Numerical Study on the Airflow Characteristics Caused by Wood Combustion

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Abstract

In the present study, we developed a fluid-combustion interaction analysis method. The chemical reaction model for wood combustion that we used can capture the variation of mass in wood combustion process. In order to obtain data of air flow temperature in a fire plume, we conducted a combustion experiment. As a result of the simulation targeted to our experiment, although the temperature far from the wood element was in good agreement with the experimental result, the temperature close to the wood element had difference to the experimental result. This result suggests the need to find out the appropriate external heat condition to ignite the wood element.

Keywords: Wildfire, Wood combustion model, Fluid-combustion interaction analysis.

Introduction

Regardless of the scale, in Japan, thousands of wildfires have occurred in every year. Especially, in the end of winter to spring, the fires occur intensively because of dry and windy weather. Although a simulation model was developed in order to predict spread of wildfire and it has been used still now, several weak points in the model have been discussed. For example, although a wind velocity and direction affect spread of fire, the simple wind prediction model only based on the continuity equation was employed. As a result, the resolution of wind was low (only 1 km). Therefore it is difficult to consider the local wind field. Moreover, for the prediction of combustion, not chemical reaction equations but experimental relations were coupled.

On the other hands, in the countries which has more severe wildfire, such as USA, Australia and EU, they have simulation methods based on CFD and combustion analysis [1]. Therefore, we think that a new accurate simulation method for wildfire should be developed in our country. For the purpose of the simulation for wildfire, we developed a new

fluid-combustion interaction analysis method by using CFD and chemical reaction model of a wood combustion. In order to validate the simulation, we conducted a combustion experiment.

Governing equations for flluid

In the case of fire, the air flow temperature becomes so high that a change in air density must be taken into account. Accordingly, although the compressible flow solver should be used, it is well known that the convergence of the time dependent compressible flow solver gradually decrease in a low Mach number flow on which we focused [2]. Therefore, in the present study, we adopted the low Mach number approximation in which pressure is divided into the thermodynamic and dynamic parts [3] for fluid.

The mass, momentum and energy transport equations were as follows:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_j}\left(\rho u_j\right) = 0 \qquad \text{(Eq. 1)}$$

$$\frac{\partial\left(\rho u_i\right)}{\partial t} + \frac{\partial\left(\rho u_i u_j\right)}{\partial x_j} = \frac{\partial \sigma_{ij}}{\partial x_j} + g_i\left(\rho - \rho_0\right) + \rho f_i \qquad \text{(Eq. 2)}$$

$$\sigma_{ij} = -p\delta_{ij} + \mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) \qquad \text{(Eq. 3)}$$

$$\frac{\partial\left(\rho\varepsilon\right)}{\partial t} + \frac{\partial\left(\rho\varepsilon u_j\right)}{\partial x_j} = \frac{\partial}{\partial x_j}\left(k\frac{\partial T}{\partial x_j}\right) + S_r \qquad \text{(Eq. 4)}$$

$$\varepsilon = C_p T \qquad \text{(Eq. 5)}$$

$$p_0 = \rho_0 T_0 = \rho T = \text{const.} \qquad \text{(Eq. 6)}$$

where, ρ is fluid (air) density, u_i is fluid velocity, p is pressure and T is fluid temperature. We treated these as unknown variables. In eq. 2 and eq. 5, subscriptions 0 denotes the initial values. μ is molecular viscosity, g_i is gravity, f_i is body force, C_p is specific heat of the air, k is conductivity, S_r is chemical reaction heat from wood which will be described in detail at the next chapter.

The residual based variational multiscale method (VMS method) proposed as a new turbulence modelling in finite element flow analysis [4] was employed for the discretization of the governing equations for fluid motion.

In the present study, the finite element method was employed for the spatial discretezation with linear hexahidral elements. The Crank-Nicolson method for the time integration, the GMRES method for the solveing linear system were used.

Wood combustion model

In order to simulate the wood combustion process, the chemical reaction model of a piece of wood proposed by Morvan et al. [5] is employed. The process of combustion can be modelled as the following three stages. These stages are as follows: 1) water vaporization, 2) pyrolysis, 3) char oxidation. The rate of chemical reactions of each stages are written in ordinary differential equations with the Arrhenius law.

Vaporizarion $$\omega_{H_2O} = k_{H_2O} m_{H_2O} T_s^{-1/2} \exp\left[-E_{H_2O}/T_s\right] \quad \text{(Eq. 10)}$$

Pyrolysis: $$\omega_{pyr} = k_{pyr} m_{pyr} \exp\left[-E_{pyr}/T_s\right] \quad \text{(Eq. 11)}$$

Char oxidation: $$\omega_{char} = \nu_{O_2}^{-1} k_{char} \alpha_s \sigma_s m_{O_2} \exp\left[-E_{char}/T_s\right] \quad \text{(Eq. 12)}$$

Model parameters in above equations we used [5, 6] are as follows:

$k_{H_2O} = 6\times10^5\ s^{-1}K^{-1/2}$, $k_{pyr} = 3.63\times10^4\ s^{-1}$, $k_{char} = 430\ ms^{-1}$,

$E_{H_2O} = 5800\,K$, $E_{pyr} = 7250\,K$, $E_{pyr} = 9000\,K$, $\nu_{O_2} = 8/3$,

$\alpha_s = 0.5$, $\sigma_s = 4550\ m^{-1}$

The mass of whole wood and three components in wood (e.g. whole wood m_s, water content m_{H_2O}, dry wood m_{pyr}, char m_{char}) are related to the rate of chemical reactions.

$$\frac{d}{dt}\left(m_{H_2O}\right) = -\omega_{H_2O} \quad \text{(Eq. 13)}$$

$$\frac{d}{dt}\left(m_{pyr}\right) = -\omega_{pyr} \quad \text{(Eq. 14)}$$

$$\frac{d}{dt}\left(m_{char}\right) = \nu_{char}\omega_{pyr} - \omega_{char} \quad \text{(Eq. 15)}$$

$$\frac{d}{dt}\left(m_s\right) = -\omega_{H_2O} - \left(1-\nu_{char}\right)\omega_{pyr} - \left(1-\nu_{ash}\right)\omega_{char} \quad \text{(Eq. 16)}$$

where, $\nu_{char} = 0.3$, $\nu_{ash} = 0.1$ were used.

The temperature of a piece of wood is calculated from the heat transfer equation combined with the chemical reaction equations.

$$m_s \frac{dT_s}{dt} = D_m + Q_c + Q_r + \overline{Q} \quad \text{(Eq. 17)}$$

$$D_m = -L_{H_2O}\omega_{H_2O} - L_{pyr}\omega_{pyr} - \alpha_{sg}L_{pyr}\omega_{pyr} \quad \text{(Eq. 18)}$$

$$Q_c = \alpha_s \sigma_s h_c \left(T - T_s\right) \quad \text{(Eq. 19)}$$

$$Q_r = \alpha_s{}^2 \sigma_s \sigma \left(T^4 - T_s^4\right) \quad \text{(Eq. 20)}$$

$$S_r = L_{H_2O}\omega_{H_2O} + \left(1-\nu_{char}\right)L_{pyr}\omega_{pyr} - \left(1-\alpha_{char}\right)L_{char}\omega_{char} \quad \text{(Eq. 21)}$$

where, L_{H2O} = 2.26x10^6 J/kg, L_{pyr} = 4.18x10^2 J/kg, L_{char} =-1.2x10^7 J/kg, α_{sg}=0.5, h_c=100 W/m^2/K. σ is Stefan-Baltzman constant. $\overline{Q}$ is an external heat term in order to express the ignition. The reaction heat S_r during the combustion of a piece of wood is incorporated into the right hand side of the energy equation of fluid.

For the purpose of the check of the chemical reaction model, we calculated the variation of mass loss of a piece of wood. We compared our computational result to the experimental result based on the TGA test by Vovelle et al. [7]. Equal to the experimental condition, the external heat in eq. 17 Q = 79.5 kJ/s was imposed. It corresponds to the temperature rate 0.167 K/s. The time integration interval was set at Δt = 0.1 s, 4000 s was totally calculated. As same as the computation of Morvan et al. [5], the initial conditions were set as ρ_s = 680 kg/m^3, α_s = 0.029, m_{H2O} / m_s = 0.2, m_{pyr} / m_s = 0.8, m_{char} / m_s = 0.0. As shown in figure 1, our result is in good agreement with the experimental result. We confirmed that this chemical reaction model can be applied for the wildfire simulation.

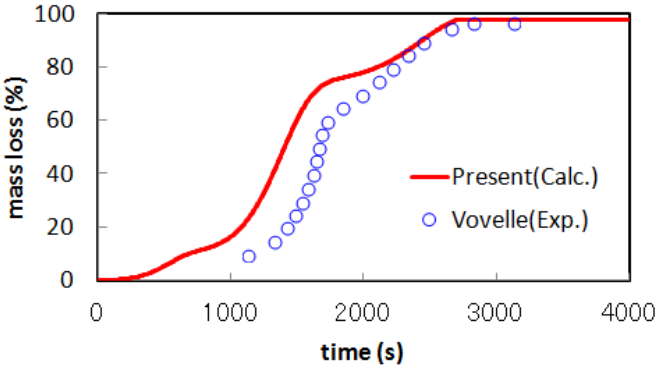


Figure 1. Mass loss rate of a piece of wood

Measurement of the temperature in a fire plume

Because of the lack of temperature data in wildfire, we conducted a combustion experiment in order to measure the air flow temperature in a fire plume. Fallen leaves were used as the combustion material in our experiment. Figure 2 shows experimental setup. Fallen leaves were placed at the center of the experimental table with the area of 100 cm^2 and the depth of δ = 5 cm (corresponding to the sediment density of 1.0 kg/m^2). Air flow temperatures were measured by K type thermocouples. Measured points were located at the center of fallen leaves and the height of 5, 15, 25 cm from the bottom. At the ignition line in fig.2, we ignited by using an oil lighter.

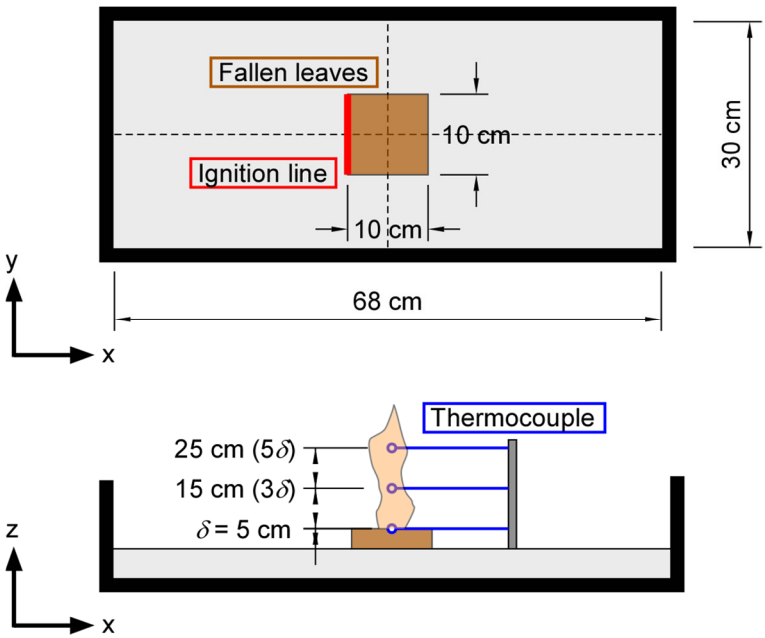


Figure 2. Setup of combustion experiment.

Figure 3 shows a snapshot of the experiment. The frame reached to the highest thermocouple (5δ). Measured air temperatures are shown in Figure 4. The temperature of δ and 3δ varied almost same time history. The maximum temperature reached 1100 K. On the other hands, the temperature of the highest thermocouple was quite low compared to the other two results. Rapid change of temperatures between these two measurement points was confirmed.

Figure 3. Snapshot of experiment

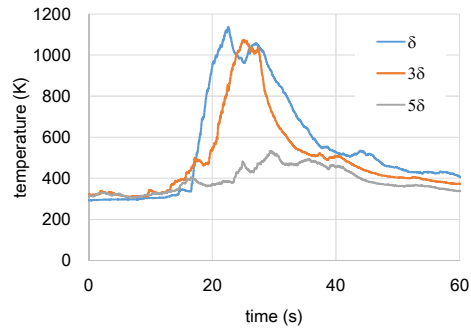


Figure 4. Measured air temperatures.

Computation of the air flow temperature

We conducted a fluid-combustion interaction simulation targeted to the experiment indicated in the previous chapter. The computational condition shows in figure 5. In order to prevent computational instability, the length of computational domain L was set at 0.1 m which is smaller than the experimental domain. In other words, we conducted a simulation of 1/10 scale compared to the experiment. A piece of wood elements was set at the centre of the bottom in the computational domain.

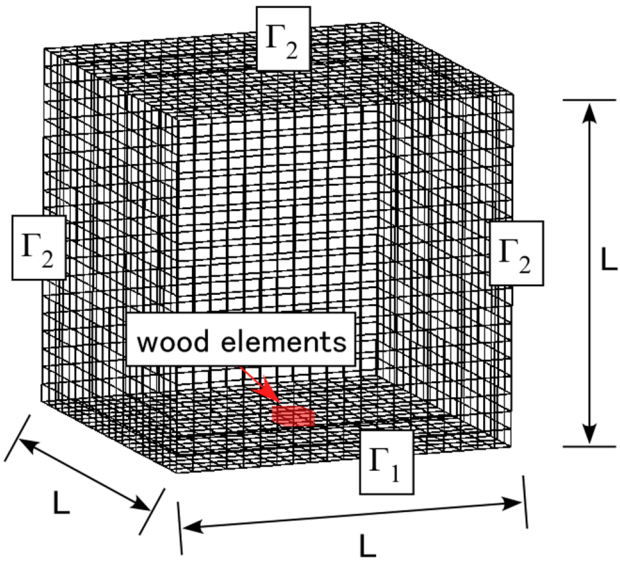
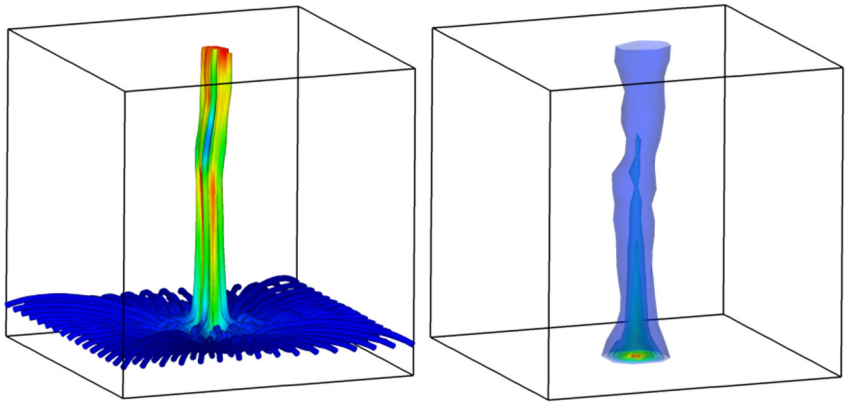


Figure 5. Compuational conditions

The external heat $\overline{Q} = 3.0$ MJ/s which corresponded to the heat value of an oil lighter was added to the wood for the purpose of the ignition. The upper and side boundaries were imposed as open boundary condition. The bottom boundary was imposed as no-slip condition.

Figure 6 shows the results of streamline and temperature around burning wood elements. An upward and periodic fluctuation flow driven by the effect of the buoyancy were observed. We checked the time history of temperature at the same nondimentional height to the experiment. The result shows in figure 7. At the measurement point of 5δ, the computational result was in good agreement with the experimental result. However, the result at the other two points (δ and 3δ) had large difference to the experimental one. Especially, the time between the start of rise of temperature to the reach of the maximum temperature was longer than the experimental result. That is, this result implies that it is necessary to react wood elements more quickly by applying more large external heat.



(a) Streamline (b) Temperature

Figure 6. Numerical result of airflow around burning wood elements.

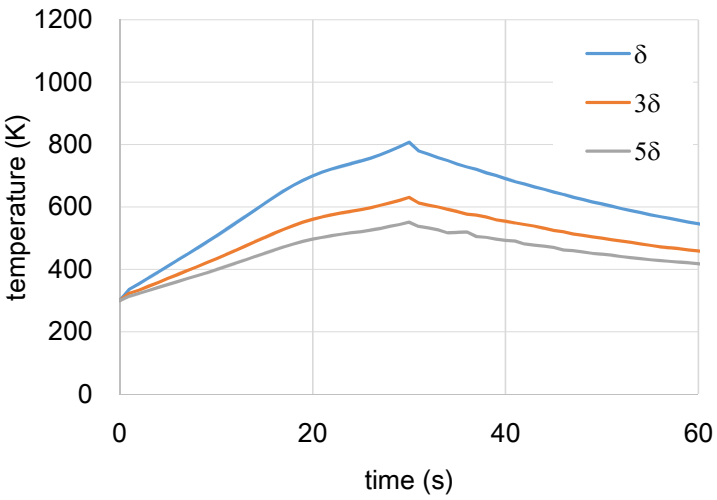


Figure 7. Computational result of temperature

Concluding remarks

In the present study, we developed a fluid-combustion interaction analysis method by using CFD and a chemical reaction model for wood combustion. The chemical reaction model captured the variation of mass loss in wood combustion process. In order to validate our computational method, we conducted the combustion experiment to obtain data of the air flow temperature in fire plume. As a result of the simulation targeted to our experiment, we confirmed that the temperature far from the wood element was in good agreement with the experimental result. However, the temperature close to the wood element had large difference to the experimental result. Since the time between the start of rise of temperature to the reach of the maximum temperature was longer than the experimental result, it is necessary to find out the appropriate external heat condition to ignite the wood element.

Acknoledgement

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