A Study on the Generation and Development Mechanisms of Fire Whirls

Part 4 Construction of a Generation and Attenuation Model of Fire Whirls

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1. BACKGROUND

To date, various studies have been undertaken in order to understand the characteristics and the generation mechanism of fire whirls by using scaled models and theoretical analyses. However, there are very few reports and practical models which systematically describe how fire whirls emerge and decay. Therefore, with reference to past reports and models, an experiment was conducted in order to establish a model that expresses a series of processes with respect to fire whirls, from their generation to their decay.

2. MODELING THE FIRE WHIRL PHENOMENON

By assuming the phenomenon of fire whirls, a model was established.

2.1 Generation of fire whirls (inducing an air parcel of heat containing flammable gas)

In a fire occurring in a wide area, the ascending air current is yielded as the combustion progresses. However, since the center of the fire lacks CO, the combustion is incomplete. Given such a case of fire burning, let us assume that an air parcel of heat containing flammable gas flows along with the ambient air and drifts in air outside of the fire. This air parcel of heat consists of two main structures, namely a high-temperature internal structure (nucleus) and a low-temperature external one. The heated nucleus drifts upward due to buoyancy, and an ascending air current is yielded in the interior space. When the circulation yielded in the fire drifts into the space that satisfies the generation condition of the vortex, the air parcel of heat drifting together with the ambient air becomes a vortex.
2.2 Transition to an air column, vortex formation, development and decay

The air parcel of heat becomes an air column consisting of two parts: the internal reactive region (inside) and the external region supplying flammable gas (outside). The column-shaped vortex maintains its swirling by drawing in the flammable gas from the outside to the inside, whereby the outside regions lose flammable gas and decay by the portion of flammable gas drawn inside. The vortex decays completely when the inside ceases to be reactive after using up the flammable gas on the outside.

3. PRELIMINARY CALCULATIONS FOR THE MODEL

The preliminary calculations of this experiment cover the development and the decay of a column-shaped vortex that is already in a swirling state.

The following are the numerical assumptions for the swirling phenomenon of this experiment.

3.1 Governing equation

- Mass conservation law: \( \frac{\partial \rho u}{\partial x} + \frac{\partial \rho v}{\partial y} + \frac{\partial \rho w}{\partial z} = 0 \) (a)

- Momentum preservation equation: \( \frac{\partial \rho w}{\partial t} + \frac{\partial \rho w}{\partial z} = \frac{1}{\rho} \left( \rho \frac{\partial \rho}{\partial t} + \rho \frac{\partial U}{\partial x} + \frac{\partial \rho u}{\partial x} + \frac{\partial \rho v}{\partial y} + \frac{\partial \rho w}{\partial z} \right) + \rho g \beta T \) (b)

- Energy preservation equation: \( \frac{\partial T}{\partial t} + w \frac{\partial T}{\partial z} = \frac{k}{\rho C_p} \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) + \frac{Q}{\rho C_p} \) (c)

- Preservation equation for chemical species: \( \frac{\partial Y_a}{\partial t} + w \frac{\partial Y_a}{\partial z} = \frac{R}{\rho} \left( \frac{\partial^2 Y_a}{\partial x^2} + \frac{\partial^2 Y_a}{\partial y^2} + \frac{\partial^2 Y_a}{\partial z^2} \right) \) (d)

- Equation of state: \( P = \rho RT \) (e)

In the momentum preservation equation, only the component \( w \) was taken into consideration, and components \( u \) and \( v \) were ignored. The buoyancy term (3rd term to the right) was approximated by using the Boussinesq approximation. In \( D = \mu / \rho S_c \), the turbulent diffusion coefficient \( D \) was given a value of \( D=0.1 \text{m}^2/\text{sec} \), where the turbulent viscosity coefficient \( \mu \) is 0.1 kg/m/sec and the Schmidt number \( S_c \) is 1.0[-].

3.2 Calculation summary

In this experiment, as shown in Figure 1, the region used for the model calculation is divided into two distinctive parts, namely the internal reactive area and the external area supplying flammable gas, and the number of the grids is 20 \( \times \) 20 for both the inside and the outside areas.
Figure 1 Region of the calculating model and boundary conditions

### 3.3 Calculation process

The following is a summary of the intended model. The Euler method is used for time integration.

#### 3.3.1 Calculation of velocity field

By using the average temperature ($\bar{T}$) and the average density ($\bar{\rho}$), the average ascent velocity of the buoyancy of the inside was calculated from the momentum preservation equation (*Equation b*).

The following *Equation 1* is given, where the thermal expansion coefficient is $\beta = 1/T$, by taking into account the governing component of this model.

$$\frac{\partial \bar{w}}{\partial t} = g \frac{\bar{T} - T_0}{\bar{T}} - \frac{1}{\rho_1(r_1)} \tau$$

Here, $\tau$, which is the shear stress on the boundary between the inside and outside region, is expressed by *Equation 2*. Furthermore, $\mu$ is the turbulent viscosity coefficient.

$$\tau = \mu \frac{\partial \bar{w}}{\partial r}$$

In order to offset the thermal heat that has drifted from the inside into the outside space due to the ascending air current, the flammable gas is supplied from the outside to the inside. Then, based on the mass conservation law (a), the following relational expression is given.

$$\pi r_1^2 w_1 \rho_1 = 2 \pi r_2 \rho_2 \frac{\partial r_2}{\partial t}$$

The mean descent velocity ($\bar{w}_2$) of the outside air can be calculated by assuming the following mass conservation law.

$$\pi r_1^2 w_1 \rho_1 = \pi (r_2^2 - r_1^2) \bar{w}_2 \rho_2$$

#### 3.3.2 Convection and diffusion of the heat and the chemical species

The convection and the diffusion of the heat and the chemical species were expressed through *Equations c* and *d*, respectively, by using the velocity field as calculated in 3.3.1. The 1st-order upwind difference scheme and 2nd-order central difference scheme are used for the convection term and the diffusion term, respectively.
3.3.3 **The generation term of the heat and the chemical species**

The following thermo-chemical equation was used for the combustion reaction.

\[
C + O_2 = CO_2 + 394.0 [kJ / mol]
\]  

The simplified vortex breakdown model was used for the generation of the heat and the chemical species.

The term of the heat generation, \( Q_h \) [J/m\(^3\)sec], and the term of the chemical species \( \alpha \), \( R \alpha \) [kg/m\(^3\)sec], are determined as follows.

The amount of substance \( A \) [mol/m\(^3\)] for which \( C \) and \( O_2 \) react is given by:

\[
A = \min \left( \frac{\rho Y_c}{M_c}, \frac{\rho Y_{O_2}}{M_{O_2}} \right)
\]  

\( Q_h \) and \( R \alpha \) are given by:

\[
Q_h = \frac{394.0 \times 10^3 A}{t_{vb}}
\]

\[
R \alpha = \frac{AM}{t_{vb}}
\]

Here, \( t_{vb} \) is the vortex breakdown time [s], which is the chemical reaction speed for \( C \) and \( O_2 \). In this model, the vortex breakdown time was set as a value where the steady temperature of the vortex in the model becomes approximately the mean value of the temperature of the main axis of the swirling flame, which was obtained from the scaled model described in Part 1 of this experiment, Experimental Analysis by using a Scaled Model. Therefore, 0.5s is the value used for this calculation.

3.4 **Law of similarity on this model**

3.4.1 **Heat release rate and radius of the fire whirl**

The representative length and the heat release rate of the experiment and the model are \( D_s, D_f, Q_s \) and \( Q_f \), respectively and the representative value of the heat release rate \( Q \) was calculated from Equation 9.[2]

\[
\frac{Q_s}{Q_f} = \left( \frac{D_s}{D_f} \right)^\frac{2}{3}
\]

3.4.2 **Estimation of vortex height**

By using the radius of the swirling flame obtained from the experiment and the inside radius obtained from the model, the circulation \( (\Gamma_f) \) in the model can be given by Equation 10.

\[
\Gamma_f = \left( \frac{D_f}{D_s} \right)^\frac{1}{3} \Gamma_s
\]

Therefore, based on Equation 2 [1] and Figure 2 of Part 1, the vortex height \( (H_f) \) in the model can be obtained from the following equation.

\[
H_f = D_f H_s
\]
3.5. Calculation Conditions

In this preliminary calculation, by assuming a vortex with an internal radius of 10 m, the vortex height was set to 100 m based on the law of similarity described above. The pressure was kept steady at 101 kPa. Based on the existing data, the initial temperatures of the inside and the outside regions were set to values between 800°C (the average temperature of a flame in a fire occurring in a closely-spaced area) and 1200°C (the maximum temperature of a fire in a wood-framed house). Regarding the gas concentration, 5.0 % of the C concentration was given assuming the ratio of the incomplete combustion of a wide-area fire is 40% and the ascent speed of the flame is 5.0m/sec C. The volume fraction of \(O_2\) is regarded as the amount necessary to induce complete combustion, and the volume fraction of \(CO_2\) is determined accordingly from the gas analysis of the vortex condition described in Figure 4 of Part 1.

Table 1 gives the initial input conditions for the vortex.

<table>
<thead>
<tr>
<th>Table 1 Initial input for the vortex</th>
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<tbody>
<tr>
<td>Inside area</td>
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<tr>
<td>Height [m]</td>
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<tr>
<td>Radius [m]</td>
</tr>
<tr>
<td>Pressure [kPa]</td>
</tr>
<tr>
<td>Temperature [°C]</td>
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<tr>
<td>Volume fraction of C</td>
</tr>
<tr>
<td>Volume fraction of (O_2)</td>
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<tr>
<td>Volume fraction of (CO_2)</td>
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4. EXPERIMENTAL RESULTS AND DISCUSSION

Figure 2 shows the time-series behavior of the mean ascent velocity of the buoyancy of the inside air and the mean descent velocity of the outside air. Figure 3 shows the time-series behavior of the temperature at an arbitrary point on the main axis on the inside, as well as the average temperature of the inside and the outside regions.

Figure 2 Average velocity of the inside and the outside regions

Figure 3 Temperature of the inside region
As shown in Figures 2 and 3, the ascent velocity of the buoyancy ($w_1$) is small up to 5.0 s, while the temperature of the inside region increases drastically since the heat $Q$ [W] released from the combustion reaction of $C$ and $O_2$ at $t_{eb}$ [s] remains in the internal reactive region. After 60 s, the supply of air from the lower area of the outside region remains unchanged, although the heat release starts to gradually deteriorate since most of the flammable gas has been consumed, and the temperature of the inside begins to decrease.

Figures 4 and 5 show the temporal transition of the temperature and the mass fraction of the inside region. Due to the burning reaction of $C$ with the residual $O_2$ of the inside region, the temperature is still increasing even though the amount of $C$ is limited. As the ascending air current increases, the high-temperature range moves upward due to the fact that the residual $C$ burns at the upper area of the $z$ axis. The radius of the outside region diminishes sequentially since the inside region is supplied with flammable gas from a fuel tank on the outside. The point where the supply of $O_2$ is no longer sufficient to burn the residual $C$ is considered as the point where the vortex becomes extinct, since no more combustion is expected. Therefore, in this calculation, the vortex became extinct after 78.4 s.

Figure 4  Temperature distribution inside the vortex

Figure 5  Distribution of mass fraction of $C$ inside the vortex
5. CONCLUSION

In this experiment, a vortex model which can be used to analyze fire whirls from their generation to their extinction was presented together with the corresponding preliminary calculations. Although several aspects of the calculation were parametrized in order to extend the scaled experiment into a full-fledged model, many details are still hypothetical. Additional experiments needed with respect to the various conditions, in order to obtain more useful data.

REFERENCES