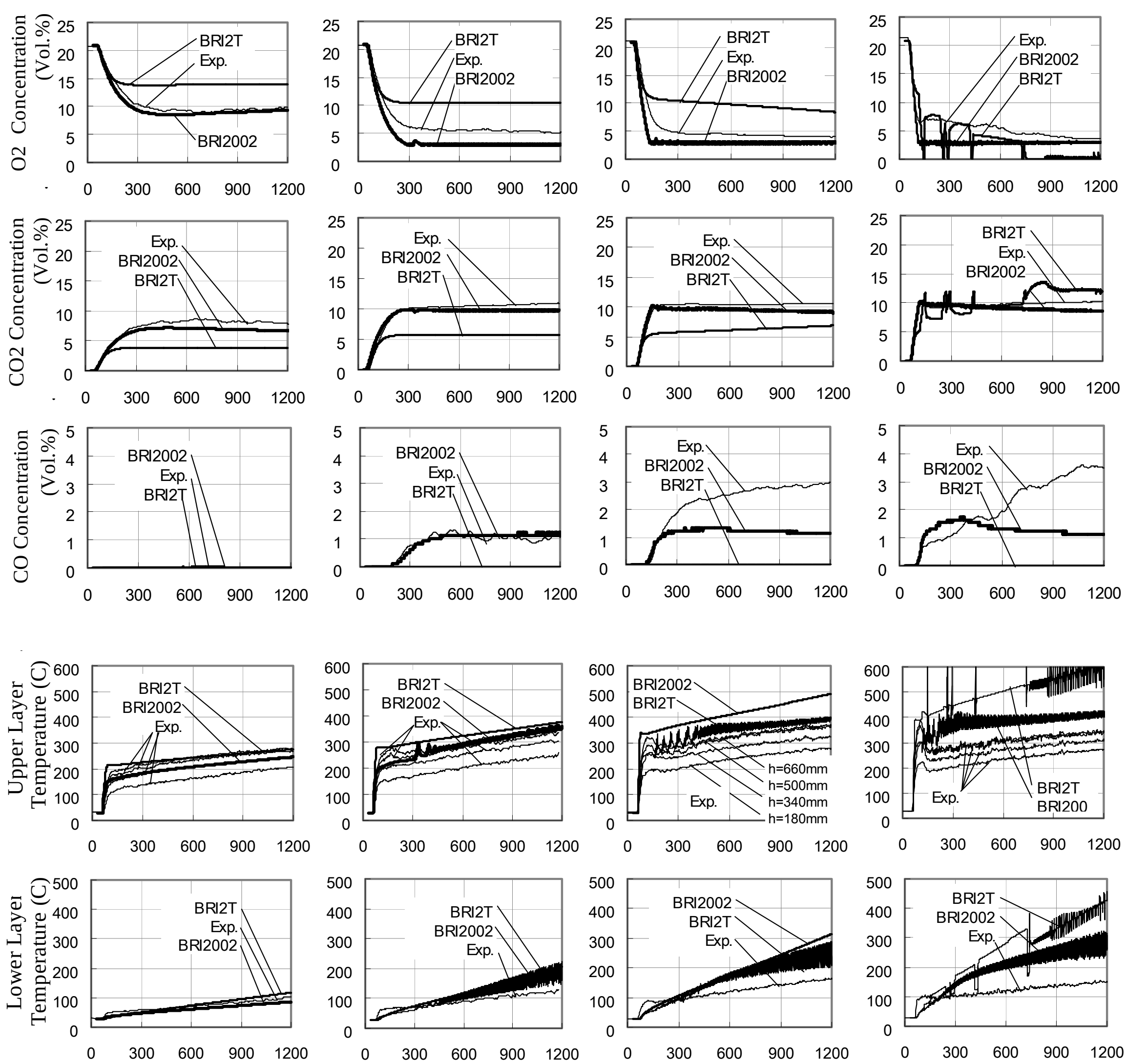
A small-scale fire experiments, using a compartment of 0.84m (width) x 0.84m (depth) x 0.73m (height) were conducted in an effort to develop a prediction method for generation rate and concentration of CO in compartment fire configuration. Methanol pool fires were the fire sources. The experiments were carried out for 4 different sizes of the fuel tray as shown in Table1. The heat release rate for each pool diameter was determined from the pre-measured mass burning rate in free space. The room temperatures were measured by 18 thermocouples vertically arrayed on two thermocouple wires at two different locations (9 thermocouples at each location). The gas sampling was made from the upper part of the test room for measuring O_2, CO_2 and CO concentrations.

Table 1. Fire Source Conditions of the Small-scale Experiments

	Test No.1	Test No.2	Test No.3	Test No.4
Pool diameter (m)	0.20	0.25	0.30	0.35
HRR at free burning (kW)	6.6	10.6	15.9	22.2

The compartment only had a small opening of 0.15m (width) x 0.15m (height) in the lower part of one of the walls and this poor ventilation condition caused more or less pulsating fires in every test case. Such was one of the cases at which BRI2 sometimes experienced difficulty in continuing an adequate prediction.

Figure 3 compares the temperatures and O_2, CO_2 and CO concentrations from the experiments and the predictions by BRI2002 and BRI2T, the preceding version of BRI2 series. As can be seen, the predictions of these layer properties have been improved considerably by BRI2002, although it still under-predicts the CO concentrations in Test No. 3 and 4. The discrepancy may be attributed to that the fire sizes in Test No.3 and 4 were so large that the gases were sampled from inside the flames. The pulsating behavior due to the limited opening conditions of the fire room induced the oscilation of the room temperature particularly when the fire size is large as shown in the figures. The prediction by BRI2002 also shows oscilation but this behavior is not necessarily well predicted.



Elapse time (sec) Elapse time (sec) Elapse time (sec)
Elapse time (sec)

Test No.1 Test No.2 Test No.3
Test No.4

Figure 3. Comparison with Small-scale Experiments

4.2 Number of Vents and Smoke Extraction Efficiency

A sample calculation is made to show how the number of mechanical smoke extraction vents affect on smoke behavior. The model room is 20m (width) x 20m (depth) x 3m (height). The volumetric smoke extraction rate is 400m^3/min. The heat release rate and the area of the fire source linearly increases to 3,000kW and 5m^2, respectively, until 240sec. and stays constant layer on.

Figure4 shows the smoke layer height and smoke extraction efficiency for the number of vents, 1, 5 and 20. Since the total smoke extraction rate is the same, the

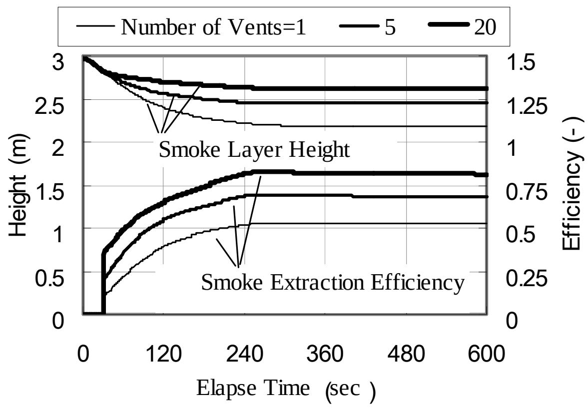


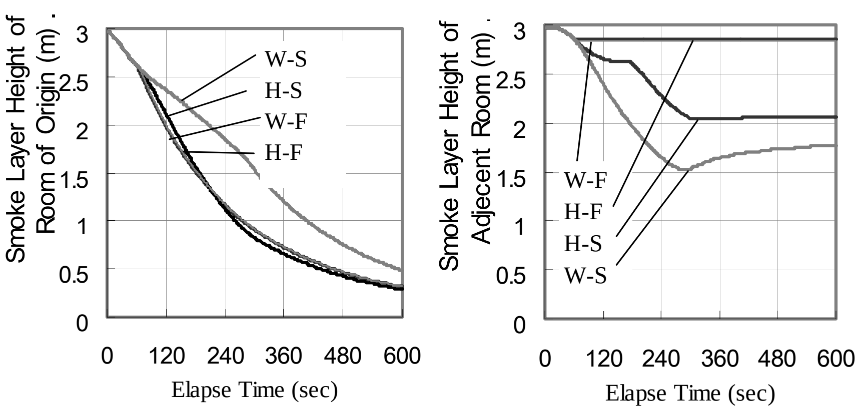
Figure 4. Smoke Extraction Efficiency for the Number of Vents

rate per a vent decreases as the number of vents increases, hence the smoke extraction efficiency rate increases and the smoke layer becomes thinner.

4.3 Smoke Behavior Under Vertical Closing of A Fire Shutter

A model space is a building consisting of two rooms, each of which is 20m (width) x 20m (depth) x 3m (height), connected by a opening which is 10m (wide) x 3(height). The opening is scheduled to close by horizontal or vertical vent in 10 seconds or 240 seconds after the onset of the fire.

Figure5 shows smoke layer height of the room of fire orgin and the adjecent room. In the adjacent room, in case that closing speed is fast, the smoke behavior seemed to exhibit no different between each type of changing. Although, in case that closing speed is slow, smoke is filled up more quickly in width changing case than height changing case.



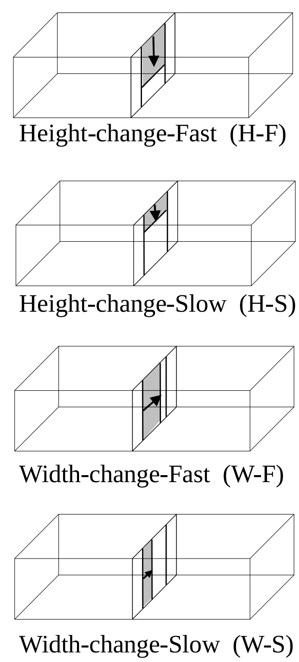


Figure 5. Smoke Behavior under Width or Height changing of the Opening

4.4 Smoke Filling in A Building With A Horizontal Vent

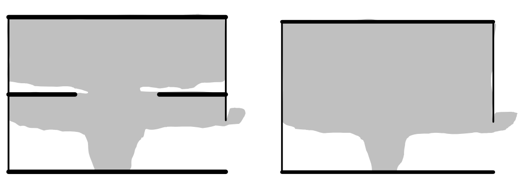
A model space is a two-story building consisting of two identical rooms, one on each floor. Each of the rooms is 10m (width) x 10m (depth) x 3m (height), connected by a horizontal vent. The vent area were 10, 40, 70, 100m^2(full opened), and for comparison, in case of one-story model was also calculated. Another vent in a wall on the first floor connects with the outdoor. Figure 6 shows schematic of model space. The smoke filling behavior is predicted with the fire source whose heat release rate increases linearly to 1,000kW until 240sec.

Figure 7 shows the temperature of the upper and lower layer, the layer height, the mass rates of inflow and outflow, and the mass balance in each room, respectively. The mass balance in Figure7 is normalized as

$$Mass\ Balance = \frac{(in\,flow\,rate - outflow\,rate)}{outflow\,rate} \tag{10}$$

The second floor has no opening connecting to the outdoor, so that bi-directional flow was predicted at a horizontal vent.

In all cases, the room on the second floor was filled up with an upper layer in early stage. Temperature of the second floor becomes high and that of the first floor becomes low as the increase of the horizontal vent area. The mass balance becomes nearly zero in quasi steady state, so that the prediction is implied to be accurate.



Two-story Model One-story Model

Figure 6 Schematic of model space

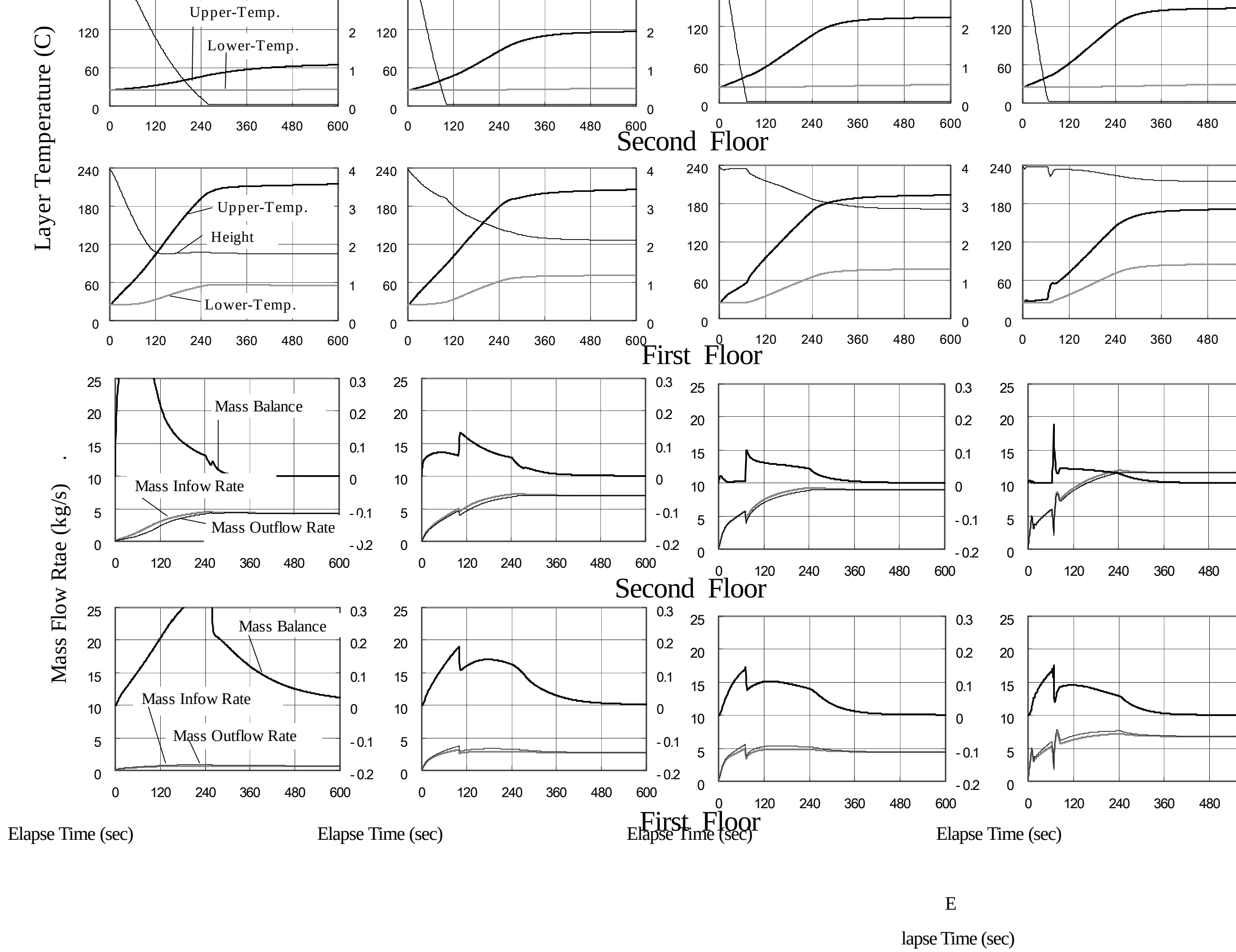
5. Conclusion

Some improvements were made in the revision of BRI2, and named as BRI2002. Sample predictions using BRI2002 were conducted as follows. 1) Comparison with small-scale experiments for gas concent-ration, 2) Number of vents and smoke extraction efficiency, 3) Smoke behavior under vertical closing of a fire shutter, 4) Smoke filling in a building with a horizontal vent

It thought that accuracy of prediction is improved.

Symbols

A_{ij} : opening area between room i and j.
c_p : specific heat of gas [kJ/kgK]
M : average molecular mass of layer gas [kg/mol]
M_f : molecular masses of fuel [kg/mol]
M_l : molecular masses of species l [kg/mol]
m_b : mass burning rate [kg/s]
m_{ex} : mechanical smoke extraction rate [kg/s]
m_{ij} : mass flow rates from layer i to j across the layer boundary [kg/s]
P : absolute pressure [Pa]
Q : heat release rate of a fire source [kW]
Q_h : net heat gain of layer i as the result of heat transfer [kW]
Q_i : net heat gain of room gas of room i [kW]
R : universal gas constant [kJ/molK]
R_{eff} : smoke extraction efficiency
T_j : temperature of zone i [K]
T_∞ : ambient air temperature [K]
V_i : volume of zone j [m3]
Y_l : mass fraction of species l
Z_s : smoke layer thickness [m]
$Z_{s,min}$: critical smoke layer thickness [m]
Γ_l : generation rate of species l by combus-tion [kg/s]
ν'_l : chemical numbers of species l in react-ants system.
ν''_l : chemical numbers of species l in pro-ducts system.
ρ : gas density of zone i [kg/m^3]
ρ_a : lower layer gas density [kg/m^3]
ρ_i : gas density of zone i [kg/m^3]
ρ_∞ : ambient air density [kg/m^3]



Opening Area ($10m^2$) Opening Area ($40m^2$) Opening Area ($70m^2$)

Full Opened One-story

Figure 7 Smoke Filling in A Building with A Horizontal Vent

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