NUMERICAL SIMULATION OF EARLY STAGE OF A COMPARTMENT FIRE

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1. INTRODUCTION

Recently deaths due to the toxicity of imperfectly combusted gas in a compartment fire has increased remarkably in Japan. Those deaths are related to the advent of fireproof, high buildings with airtight windows and furniture and utensils made of synthetic chemicals. These chemicals generate toxic gases in the early stage of fires. As a foundation for countermeasures against these accidents, a “field equation” model was developed by the staff of Center for Fire Science and Technology, Science University of Tokyo. The model represents the chemical reactions of combustion, gas flow vectors, temperature and gas diffusion in a compartment fire successfully.

2. GOVERNING EQUATIONS

2.1 Field model

For the expression of gas flow and temperature field, equations for the compressible and inviscid condition were adopted after Hasemi\textsuperscript{1)} and the others\textsuperscript{2),3)}. In order to suppress acoustic waves and prevent computational instability, air pressure $p$ and temperature $T$ are treated as the average values computed in each mesh cell and the flow vector $u_i$ is gotten from the values computed on mesh walls. The smoothing technique in a proper time interval and the assumption : $\rho = \rho_0/RT$ are introduced for the pressure computation. The used nomenclature is shown in Appendix 1. Equation of momentum:

$$\frac{\partial \bar{\rho} u_i}{\partial t} + \frac{\partial \bar{\rho} u_i u_j}{\partial x_j} = - \frac{\partial \bar{p}}{\partial x_i} + \frac{\partial \bar{\sigma}_{ij}}{\partial x_j}$$

$$- \left[ \frac{\partial (\rho u_i) \bar{u}_j}{\partial x_i} + \left\{ \frac{\partial (\rho u_j) \bar{u}_i}{\partial x_j} + \frac{\partial (\rho u_j) \bar{u}_i}{\partial x_j} \right\} \right]$$

$$- \delta_{ij} \bar{\rho} g$$

where $\bar{\rho} u_i$ and $\bar{\sigma}_{ij}$ are computed under the assumption of $\bar{\rho} u_i \approx \rho u_i - K \frac{\partial \rho}{\partial x_i}$ and...
\[
\bar{\sigma}_{ij} = \sigma_{ij} = \mu \left( \frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i} \right)
\]

Continuity equation:
\[
\frac{\partial \bar{\rho}}{\partial t} + \frac{\partial \bar{\rho} \bar{u}_i}{\partial x_i} = 0 \quad (2)
\]

Energy equation:
\[
\bar{\rho} \frac{\partial \bar{h}}{\partial t} + \frac{\partial \bar{\rho} \bar{u}_i \bar{h}}{\partial x_i} = Q + \frac{\partial \bar{P}}{\partial t} + \frac{\partial}{\partial x_i} \left( K \frac{\partial \bar{T}}{\partial x_i} \right)
\]
\[-\left\{ \frac{\partial \bar{\rho} \bar{h}'}{\partial t} + \frac{\partial \left( \bar{\rho} \bar{u}_i \bar{h}' \right)}{\partial x_i} \right\} \ldots \ldots \ldots \ldots (3)
\]

where \( K = \bar{u}^{1/2} \), \( \bar{h} = C_p \bar{T} \).

Equation of state:
\[
\bar{P} = \bar{\rho} \bar{R} \bar{T} \quad (4)
\]

The average values of \( T, P, \rho \) and \( h \) in a mesh are replaced by the values at the mesh center, e.g.
\[
\bar{\rho}_1 = \frac{1}{\Delta x_1 \Delta x_2 \Delta x_3} \int_{x_1,\Delta x_1,\Delta x_2,\Delta x_3} \rho dx dy dz / \Delta x_1 \Delta y_1 \Delta z
\]
\[
\approx \rho_1
\]

and flow components are calculated from the values on the mesh wall, e.g. \( \bar{u} = (u_{i+\Delta x/2} + u_{i-\Delta x/2})/2 \). The bar over variables denotes the average values in each mesh cell and the prime means the deviation from the average value. Diffusion and mass conservation of the gas:
\[
\frac{\partial \bar{\rho}_\alpha}{\partial t} + \frac{\partial \bar{\rho}_\alpha \bar{u}_j}{\partial x_i} = \frac{\partial}{\partial x_i} \left( -\bar{J}_{\alpha i} \right) + \bar{F}_\alpha \ldots \ldots (5)
\]

where \( -\bar{J}_{\alpha i} = \bar{\rho} K \frac{\partial \bar{w}_\alpha}{\partial x_i} \)

For the computation of \( \bar{P} \), (1) differentiated with respect to \( x_i \) is substituted into (2) differentiated with respect to \( t \), so that
\[
\frac{\partial^2 \bar{P}}{\partial x_i^2} + \frac{\partial \bar{\rho}}{\partial x_i} \left( \frac{\partial \bar{u}_j}{\partial x_j} \right) = \bar{\sigma}_{ij} + K \left( \frac{\partial \bar{u}_j}{\partial x_j} \right)
\]

is introduced. Since \( \bar{P} \) in eq. (6) becomes a function of the predicted \( \bar{T} \) of the present time step and \( \bar{\rho} \) of the previous step under the assumption \( \bar{\rho} = \rho_0 / R \bar{T} \), the equation can be solved using the relaxation technique.

**Differentiation and time step**

The terms of the equations are transformed to difference schemes of the central type and the transfer terms are expressed with the backward differencing scheme. Differentiation of the equations are presented in the appendix 2. The time step is treated as a variable so as to satisfy the computation stability criterion as follows:
\[
\Delta t \leq \left\{ \frac{6 (K + \mu)}{(\Delta x)^2} + \frac{|\bar{u}| + |ar{v}| + |ar{w}|}{\Delta x} \right\}^{-1}
\]

**Boundary conditions**

(a) Solid boundary

Normal component of the velocity at the boundary : \( u_j^* = 0, \rho^* u_j^* = 0 \)

Parallel component of the velocity along the boundary : \( u_i^* = -\bar{u}_i, \rho^* u_i^* = -\bar{\rho} \bar{u}_i \)

Momentum at the boundary : \( q^* = -q \)

Temperature on the solid surface

in the case of an adiabatic wall : \( T^* = \bar{T} \)
in the case of a non-adiabatic wall : \( T^* \) is computed from the thermal energy balance equation on the wall (See 2.3).

(b) Free boundary

Temperature : \( T^* = \begin{cases} T_0 \text{ for inflow} \\ \bar{T} \text{ for outflow} \end{cases} \)

Momentum : \( q^* = \begin{cases} q_0 \text{ for inflow} \\ \bar{q} \text{ for outflow} \end{cases} \)
Pressure: \( P^* = P_0 - \rho \text{ogz} \) for inflow and outflow

Air density: \( \rho^* = \begin{cases} \rho_0 \text{ for inflow} \\ \bar{\rho} \text{ for outflow} \end{cases} \)

Velocity components: \( u^* = \bar{u}, v^* = \bar{v} \) and \( w^* \) is the solution of

\[
\frac{\partial \rho^* u^*}{\partial x} + \frac{\partial \rho^* v^*}{\partial y} + \frac{\partial \rho^* w^*}{\partial z} = 0
\]

Mixing length in \( K : l^* = l \)

**Initial condition**

Temperature: \( T = T_0 = 293 \text{ K} \)

Momentum: \( \bar{q} = q_0 = 0 \)

Pressure: \( \bar{P} = P_0 - \rho \text{ogz} \)

Air density: \( \bar{\rho} = \rho_0 \)

Velocity components: \( \bar{u} = \bar{v} = \bar{w} = 0 \)

### 2.2 Chemical reaction model

The combustion of a solid body can be represented by an empirical relation for the combustion rate \( RB \) as follows (Fig. 1);

- \( RB = \alpha t^2 \) for \( t < t_1 \) \hspace{1cm} (7-a)
- \( RB = \text{const} \) for \( t \geq t_1 \) \hspace{1cm} (7-b)

Solid mass decreases in proportion to the combustion rate and generates the pyrolysis gases. The constitution of pyrolysis gas for a crib is shown in Table 1\(^6\). The components, C, H and O of the pyrolysis gases, burn in the same mesh cell as the solid pyrolysis, using the available \( O_2 \) gas\(^7\)\(^8\).

<table>
<thead>
<tr>
<th>Component</th>
<th>Weight %</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>43.5 %</td>
</tr>
<tr>
<td>H</td>
<td>5.2</td>
</tr>
<tr>
<td>O</td>
<td>38.3</td>
</tr>
<tr>
<td>[Hetc]</td>
<td>13.0</td>
</tr>
</tbody>
</table>

\( RB_1 = 12.5 \text{ g/s} \)

\( Q = 1647 \text{ Kcal/s} \)

\( \text{for } RB = RB_1 \)

---

Fig. 1 Model of the combustion rate.

Chemical equations in the case of complete combustion under sufficient \( O_2 \) supply from the atmosphere will be

\[
\begin{align*}
\text{C} + \frac{1}{2} \text{O}_2 & \rightarrow \text{CO}_2 \hspace{1cm} (8-a) \\
\text{H}_2 + \frac{1}{2} \text{O}_2 & \rightarrow \text{H}_2\text{O}. \hspace{1cm} (8-b)
\end{align*}
\]

In the case of low \( O_2 \) concentration, a transitional process is added where \( CO \) gas in produced.

\[
\begin{align*}
\text{C} + \frac{1}{2} \text{O}_2 & \rightarrow \text{CO} \hspace{1cm} (8-c) \\
\text{CO} + \frac{1}{2} \text{O}_2 & \rightarrow \text{CO}_2 \hspace{1cm} (8-d)
\end{align*}
\]

Equilibrium constants for the equations are determined from experimental data with the parameters of \( O_2 \) concentration and air temperature\(^9\).

The generation of toxic gases from solid combustion are also estimated from the experimental generation rates and their concentrations are computed through the common diffusion equation (5), though they are not considered in the computation of gas combustion, except \( CO \), since their concentrations are very small in comparison to the main combustible gases, C and \( H_2 \).
2.3 Radiation model

The radiation energy from a flaming mesh cell with a temperature higher than 300°C or a smoke mesh cell over 200°C is computed through the following equation:

\[
S = \varepsilon \sigma T^4
\]

where \( \varepsilon \) : emisivity, 0.8 for T 573 K and 0.9 for T = 473 ~ 573 K
\( \sigma \) : 1.385 x 10^-11 Kcal/sec m^2 deg^4

The criteria for the radiation computation are set to save computation time, based on experience and simple evaluations that temperature of a flame will usually exceed 300°C and that radiation from temperatures lower than 200°C is of the same order of magnitude as the atmospheric radiation energy. It reaches about 10 times the natural level at 200°C, 20 times at 300°C and 70 times at 500°C. Furthermore, the following assumptions are adopted for practical computation:
(a) If the neighboring mesh cell is occupied also with hot smoke and it radiates, the radiation exchange between these neighboring mesh cells cancel each other.
(b) Radiation energy is not absorbed in the clean air, so it will reach the wall if every mesh cell between the flaming cell and the wall is not filled with smoke.

The radiation energy from a flaming mesh cell is given ultimately by

\[
R' = S \cdot \Delta x^2 \cdot \text{MEN}
\]

where \( \Delta x \) : mesh size
\( \text{MEN} \) : number of mesh cells that contact with the other, cooler cells under 200°C

\[
SW = (R' - \varepsilon \sigma T_w^4 \cdot \Delta x^2) \frac{\omega}{4 \pi} \Delta t + SW_{dd}
\]

where SW : integrated radiant energy, absorbed per \( \Delta x^2 \) (Kcal)
\( \omega \) : solid angle subtended a wall unit, surface on \( \Delta x^2 \), from the combustion mesh cell
SW_{dd} : SW of the previous time step
(The initial value is 0.)
Tw : temperature of the wall surface

Then, the thermal energy balance at the wall surface is computed through

\[
Tw = \text{Res} \cdot \frac{SW}{\Delta x^2 \cdot t} + Tout
\]

where Res : resistance of the thermal energy flow (m^2 sec deg/Kcal)

\[
= R_{s1} + \Sigma R_{ci} + \Sigma R_{air} + R_{s2}
\]

Rs_1, Rs_2 : resistance of thermal flow on the inner and outer surface of the wall (m^2h deg/Kcal)
R_{ci} : resistance of thermal conductivity in each layer of the wall (m^2h deg/Kcal)

![Diagram](image)

Fig. 2 Model structure of the wall and temperature profile across it.
R'air : resistance of thermal conductivity of air layers in the inside of the wall (m²h deg/Kcal)

Fig. 2 shows a model structure of the wall and temperature profile across it.

3. NUMERICAL SIMULATION OF THE REAL SCALE COMPARTMENT FIRE

3.1 Condition of the computation

size of compartment : 3 m x 3 m x 2.4 m

The compartment has a soffit of 0.6 m over the entrance.
mesh size : $\Delta x = \Delta y = \Delta z = 0.3$ m

case 1

Fire source : 2 mesh cells on the floor of central interior part
fuel : crib (constant combustion after the initial quadratic rise : $t_1 = 1.0$ sec,
$RB_1 = 12.5$ g/sec, $Q = 800$ Kcal/sec x 2)
The combustion condition is to be referred to 2.2.
entrance : The entrance is opened fully, 3.0 m width.

case 2

Fire source : the same as case 1
fuel : crib (constant combustion after the initial quadratic rise : $t_1 = 30.0$ sec,
$RB_1 = 12.5$ g/sec, $Q = 800$ Kcal/sec x 2)
entrance : The entrance is a door of 1.2 m width.

3.2 Result of the computation

Vertical and horizontal flow patterns will be shown for two cross sections and versus time for the three grid points indicated in Fig. 3. These points were selected in accordance with the measuring points of the experiment. (See 4.1)

Fig. 3 Cross section and grid points (1, 2 and 3) for the output. 4 is the fire source. The numbers in parenthesis corresponds to the mesh number in the coordinate.

Fig. 4 shows the vertical and horizontal cross sections of the flow field after 13.0 sec. from ignition. The flow vectors in the vertical cross section, X direction (upper left), form a circulation around a point in the middle layer near the compartment center. The maximum flow of about 3 m/sec is found over the combustion cells. In the vertical section, Y direction (lower left), two symmetric circulations are seen in the middle and upper layers, and divergent and convergent tendencies are recognized in the lower and upper layers respectively.

The horizontal distribution of the flow vectors in the upper layer above the soffit
(upper right) shows the air convergence over the fire source and the uniform down draft due to the blockage effect of the soffit. In the middle layer (lower right), convergence of updraft air inside the discontinuity line is remarkable and the air flows out uniformly through the entrance.

Fig. 5 shows the patterns of temperature, pressure deviation and O₂ density in the vertical and horizontal cross sections. Temperature exceeds 450 K in the interior part from the combustion cell to the ceiling and 400 K in the space above the soffit. The maximum and minimum pressure deviations are seen on the floor and under the ceiling near the entrance respectively. The lower O₂ density corresponds to the higher temperature zone.

Fig. 6 shows the time variations of O₂ density at the three grid points and in the fire source. O₂ density in the fire source cell decreased rapidly just after ignition and recovered from the minimum to about 1/3 of the natural value with the O₂ supplied by diffusion. At the ceiling, O₂ remained at its initial value for 5 ~ 6 sec. and then decreased gradually due to the convective circulation of the air with limited O₂. It approached a stationary situation of about 2/3 the level of the natural O₂ density. The O₂ cross sections in Fig. 5 can be, therefore, as the pattern of a stationary situation.

Fig. 4 Vertical and horizontal cross sections of flow field in case 1. Double broken lines denote the discontinuity of flow vectors and broken lines with arrow show the stream line.
Fig. 5 Vertical and horizontal cross sections of temperature, pressure deviation and O₂ density in case 1.

Fig. 6 Time variation of O₂ density in case 1 (1, 2, 3 and 4 correspond to the grid points in Fig. 3.)
case 2

Fig. 7 shows the distribution of flow vectors in the vertical and horizontal cross sections. In the vertical cross section, X direction, flow vectors form a circulation around the mid part of the compartment and the outflow is strengthened under the soffit due to the effect of the narrow entrance. In the vertical cross section, Y direction, symmetric circulations develop with reversed eddies in the upper and lower regions. The horizontal flow from the interior wall toward the soffit in the layer under the ceiling is driven by the air supply over the combustion and by the air sink along the soffit. In the lower layer, below the soffit edge, the air converges over the combustion part in the interior compartment and converges again toward the entrance in the outer part. Case 2 is characterized with the strong outflow for the compressing effect at the entrance.

Fig. 8 shows the vertical and horizontal cross sections of temperature, pressure deviation and O₂ density, which can be almost regarded as stationary situations. Though the temperature and O₂ patterns are quite similar to the patterns in case 1, the temperature in the higher layer, above the soffit height, is 100 ~ 150°C higher and O₂ density is 10 g/m³ lower than case 1. The pressure deviation makes a characteristic high zone just inside of the soffit edge.

Fig. 9 ~ 13 show the time variations of temperature, pressure deviation, O₂ density, turbulent energy and eddy diffusion coefficient. Since the increasing time t of the combustion has been set at 30 sec., the temperature at the output grids (1 ~ 3) rise 10 sec. after ignition and it takes 40 sec. or more for temperature to reach a stationary situation. These time lags are seen in the variations of the other elements.

The pressure deviation increases due to the air expansion caused by combustion. It is noted that the pressure deviation at the inside of the soffit exceeds the value at the entrance because of the compressing effect of the narrow entrance. The turbulent energy and the eddy diffusion coefficient at the entrance exceed the levels of the inside points as the stationary stage is approached. This result contracts markedly with case 1, where the elements in the interior part is pass through the wide entrance without inversion.

O₂ density is shown at the three grid points and in the combustion mesh cell. The O₂ density almost decreases to O in the combustion mesh cell and the values under the ceiling reach to 1/2 of the standard atmosphere at the stationary stage, while the O₂ level is 1/3 in the combustion and 2/3 under the ceiling in case 1. This suggests that a part of the inflow air through the narrow entrance arises directly to the ceiling in the middle of the compartment, because of the lateral circulation and the violent eddy diffusion, and that the O₂ supply to the fire source is insufficient for the narrow entrance. It can be said that vertical mixing is quite active in the middle part of the compartment in case 1, and two reversal flows develop in the middle and outer part in case 2.

Fig. 14 shows the temperature patterns on the walls, ceiling and floor. The temperature levels on the lower part of the interior wall and on the interior floor suggest the probability of fire spread by the radiative heat.
Fig. 7 Vertical and horizontal cross sections of flow field in case 2. Double broken lines broken lines with arrow are the same as in Fig. 4.

Fig. 8 Vertical and horizontal cross sections of temperature, pressure deviation and O₂ density in case 2.
Fig. 9 Time variation of temperature in case 2. (1, 2 and 3 correspond to the grid points in Fig. 3.)

Fig. 10 Time variation of pressure deviation in case 2. (1, 2 and 3 correspond to the grid points in Fig. 3.)
Fig. 11 Time variation of $O_2$ density in case 2. (1, 2, 3 and 4 correspond to the grid points in Fig. 3.)

Fig. 12 Time variation of turbulent energy in case 2. (1, 2 and 3 correspond to the grid points in Fig. 3.)
Fig. 13 Time variation of eddy diffusion coefficient in case 2
(1, 2 and 3 correspond to the grid points in Fig. 3.)

Fig. 14 Temperature distribution on wall, ceiling and floor in case 2.
4. VERIFYING FIRE EXPERIMENT IN A FULL SCALE COMPARTMENT

In order to get fundamental information on fire and to verify the numerical simulation, the early stage of fire was examined in the same size compartment with the similar conditions to the computations.

4.1 Outline of the experiment

Size of the compartment and arrangement of the measuring instruments are shown in Fig. 15 (a) and (b). The compartment has an entrance 180 cm wide and 207 cm high without a soffit. Fire source was set at the central interior part on the floor in front of the wall in accordance with the simulation. Table 2 shows the measuring instrument and their properties for the experiment. The instruments could not be set just around/above the fire source, since even fire-proof instruments had a standing limit of temperature and they were in danger of damage close to the fire.

The experiments were carried out for 3 cases of various fuels as in Table 3. The data from measuring instruments were taken onto magnetic tapes every 0.1 sec. using an analogue-digital conversion procedure and analyzed later with an electronic computer.

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Fig. 15-a Horizontal size of the experimental compartment and arrangement of measuring instruments.
Fig. 15-b  Vertical size of the experimental compartment and arrangement of measuring instruments.

Table 2  Measuring instruments used for the verifying experiment

<table>
<thead>
<tr>
<th>instrument</th>
<th>satofuse</th>
<th>symbol in Fig. 15</th>
<th>maker</th>
<th>type</th>
<th>measuring range and accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>anemometer with water cooling</td>
<td>1</td>
<td>WCA</td>
<td>Makino Applied Instrument Co.</td>
<td>C</td>
<td>±6 m/s</td>
</tr>
<tr>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>0.1 m/s</td>
</tr>
<tr>
<td>sonic anemometer</td>
<td>1</td>
<td>SAT A</td>
<td>Kajjo Electric Instrument Co.</td>
<td>DAT 300</td>
<td>±5 m/s</td>
</tr>
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<td></td>
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<td></td>
<td></td>
<td>response 0.005 m/s</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>0.1 sec</td>
</tr>
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<td>sonic anemometer</td>
<td>2</td>
<td>SAT B, SAT C</td>
<td>Koshin Electric Instrument Co.</td>
<td>KSS-110</td>
<td>±20 m/s</td>
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<td>response 0.01 m/s</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.1 sec</td>
</tr>
<tr>
<td>platina electric resistance thermometer</td>
<td>4</td>
<td>i ~ iv</td>
<td>Toyo Electronic Co.</td>
<td>A5130</td>
<td>−20 ~ 150°C</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>response &lt; 1.0°C</td>
</tr>
</tbody>
</table>

Table 3  The maximum values of diffusion parameters gotten in the fire experiment

<table>
<thead>
<tr>
<th>case</th>
<th>fuel</th>
<th>w' at A</th>
<th>u' at C</th>
<th>T at iii</th>
<th>T at ii</th>
<th>Kz at A</th>
<th>Kx at C</th>
<th>memo</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>alcohol</td>
<td>0.5 m/s</td>
<td>2.6 m/s</td>
<td>111.7°C</td>
<td>71.0°C</td>
<td>15cm²/s</td>
<td>61cm²/s</td>
<td>Q ≈ 1000Kcal/s</td>
</tr>
<tr>
<td>b</td>
<td>alcohol + crib</td>
<td>0.9</td>
<td>3.2</td>
<td>129.4</td>
<td>90.4</td>
<td>320</td>
<td>1280</td>
<td>Q ≈ 2000Kcal/s</td>
</tr>
<tr>
<td>c</td>
<td>crib + chair</td>
<td>1.5</td>
<td>5.9</td>
<td>&gt;126.9</td>
<td>&gt;185</td>
<td>1077</td>
<td></td>
<td>T at iii was scale out.</td>
</tr>
</tbody>
</table>

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4.2 Main results of the experiment

Characteristic results of the experiment are summarized as found in the fire field with this measuring technique. Fig. 16 shows the original record of gas velocity components measured at a point just under the central ceiling in case b with a sonic anemometer. From the chart, it can be recognized that the flow turbulence consists of continuous small wave with high frequency and sudden waves with great amplitude. Furthermore, it is clear from the data analysis that the high frequency waves continue with almost constant amplitude without regard to the intensity of fire, while the sudden large waves increase in frequency in accordance with fire intensity. Fig. 17 shows an example of statistical analysis of the flow turbulence. The power spectrum on the left side shows the occurrence distributions at the respective wave frequency. The slanting line in the high frequency part denotes a distribution tendency of the wave frequency in the natural atmosphere which is proportion to \(-5/3\) power of wave frequency. The small continuous wave in Fig. 16 correspond to the tendency of the natural atmosphere. On the other hand, although a characteristic tendency can not be found in the low frequency part, it may be concluded that the sudden low frequency waves are generated by the combustion, since the peak frequency moves to lower values in proportion to the increasing size of the heat source.

The right side of Fig. 17 shows the distribution of turbulent energy for each frequency. While the energy level of the high frequency wave exceeds the level of the low frequency part in the case of a weak heat source, the whole energy level rises higher and low frequency energy level becomes superior to the

![Chart showing flow component recorded by sonic anemometer at point A.](chart)

Fig. 16 Example of flow component recorded by sonic anemometer at point A.
high frequency part with the move intense fire source.

Fig. 18 shows a vertical trajectory patterns of air in the experimental compartment, estimated from the observed data with the anemometers, the flowing smoke and the bending of woolen indicators. The air flows into the compartment through the lower part of the entrance and returns in the upper layer after the convective rise over the heat source. This pattern was represented coincidentally in the numerical simulation. The observed maximum flow velocity (30 sec. average) is about 0.8 m/s in case a and 1.2 m/s in case b at point A. These values agree quite successfully with the computation for the corresponding grid points. The flow velocity in case c would be lower than a natural fire would produce, since the experimental combustion was controlled by spraying on the fire to preclude damage to the measuring instruments.

Fig. 17 Example of fluctuations and the statistic analysis of gas flow data at point A.
4.3 Diffusion parameters

On the assumption that the same diffusion coefficient can be used for the diffusion of thermal energy, momentum and gases, $K = q^{1/2}/l$ has been adopted in the numerical simulation. The diffusion coefficient is estimated from the observed data from the verification experiments. Although the coefficient can be introduced indirectly through the turbulent energy, $q$, and mixing length, $l$, in the simulation, a direct estimation is here examined from the elements measured in the experimental compartment as follows:

$$K_z = |w' \cdot \theta'| / (d\theta/dz)$$

for vertical coefficient at A

$$K_x = |u' \cdot \theta'| / (d\theta/dx)$$

for horizontal coefficient at C.

Table 3 shows the maximum values of average diffusion elements at 30 sec., picked up from the continuous data series. It is seen that all the elements increase in accordance with the combustion intensity, and that $K_x$ at
the lower part of the entrance usually exceeds $K_z$ at the central ceiling. The inequality mark on the temperature at iii and $K_z$ at A in case c denotes the probability of more severe values for the scale out of temperature. While the numerical simulation gave the maximum $K$ of about 3000 cm$^2$/s at A and 2000 cm$^2$/s at B in case 2, the maximum $K$ value from the experimental data was 1200 cm$^2$/s or so at C in case b. Considering the heat generation of $Q = 1600$ Kcal/s and the narrow entrance under a soffit for the simulation, and $Q = 2000$ Kcal/s and the wider entrance without soffit for the experiment, these $K$ values are regarded as reasonable levels.

Temperature ascent of $18 \sim 20$ deg/min in case a and $35 \sim 40$ deg/min in case b from the flame up to a steady condition seems to correspond to the heat generation $Q$. The maximum flow velocity has a similar tendency to the temperature. However, turbulence increases in relation to the surface area or volume of the fire source.

5. CONCLUSION

Comparing the simulation in case 2 to case 1 shows the contribution of several fundamental factors of compartment structure. The difference of door size affects the time variations and the distributions of gas flow, pressure and turbulence. Radiation affects the combustion indirectly, rising a probability of ignition of the near floor and walls.

In the future, the simulation will be used for the common arrangement of home furniture, adding subroutine programs for the thermal balance between the inside wall and contacting air, and the radiation absorption in the smoke cells.

This study was carried out as a part of Canada-Japan-USA Cooperative Study on Fire Gas Toxicity, using a CRAY-1 super computer.

Appendix 1

NOMENCLATURE

- $\rho$: air density
- $u_i$: wind component
- $P$: air pressure
- $\sigma_{ij}$: viscosity stress
- $\mu$: dynamic viscosity
- $g$: acceleration of gravity
- $h$: enthalpy
- $T$: air temperature
- $R$: gas constant
- $K$: eddy diffusion coefficient
- $q$: turbulent energy
- $l$: mixing length
- $J$: diffusive mass flux
- $\phi$: generation rate of component gas
- $W$: gas concentration
- $Q$: generation rate of energy
- $RB$: combustion rate
- $S$: radiation energy from a point source
- $\varepsilon$: emissivity
- $\sigma$: Stefan's constant
- $R'$: radiation energy from a mesh source

MEN: number of mesh cell wall

$\omega$: solid angle

SW: integrated radiation energy

Tw: temperature on inner wall surface

Tout: temperature of outer side of wall

Res: resistance of thermal energy flow

$R_{s1}, R_{s2}, \ldots$: resistance of thermal conductivity of wall layer

Rai: resistance of thermal conductivity of air in wall

$\theta$: potential temperature
Appendix 2  Differentiation of the governing equations

<table>
<thead>
<tr>
<th>EQUATION OF MOMENTUM</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho \bar{u}_i \left[ l_i + 1/2 \right]^{n+1} - \rho \bar{u}_i \left[ l_i + 1/2 \right]^n + \Delta t^n \left( \frac{\Delta \bar{p}}{\Delta x_i \left[ l_i + 1/2 \right]} + E_i \left[ l_i + 1/2 \right]^n \right) = 0$</td>
</tr>
<tr>
<td>$\bar{u}_{i+1} = \frac{1}{2} \left( \bar{u}<em>i + \bar{u}</em>{i+1} \right)$</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>POISSON TYPE EQUATION FOR P</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho \bar{u}_i \left[ l_i \right]^{n+1} - \frac{\Delta \bar{p}}{\Delta x_i \left[ l_i \right] - \rho \bar{u}_i \left[ l_i - 1/2 \right]} + Q + \bar{h} \frac{\Delta \bar{p}}{\Delta x_i \left[ l_i - 1/2 \right]}$</td>
</tr>
<tr>
<td>$\bar{h}_{i+1} = \bar{h}_i + \frac{\Delta t^n}{\rho^n} \left( \frac{\Delta \bar{h}}{\Delta x_i \left[ l_i \right]} - \rho \bar{u}_i \frac{\Delta \bar{h}}{\Delta x_i \left[ l_i \right]} \right)$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>EQUATION OF STATE</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\bar{q}_{i+1} = \rho \left[ \frac{\Delta \bar{q}}{\Delta x_i \left[ l_i \right]} + \Delta t^n \left( \frac{\Delta \bar{q}}{\Delta x_i \left[ l_i \right]} + \frac{\Delta \bar{q}}{\Delta x_i \left[ l_i - 1/2 \right]} \right) \right]$</td>
</tr>
<tr>
<td>$\bar{u}_i \left[ l_i \right]^{n+1} + K \frac{\Delta \bar{q}}{\Delta x_i \left[ l_i \right]}$</td>
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<table>
<thead>
<tr>
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<td>$\bar{u}_i \left[ l_i \right]^{n+1} + K \frac{\Delta \bar{q}}{\Delta x_i \left[ l_i \right]}$</td>
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<tr>
<td>$\bar{u}_i \left[ l_i \right]^{n+1} + K \frac{\Delta \bar{q}}{\Delta x_i \left[ l_i \right]}$</td>
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<tr>
<th>FLOW COMPONENTS AND EDDY DIFFUSION COEFFICIENT</th>
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</thead>
<tbody>
<tr>
<td>$\bar{u}_i \left[ l_i \right]^{n+1} + K \frac{\Delta \bar{q}}{\Delta x_i \left[ l_i \right]}$</td>
</tr>
<tr>
<td>$\bar{u}_i \left[ l_i \right]^{n+1} + K \frac{\Delta \bar{q}}{\Delta x_i \left[ l_i \right]}$</td>
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</table>

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<thead>
<tr>
<th>STABILITY CRITERION</th>
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</thead>
<tbody>
<tr>
<td>$\Delta t^n \leq \frac{1}{\max [\Gamma]} \left( \frac{\Delta \bar{u}_i}{\Delta x_i \left[ l_i \right]} \right)^n + \frac{1}{\max [\Gamma]} \left( \frac{\Delta \bar{u}_i}{\Delta x_i \left[ l_i \right]} \right)^n$</td>
</tr>
</tbody>
</table>

REFERENCES


[5] Yoshikawa T.: A computational scheme of air pollutant and diffusion with a fi-
nite difference method, Papers in Meteorology and Geophysics, 32, 3, 135-147, 1981.


