A NUMERICAL STUDY ON THE COMBUSTION CHARACTERISTICS OF SOLID FUEL IN A COMPLEX GEOMETRY

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INTRODUCTION

In recent years, a lot of numerical studies have been done to get physically reasonable results within a rather short period in a variety of fields. Regardless of the cost-effectiveness, the computational analysis also can provide an easy parametric study. Therefore, it is attractive enough to many researchers as well as designers who deal with a lot of machinery such as gas turbines, incinerators, combustors, and engines. It is, however, true that both many difficulties in numerical methods and inaccuracy of the solutions can be arisen in the computational field because real machines and their operating conditions are also complex. So a great deal of efforts has been done to calculate turbulent reacting flow in a complex geometry using structured grids. Murthy and Mathur[1] studied the radiation heat transfer problem using numerical methods with unstructured grid first in the world, and Kim and Baek[2] accomplished various radiation heat transfer problems which are about a complex two-dimensional geometry with obstacles. Also, Chai and Moder[3] calculated the radiation heat transfer problem related to two-dimensional complex geometry introducing multi-block method with FVM (Finite Volume Method) However, the works that has computed the turbulent reacting flow in a three-dimensional complex geometry with gas radiation effects have not been yet in articles. In this research, the generalized program that can be applied to turbulent reacting flow problems of gaseous hydrocarbon fuel in a three-dimensional complex geometry has been developed with gas radiation effect. In order to generate grid system, multi-block method is introduced with block-structured grid which implicitly treats multi-block interfaces. The solution algorithm is based on the SIMPLE method which adopts collocated grid. In this study, the developed code has been applied to combustion of volatile fuel gas of solid fuel in a three-dimensional stoker incinerator with a complex shape. After the three-dimensional shape is divided into four blocks, numerical analysis has been done to investigate the combustion characteristics of volatile fuel gas. The applied mathematical models for prediction of velocity, turbulence quantities, enthalpy, and chemical species concentration are described and discussed. By comparing the results of developed code with those of a commercial code, the developed code is confirmed and regarded as a good tool for simulating turbulence reacting flow as well as radiative characteristics.

MATHEMATICAL MODEL

The three-dimensional, steady Navier-Stokes equations and conservation equations for mass, energy, turbulent kinetic energy, eddy dissipation rate of two-equation model, and species for a chemically reacting flow are written as follows in the general form,

$$div\left(\rho\vec{u}\phi\right) = div\left(\Gamma_\phi grad\phi\right) + S_\phi \quad (1)$$

where Γ_ϕ is the diffusion coefficient, S_ϕ is the source term, and ϕ is any one of the dependent variables[4]. The standard $k-\varepsilon$ model [5] which is the one of widely used models is introduced in turbulence modeling. Turbulent combustion has been modeled by using the eddy dissipation model. Also, two-step reaction including oxidization of CO is employed [6]. While modeling the radiative heat transfer, finite volume method for radiation has been followed. Non-gray gas radiation by CO_2 and H_2O is modeled by the weighted sum of gray gas model (WSGGM).

NUMERICAL METHOD

In present study, the general governing equation is solved by FVM with multi-block. The code has been programmed using collocated grids and Cartesian velocity component $u, v,$ and w [7]. The general equation can be integrated over non-orthogonal grid following finite volume approach.

$$\int_S \rho\phi\vec{u}\cdot\vec{n}dS = \int_S \Gamma_\phi grad\phi\cdot\vec{n}dS + \int_V S_\phi dV \tag{2}$$

In order to calculate the given flow field, it is divided into some blocks with structured grids using multi-block method. Figure 1 shows interfaces between two blocks with matching CV faces. As it can be seen, the interface is both the east side of Block A and the west side of Block B. In this case, the block interface is not treated as a boundary but as a cell face. With the block information, we can approximate the fluxes through the Block-Interface as we did in the interior. Each interface contributes to the source terms for the neighboring CVs (explicit contributions to the convective and diffusive fluxes treated by deferred correction), to the main diagonal coefficient (A_P) of these CVs, and to two off-diagonal coefficients: A_L for node R A_R and for node L [7-9]. The contributions from the interface, namely A_L and A_R , make the global coefficient matrix A irregular: neither the number of elements per row nor the bandwidth is constant. However, this is easily managed by so–called SIP (Strongly Implicit Procedure) solver with ILU (Incomplete LU) decomposition. On the other hand, a special treatment is needed to manage the energy equation including the radiation heat transfer. The effect of the radiative heat transfer is shown in the energy equation as follows.

$$-\nabla\cdot q^R = \kappa_a\cdot\left(4\pi I_b - \int_{4\pi} I(\vec{r},\vec{s})d\Omega\right) \tag{3}$$

By introducing RTE (Radiative Transfer Equation) below, we can get discretized equation for radiative heat transfer assuming the radiative intensity is constant in each CV.

$$\frac{1}{\beta_0}\frac{dI(\vec{r},\vec{s})}{ds} = -I(\vec{r},\vec{s}) + (1-\omega_0)I_b(\vec{r}) + \frac{\omega_0}{4\pi}\int_{\Omega'=4\pi} I(\vec{r},\vec{s})\Phi(\vec{s}'\to\vec{s})d\Omega' \tag{4}$$

where κ_a is the absorption coefficient, σ_s is the scattering coefficient, $\beta_0(=\kappa_a+\sigma_s)$ is the extinction coefficient, ω_0 $(=\sigma_s/\beta_o)$ is single scattering albedo, $\Phi(\vec{s'}\to\vec{s})$ is the scattering phase function for radiation from incoming direction to scattered direction, and $I_b(\vec{r})$ is the boundary intensity. Moreover, in this study the method suggested by Chai and Moder[8] is applied to get radiative intensity on the block interface. Applying the condition that radiative heat flux should be conserved, we introduce the relation below [10,11].

$$Q = \left[\int_{\Delta A}\int_{2\pi} I(\vec{s},\vec{n})d\Omega dA\right]_{block\ A} = \left[\int_{\Delta A}\int_{2\pi} I(\vec{s},-\vec{n})d\Omega dA\right]_{block\ B} \tag{5}$$

$$\left[\sum_{j=1}^{J}\sum_{m=1,D_{cj}^m>0}^{M} I_j^m D_{cj}^m \Delta A_j\right]_{block\ A} = \left[\sum_{k=1}^{K}\sum_{m=1,-D_{ck}^m>0}^{M} I_k^m D_{ck}^m \Delta A_k\right]_{block\ B} \tag{6}$$

where M is the number of control angles, ΔA is the area of block interface, and J and K are the number of control volumes along the interface. In Figure 1, the above formulation will be simplified if the interface is same. Also, it is shown below.

$$I_f(x_f, y_f, z_f, \theta, \phi) = I(x_L, y_L, z_L, \theta, \phi), \qquad \vec{s}_f\cdot\vec{n}_f > 0 \tag{7}$$

$$I_f(x_f, y_f, z_f, \theta, \phi) = I(x_R, y_R, z_R, \theta, \phi), \qquad \vec{s}_f\cdot\vec{n}_f < 0 \tag{8}$$

where subscript f indicates the interface. L and R are indices for radiative intensity of both nodes. Also, $\vec{S}_f$ and $\vec{n}_f$ are the direction of radiative intensity and unit normal vector, respectively.

RESULTS AND DISCUSSION

The code has been developed on the basis of the numerical method explained above. Then, this code is applied into a 3D incinerator problem with conditions as followed below. Figure 2 shows the schematic diagram of the incinerator and the four-block grid system. At inlet $\overline{AB}$, the moisture of thrown waste firstly is evaporated. Then, as temperature goes high, the dried waste produces volatile gas, which mixes with air provided through the hoppers. If it is sufficiently heated up, it is then ignited. After finishing thermal decomposition, fixed carbon and nonflammable matters remain in this stoker. The solid combustion takes place by the fixed carbon reacting with oxygen in the air [12]. On the other hand, in Figure 2(a) $\overline{BC}$ is the stoker part of the incinerator where the air is provided for combustion. On the surface, volatile gas is evaporated. In this research, it is assumed that the fuels and oxidizer are premixed. The walls are maintained by constant temperature of 1123K similar with a real incinerator. The outlet boundary condition is implemented by atmospheric pressure. The result is presented in Figure 3, and it has a good agreement with a numerical result from a commercial code called Fluent 5.5. Also, as shown in

Table 1, the mass averaged value in the exit is quantitatively similar with those of the commercial code. According to Figure 3, the temperature distribution is very similar to each other. Additionally, the pressure is maximum below the primary combustion zone because it has a minimum velocity there. Also, the flow passing the zone accelerates because of both the chemical reaction and the decrease of area. When the flow passes the primary combustion zone, the velocity increases and then decreases around the outlet. The velocity distribution results from the change of area. The area decreases due to a recirculation region around the left side of the incinerator, then it increases when the flow adheres to the wall again. For temperature distribution, the high temperature zone exists around the primary combustion zone, and the flame somewhat leans to the right wall. It is caused by the flow pattern generated from the geometry. The high temperature gradient is observed because the radiative heat transfer is not considered.

The CO distribution is relatively important from the viewpoint of environment. Thus, it is interested that the CO value should decrease in the outlet. For the mass distribution and reaction rate of CO, CO distribution is very low in the outlet since most CO reacts with oxygen. But CO_2 is widely distributed inside the incinerator except on the stokers because the reaction happens there. Although the reaction exists on the stoker, the oxygen is much distributed in the combustion zone. The air is supplied more than it is needed for reaction. Hence, in general it is advantageous that the supply of excess air is to lead a complete reaction from the environmental aspect. Much vapor is generated in the part of evaporation, and it almost does not exist passing the primary combustion zone. This phenomenon is very similar with a real case.

Figure 4 shows the temperature distribution between without radiation and non-gray gas radiation. The reaction product of hydrocarbon fuel is very sensitive to the radiation, so it should not be overlooked. In this case, the scattering effect by the product is ignored. For solid fuel combustion flow in a 3D incinerator, the high temperature zone becomes smaller than the case without it due to the radiant energy loss. Additionally, when gray gas radiation is considered, the differences between temperature distributions with and without radiation effect are mainly observed near the exit. However, the radiation effect is observed in all regions when the non-gray gas radiation is included. Figure 5 shows the comparison of the radiative heat flux toward the inlet with different absorption coefficients for gray and non-gray gas radiation. As a result, the radiative heat flux is minimized in the case of non-gray gas radiation. As the gas absorption coefficient increases, the radiative heat flux toward the inlet decreases because the gas plays a role as heat blockage.

CONCLUSION

A 3D multi-block program has been developed to simulate the turbulent reacting flow considering non-gray gas radiation in a 3D complex geometry. In this study, the developed code is validated by comparing the results with those from a commercial package of Fulent5.5. To deal with the interfaces between blocks implicitly, structured grid has been employed. In addition to it, FVM (Finite Volume Method) and WSGGM (Weighted Sum of Gray Gas Model) are introduced to manage the radiative heat transfer mode.

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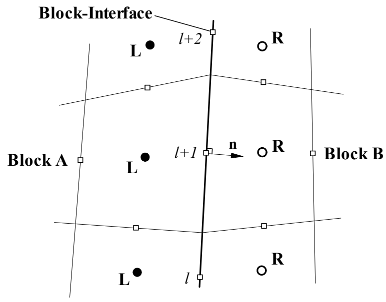
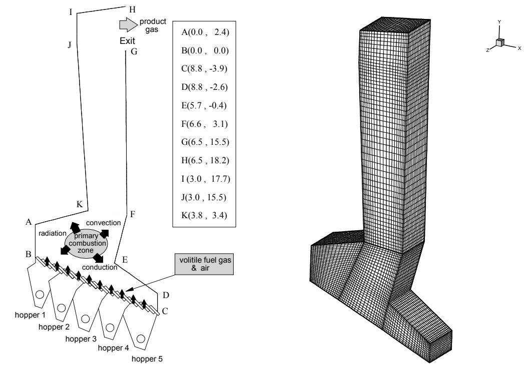


Figure 1 Interfaces between two blocks matching, showing interface CV faces



(a) Schematic diagram (b) 4-block grid system

Figure 2 The schematic and grid generation of the incinerator

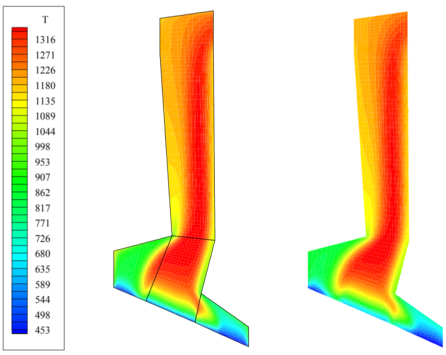


Figure 3 Comparison temperature distribution between (a) developed code and (b) commercial code

Variable	Present	Fluent 5.5
Temperature	1222.412 K	1231.119 K
Fuel 1	1.7626×10^{-10}	2.1002×10^{-10}
Fuel 2	1.7626×10^{-10}	2.1002×10^{-10}
Fuel 3	4.1989×10^{-10}	4.4668×10^{-10}
CO	7.9106×10^{-9}	9.1111×10-9
CO_2	0.172012	0.173162
O_2	0.044422	0.039733
H_2O	0.141033	0.149201

Table 1 Comparison of the mass averaged value at exit of the incinerator

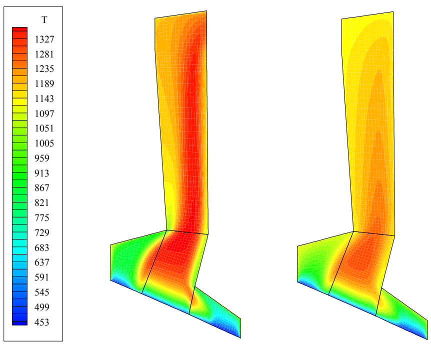


Figure 4 Comparison temperature distribution between (a) without radiation and (b) with non-gray gas radiation

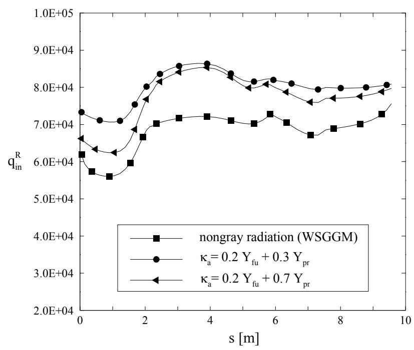


Figure 5 Comparison of the radiative heat flux distribution on the inlet between with gray and non-gray gas radiation