Evaluation of radiative heat transfer effect on fire whirlwind

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Abstract

Radiative-convective heat transfer analysis with respect to fire whirlwind is performed in consideration of participating media using Radiation Element Method by Ray Emission Model (REM2), in which three dimensional analyses are then performed to investigate the thermal and flow fields by using the Finite Volume Method with introducing divergence of radiative heat flux for gas medium. The SIMPLE method is utilized to solve the discretized equations. Natural convection is caused from a plane source of constant temperature in the flat ground. Fire whirlwind is forcely generated stably just above the heat source with introducing air currents from four corners. In the analysis, one dimensional radiative exchange analysis above the heat source is compared with three dimensional one to reduce the computational load and time. Then, the composition of participating gases is altered to discuss the effect of radiative heat exchange to the whirlwind flow field.

Key Words: *Fire Whirlwind, Radiative Heat Exchange, Participating Media, Natural Convection*

Introduction

Our Japanese, especially the residents in east area of Japan, have experienced a large earthquake on March 11, 2011, i.e. East Japan great earthquake disaster (Takewaki et al., 2011). There were a lot of fires in the northeast area of Japan, for example in Kesen-numa City. Despite of a number of town area fires, a fire whirlwind was never observed in this disaster. However, fire whirlwind is still one of the concerned accidents in the earthquake (Hough & Bilham; 2005).

When a large-scale wide area fire such as a town area fire or a forest fire occurs, there can be a strong rotating flow to be called fire whirlwind. Fire whirlwind is a tornado that includes flames, hot winds and sparks. Fire whirlwind is regarded as one of the worst cases which we should avoid at the time of a large-scale fire, because the whirlwind itself is critical and scatters sparks widely to promote spread of a fire.

As a fire occurs, a flame makes an ascending current of air and uses up neighboring oxygen. Furthermore, to collect oxygen from a wide area, there is a current of air against the flame, resulting in big natural convection in the fire current of air. When the wind from a certain specified direction blows in this fire current of air, homogeneity of suction of air with an ascending current of air collapses. Then, a vortex is easy to come to occur, the fire current of air becomes a fire whirlwind that is an ascending current of air accompanied with rotating. Fire whirlwind may be pushed away by wind downstream, or may move in search of oxygen.

Aiming at a property and elucidation of an outbreak factor of fire whirlwind as examples of the pasts for a lesson, investigation and a reproduction experiment of the outbreak situation (Graham, 1955; Emmons & Ying, 1967; Byram & Martin, 1970; Haines & Updike, 1971; Martin et al., 1976; Muraszew et al., 1979; Emori & Saito, 1982; Satoh & Yang, 1996; Hayashi et al., 2003; Liu, 2005; Kuwana et al., 2007; Liu et al., 2007; Kuwana et al., 2008; Chuah et al., 2011), numerical analysis are performed till now (Satoh & Yang, 1997; Battaglia et al., 2000; Snegirev et al., 2004; Hassan et al., 2005; Chuah et al., 2007; Grishin et al., 2009). Though various factors are thought about outbreak of a fire whirlwind, such as climatic condition or existence of underground flammable gas, it is hard to say that property and outbreak mechanism of a fire whirlwind are to be elucidated enough.

Convective and radiative-convective heat transfer analyses with respect to fire whirlwind were also performed in our laboratory on former studies (Sakai and Watanabe, 2007; Sakai and Miyagi, 2010; Sakai, 2012), just radiative exchange between solid surfaces was carried out. Therefore, in this study, radiative heat exchange is dealt in consideration of radiative gas using Radiation Element Method by

Ray Emission Model (REM2) (Maruyama & Aihara, 1997). Radiative heat transfer effect on fire whirlwind is discussed.

Then, three dimensional analyses are performed to investigate the thermal and flow fields by using the Finite Volume Method (Patankar, 1980) with introducing divergence of radiative heat flux for gas medium. The SIMPLE method is utilized to solve the discretized equations. Natural convection is caused from a plane source of constant temperature in the flat ground. Fire whirlwind is forcely generated stably just above the heat source with introducing air currents from four corners. For making of analysis models, a representative example of the fire whirlwind that occurred at Tokyo in the Great Kanto Earthquake (1923) is referred.

In the analysis, one dimensional radiative exchange analysis above the heat source is compared with three dimensional one to reduce the computational load and time. Then, the composition of participating gases is altered to discuss the effect of radiative heat exchange to the whirlwind flow field.

Analysis and Modelling

Radiative Exchange We consider the radiation element of participating medium, which is comprised of a polyhedron surrounded by polygons as shown in Fig. 1. The spectral radiation intensity, I_λ, at $\vec{r}$ in the direction $\hat{s}$ can be expressed in terms of the radiation energy balance by

$$\frac{dI_\lambda(\vec{r},\hat{s})}{dS} = -(\kappa_\lambda + \sigma_{s,\lambda})I_\lambda(\vec{r},\hat{s}) + \kappa_\lambda I_{b,\lambda}(T) + \frac{\sigma_{s,\lambda}}{4\pi}\int_{4\pi} I_\lambda(\vec{r},\hat{s}')\Phi_\lambda(\hat{s}'\to\hat{s})d\omega, \tag{1}$$

where κ_λ and $\sigma_{s,\lambda}$ are spectral absorption and scattering coefficients, respectively. $I_{b,\lambda}$ is spectral black-body radiation intensity. Here, S is the path length in the direction $\hat{s}$ and $\Phi_\lambda(\hat{s}'\to\hat{s})$ is the phase function from the direction $\hat{s}'$ to $\hat{s}$.

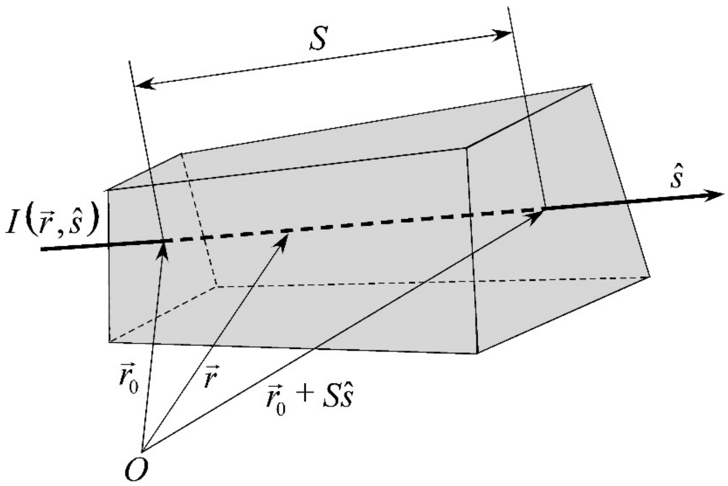

Fig. 1. Radiation element

Considering the i-th participating radiation element, we assume that each radiation element is at a constant uniform temperature of T_i and its refractive index and heat generation rate per unit volume, $q_{X,i}$, are also constant and uniform throughout the element. A ray passing through the radiation elements attenuates by absorption, and a part of the ray is scattered. The ray is separated into absorbed, scattered and transmitted fractions. Moreover, it is assumed that the scattered radiation is distributed uniformly over the element.

For anisotropic scattering media, we introduced an apparent extinction coefficient β_λ^* and thus, a corrected scattering albedo Ω_λ^* by introducing the delta function approximation (Maruyama, 1998). Thus, an anisotropic scattering medium can be treated as an isotropic scattering one. The third term on the right hand side of equation (1) can be approximated by

$$\frac{\Omega_\lambda}{2}\int_{-1}^{1} I_\lambda(x,\mu')\Phi_\lambda(\mu')d\mu' \approx \frac{\Omega_\lambda^*}{2}\int_{-1}^{1} I_\lambda(x,\mu')d\mu' \approx \Omega_\lambda^* I_\lambda^D , \tag{2}$$

where I_λ^D is the average scattered radiant intensity and μ' is directional cosine.

A radiation element i can be regarded as either a volume element or a surface boundary. Equation (1) is integrated along the path length $\bar{S}_i(\hat{s}) = V_i/A_i(\hat{s})$ and over all discretized solid angles, in which V_i and $A_i(\hat{s})$ are the volume and area projected onto the surface normal to $\hat{s}$, respectively. The spectral radiation energy, $Q_{J,i,\lambda}$, from the radiation element i, is given by

$$Q_{J,i,\lambda} = \pi\left(\varepsilon_{i,\lambda} I_{b,i,\lambda} + \Omega_{i,\lambda}^D I_{i,\lambda}^D\right) A_{i,\lambda}^R , \tag{3}$$

where $\varepsilon_{i,\lambda} = 1 - \Omega_{i,\lambda}^D - \Omega_{i,\lambda}^S$, in which $\varepsilon_{i,\lambda}$, $\Omega_{i,\lambda}^D$ and $\Omega_{i,\lambda}^S$ are emissivity, diffuse reflectivity and specular reflectivity, respectively. $A_{i,\lambda}^R$ is the effective radiation area (Maruyama & Aihara, 1997) which is defined as follows,

$$A_{i,\lambda}^R \equiv \frac{1}{\pi}\int_{4\pi} A_i(\hat{s})\left[1 - \exp\left(-\beta_{i,\lambda}^* \bar{S}_i(\hat{s})\right)\right] d\omega . \tag{4}$$

By introducing the absorption view factors $F_{i,j}^A$ and the diffuse scattering view factors $F_{i,j}^D$ defined by Maruyama (Maruyama, 1998) and equation (3), we can obtain the following equations:

$$Q_{T,i,\lambda} = \pi\varepsilon_{i,\lambda} I_{b,\lambda} A_{i,\lambda}^R , \tag{5}$$

$$Q_{J,i,\lambda} = Q_{T,i,\lambda} + \sum_{j=1}^{N} F_{j,i}^D Q_{J,j,\lambda} , \tag{6}$$

$$Q_{X,i,\lambda} = Q_{T,i,\lambda} - \sum_{j=1}^{N} F_{j,i}^A Q_{J,j,\lambda} . \tag{7}$$

The heat transfer rate of the emissive power, $Q_{T,i,\lambda}$, or the net rate of heat generation, $Q_{X,i,\lambda}$ for each radiation element is given arbitrarily as a boundary condition. The unknown $Q_{X,i,\lambda}$ or $Q_{T,i,\lambda}$ can be obtained by solving equations (6) and (7) using the method previously described by Maruyama and Aihara (Maruyama & Aihara, 1997). The relationship between $q_{X,i}$ and $Q_{X,i,\lambda}$ is obtained by

$$q_{X,i} = \frac{Q_{X,i}}{V_i} = \frac{1}{V_i}\int_0^\infty Q_{X,i,\lambda} d\lambda . \tag{8}$$

An analytical method for radiative heat transfer, i.e. the radiation element method by ray emission model, REM2, is used in radiative heat transfer analysis, and the Statistical Narrow Band (SNB) model is combined to the REM2 to consider the spectral dependence of the radiative properties.

Thermal and Fluid Flow Fields The governing equations of thermal and flow fields are the continuum equation, the Navier-Stokes equation, and the energy equation. The thermal and flow fields are assumed to be unsteady state and three dimensional. These equations are normalized and transformed to the following generalized conservation equation.

$$\frac{\partial\phi}{\partial t} + \frac{\partial}{\partial x}(u\phi) + \frac{\partial}{\partial y}(v\phi) + \frac{\partial}{\partial y}(w\phi) = \Gamma\left(\frac{\partial^2\phi}{\partial x^2} + \frac{\partial^2\phi}{\partial y^2} + \frac{\partial^2\phi}{\partial z^2}\right) + S , \tag{9}$$

where u, v and w are the normalized velocity components for x, y and z directions, respectively. Variable ϕ takes 1 for the continuum equation, u, v and w for the Navier-Stokes equation, and normalized temperature T for the energy equation. Generalized diffusion coefficient Γ takes 0 for the continuum equation, $1/Re$ for the Navier-Stokes equation and $1/(Re \cdot Pr)$ for the energy equation. Normalized source term S takes 0 for the continuum equation, the summation of the normalized pressure term and the normalized buoyancy term by Boussinesq approximation, and the normalized source term from radiative exchange mentioned in the previous section (equation(8)). Turbulent flow is treated by using high Reynolds number turbulence model.

In the thermal and fluid flow analysis, equation (9) is discretized by using the Finite Volume Method (Patankar, 1980). The SIMPLE method is utilized to solve the discretized equations. Physical properties of the mixture are altered depending on the change of temperature.

Analysis Procedure Fig. 2 shows an analysis procedure in this study. Temporal temperature distribution is initially given to analyze nongray radiative heat transfer by REM2. Then, the derived heat generation rate is introduced to the energy equation, and the thermal and flow field is analyzed by FVM using the SIMPLE method. The derived temperature is introduced to the REM2 again as an initial temperature distribution, and iteration is repeated until the derived distribution is converged to the initial distribution. Steady state solution is obtained through this iteration loop.

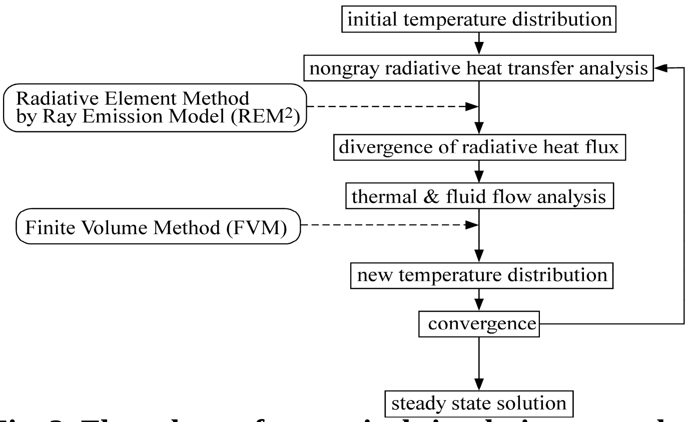

Fig. 2. Flow chart of numerical simulation procedure

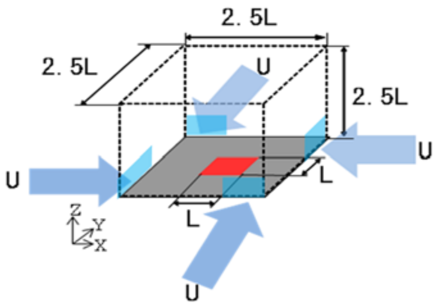

Fig.3. Analytical domain

Analytical Model Fig. 3 shows analytical domain for calculation, which scale is based on the Great Kanto Earthquake (1923) in Japan. Heat source on the bottom center has 800m in width and depth, and this value is representative length L. Therefore, the analytical domain is a cubic of 2,000m in width, depth and height. Heat source is applied uniform temperature of 2,000K, and the domain is assumed to be surrounded by circumstance of 293.15K. Initial temperature of the domain is also set to 293.15K. Mixture gas is constituted by water vapor, CO_2 and Nitrogen. All the domain surfaces are assumed to be black for radiative exchange, and the surfaces except the bottom are opened. Fire whirlwind is forcely generated stably just above the heat source with introducing air currents from four corners. The currents velocities U are constant of 5m/s at the inlet surfaces of 600m in width and 200m in height. Combustion nor chemical reaction is not considered in the calculation.

Table 1 shows concentration of participating gases in mixture for radiative heat exchange. Carbon dioxide has three values; no concentration, concentration in general atmosphere and the maximum concentration in case of fire. Water vapor also has three values; no concentration, concentration of saturated water vapor at the initial temperature and the concentration of saturated water vapor at boiling point.

Table 1 Concentration of participating gases

	Concentration of CO_2 (ppm)	Concentration of H_2O (ppm)
Case A	0	0
Case B	0	3.56×10^4
Case C	3.60×10^2	3.56×10^4
Case D	8.00×10^4	3.56×10^4
Case E	8.00×10^4	1.02×10^6

Results and discussions

In our previous study, performing the numerical analysis of fire whirlwind with respect to scale effect, it was examined whether a relationship exists between a real phenomenon and the phenomenon in the reduction model with taking into account radiative heat transfer (Sakai & Miyagi, 2010). The P-1 model was utilized to simulate the radiative heat transfer from the heat source at high temperature.

It was found that radiative heat exchange played an important role in the heat transfer at the higher temperature field, whereas just radiative exchange between solid surfaces was carried out.

In this study, radiative heat exchange is dealt in consideration of radiative gas using Radiation Element Method by Ray Emission Model (REM2) (Maruyama & Aihara, 1997). Radiative heat transfer effect on fire whirlwind is discussed.

Comparison of 1-d and 3-d radiative heat exchange One dimensional radiative exchange analysis above the heat source is compared with three dimensional one to reduce the computational load and time. Fig. 4 shows the comparison of divergence of radiative heat flux above the heat source between one dimensional parallel analysis model and three dimensional analysis model. Even though the one dimensional analysis model omitted the effect of surrounding boundaries, these two results coincide comparable. Therefore, further analysis employs one dimensional model for radiative heat exchange.

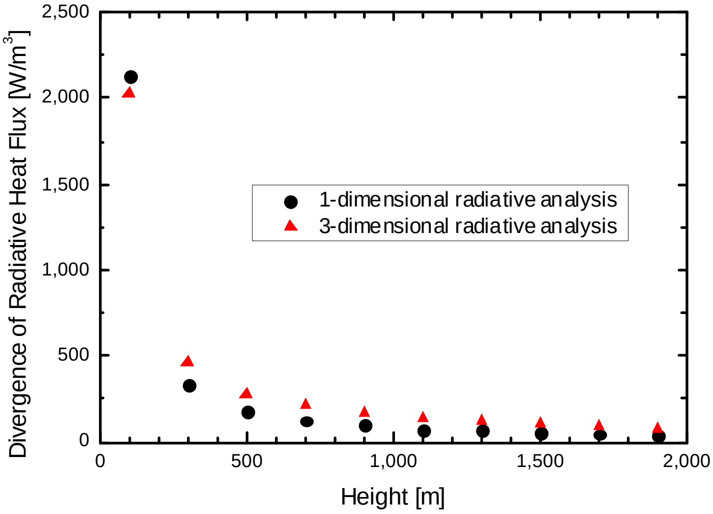

Fig. 4. Comparison of 1-d and 3-d radiative analysis (Distribution of divergence of radiative heat flux above the heat source)

Comparison of convective flow analysis and radiative-convective flow analysis Fig. 5 shows heat generation rate for convective flow analysis and divergence of radiative heat flux for radiative heat exchange above the heat source. Though values of divergence of heat flux are smaller than those of heat generation rate, just convective flow analysis ignores these amounts to simulate. It is easily expected that the radiative heat exchange due to participating media plays an important role more than the radiative heat exchange between surfaces.

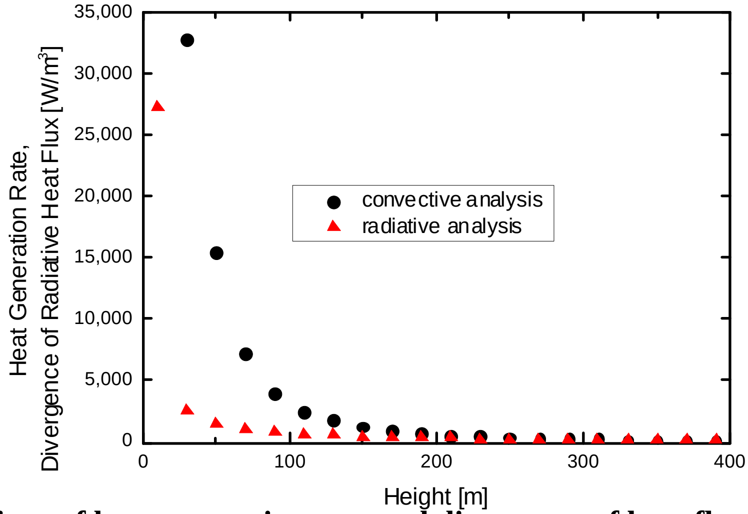

Fig.5. Comparison of heat generation rate and divergence of heat flux above the heat source

Fig. 6 shows comparison of temperature distribution above the heat source after 30 minutes from air current induction between convective flow analysis and combined radiative-convective flow analysis.

As expected from the distribution of heat generation and divergence of radiative heat flux, temperature distribution is different, especially until lower height 100m. Participating media have much influence to the temperature distribution, and play an important role.

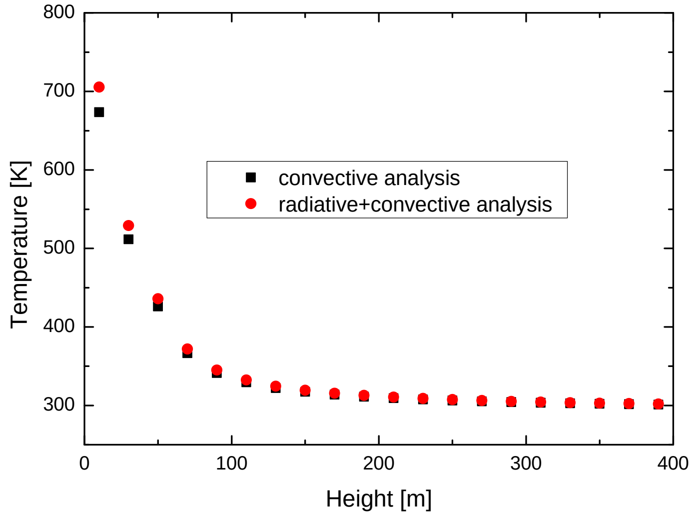

Fig.6. Comparison of temperature distribution above the heat source after 30 minutes from air current induction between convective flow analysis and combined radiative-convective flow analysis

Fig. 7 shows streamlines of the flow field. Lines are colored by velocity magnitude. Whirlwind is stably generated above the heat source, and is shrinked sharply with the height from the heat source.

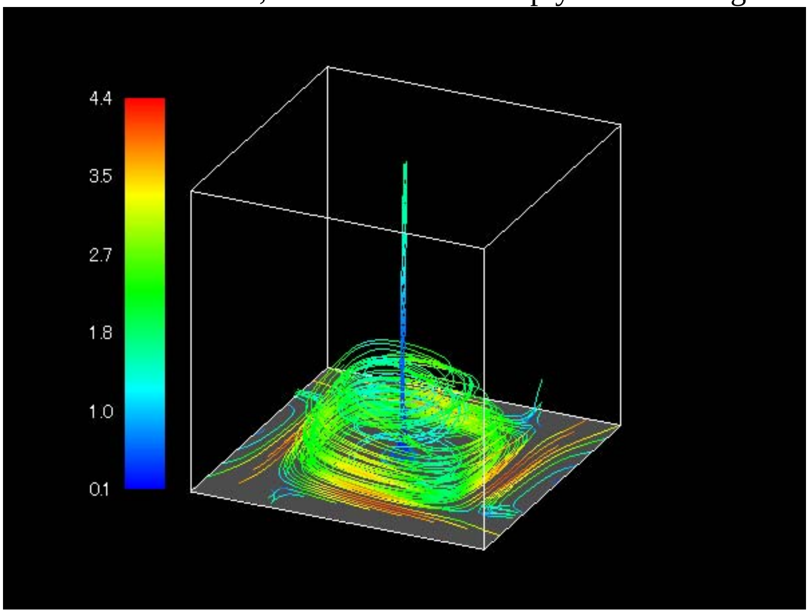

Fig.7. Streamlines of whirlwind

Influence of Participating Media Concentration on Heat Exchange and Flow Distribution In practical fire whirlwind, combustion and chemical reaction release some participating media. In this section, representative participating media, i.e. carbon dioxide and water vapor is considered, and the concentration of these participating media is altered to evaluate the influence on heat exchange and flow distribution.

Figs.8 and 9 shows temperature at the height of 10m from the bottom surface with changing the concentration of carbon dioxide and that of water vapor, respectively. Some values of both participating media concentration are added from the Table 1 for the combined analysis to observe the tendency between temperature and concentration. Water vapor plays more important role to the thermal field than carbon dioxide.

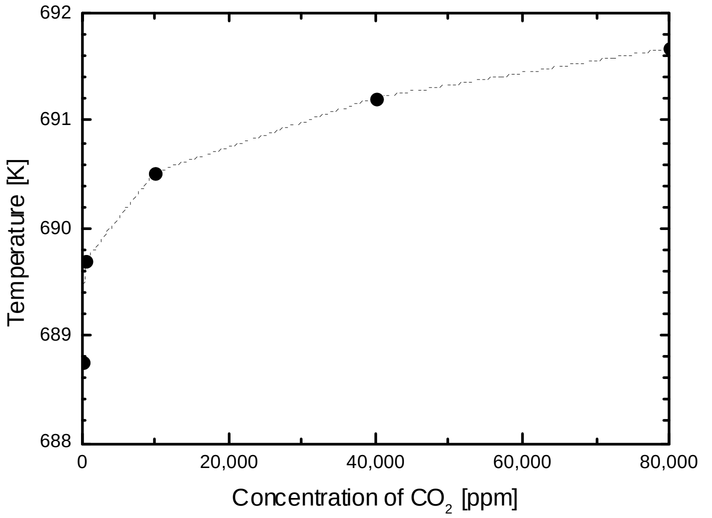

Fig.8. Temperature at the height of 10m from the bottom surface with changing the concentration of carbon dioxide

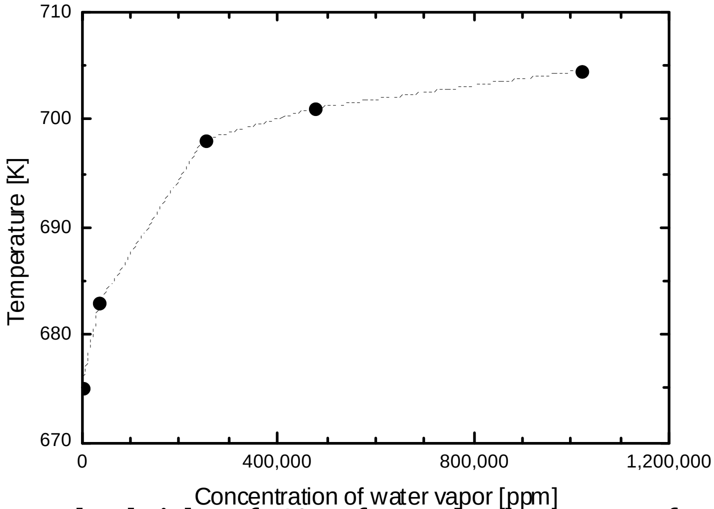

Fig.9. Temperature at the height of 10m from the bottom surface with changing the concentration of water vapor

Conclusions

In this study, three dimensional analyses are performed to investigate the thermal and flow fields by using the Finite Volume Method with introducing divergence of radiative heat flux for gas medium. Fire whirlwind is forcely generated stably just above the heat source with introducing air currents from four corners. One dimensional radiative exchange analysis above the heat source is compared with three dimensional one to reduce the computational load and time. Then, the composition of participating gases is altered to discuss the effect of radiative heat exchange to the whirlwind flow field. The following concluding remarks are gotten from the combined heat transfer analysis.

- From the comparison of thermal and flow field between convective flow analysis and combined radiative-convective flow analysis, radiative heat exchange has a great influence to the thermal field and a less influence to the flow field. Flow field is much characterized by turbulent.
- Increase of participating media concentration gives raise of temperature due to absorption and re-emission, and water vapor influences thermal field more than carbon dioxide. However, these calculations employ uniform concentration over the analytical domain. Release and diffusion of participating media have to be considered for more practical evaluation of the whirlwind.

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