A NUMERICAL SIMULATION OF INFRARED RADIATION OF EXHAUST PLUME

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배기 후류의 적외선 방사 특성 모사를 위한 수치적 연구

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The infrared radiation of exhaust plume was investigated numerically by a finite volume method (FVM) with anisotropic scattering particles. The exhaust plume is considered to absorb, emit and scatter radiant energy isotropically as well as anisotropically. The spatial and spectral distribution characteristics were obtained for the detection wavelength with 2.7μm. The radiative intensities were presented for the different detective direction.

Key Words : Exhaust Plume, Infrared Radiation, Anisotropic Scattering, Finite Volume Method

1. INTRODUCTION

Recently the research on the infrared radiation characteristics of high temperature stream gas flow including particles has led to some interesting application in the area of target detection, combustion diagnosis and temperature measurement of flame. A representative of high temperature stream flow is the exhaust plume in the high-speed exhaust system of an engine.

The research of infrared radiation based on exhaust plume is associated with radiative heat transfer, aerodynamics, infrared physic and chemistry. It is vital to develop the proper simulation technique for the infrared radiation. There are various methods which include zonal method, discrete ordinate method, Monte Carlo method and finite volume method (FVM). Among those methods, the finite volume method for making practical calculations of radiative heating of exhaust plume has been developed recently. Ludwing[1] investigated the standard infrared radiation model (SIRRM) with two-flux scattering and six-flux scattering. Xu[2] calculated the integrate infrared radiation for typical direction and spectral distribution.

In the finite volume method the total solid angle is divided into a discrete number of directions and all directional intensities are calculated by the marching procedure as in the case for flux-type methods. It can be applied to multi-dimensional and complex geometry, anisotropic scattering and variable parameter problems.

In this paper, the two-dimensional exhaust plume field was simulated using the dispersion controlled dissipating scheme. The Al_2O_3 particle scattering coefficients were calculated by Mie method[3], while the spectral absorption coefficients were calculated by using HITRAN and HITEMP[4]. The infrared radiation characteristics of exhaust plume were investigated by the finite volume method with anisotropic scattering particles.

2. THE CALCULATION OF THE EXHAUST PLUME RADIATIVE TRANSFER EQUATION (RTE)

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2.1 RADIATIVE TRANSFER EQUATION

In an emitting, absorbing, and scattering medium, the radiation transfer equation (RTE) can be written as:

$$\frac{dI_\lambda(r,s)}{ds} = -k_{e\lambda} I_\lambda(r,s) + k_{a\lambda} I_{b\lambda}(r,s) + \frac{k_{s\lambda}}{4\pi}\int_{4\pi} I_\lambda(r,s')\Phi(s,s')d\Omega' \tag{1}$$

where $I_\lambda(r,s)$ is the spectral radiation intensity at location r and in the direction s; $I_{b\lambda}(r,s)$ is the spectral radiance intensity of the blackbody. $\Phi(s,s')$ is the scattering phase function of energy transfer from the incoming direction s' to the scattered direction s. Ω' is solid angle. $k_{e\lambda}, k_{a\lambda}, k_{s\lambda}$ are separately denoted the spectral enervation, absorption, scattering coefficient. And, we have

$$S_\lambda = k_{a\lambda} I_{b\lambda}(r,s) + \frac{k_{s\lambda}}{4\pi}\int_{4\pi} I_\lambda(r,s')\Phi(s,s')d\Omega' \tag{2}$$

By combining Equation (1) and Equation (2), we have

$$\frac{dI_\lambda(r,s)}{ds} = -k_{e\lambda} I_\lambda(r,s) + S_\lambda \tag{3}$$

Finally, the radiative energy balance equation for a certain element can be derived as

$$\int_{\Omega=4\pi}\frac{dI_\lambda(r,s)}{ds}d\Omega = -\int_{\Omega=4\pi} k_{e\lambda} I_\lambda(r,s)d\Omega + \int_{\Omega=4\pi} k_{a\lambda} I_{b\lambda}(r,s)d\Omega + \frac{k_{s\lambda}}{4\pi}\int_{\Omega=4\pi}\int_{\Omega'=4\pi} I_\lambda(r,s')\Phi(s,s')d\Omega' d\Omega \tag{4}$$

2.2 THE FINITE VOLUME METHOD FOR THE TRANSFER EQUATION

In order to derive the discretization equation, the Equation (1) is integrated over a control volume $\triangle V$ and a control angle $\triangle\Omega'$ [7] as shown in the Figs. 1 and 2. It is assumed that the magnitude of intensity is constant over a given control volume and a control angle, but its direction may vary.

After integration, the following finite volume formulation can be obtained:

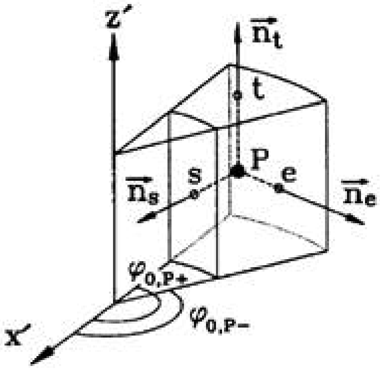

Fig. 1 Infinitesimal control volume

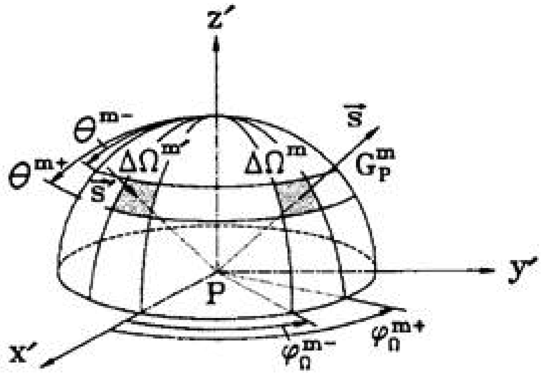

Fig. 2 Angular discretization

$$\sum_{i=1}^{NA} A_i I_{i\lambda}\int_{\triangle\Omega'}(s, n_i)d\Omega' = (-k_{e\lambda} I_\lambda' + S_\lambda')\triangle V \triangle\Omega' \tag{5}$$

where A_i is the control surface and NA is the number of all the control surfaces, $s \cdot n_i$ is the vector due to the solid angle direction and normal vector at the base plane. The Equation (5) indicates that the net outgoing radiant energy out of the control volume must be balanced by the net generation of radiant energy within control volume and control angle.

There have been many schemes which relate control volume face intensity to the nodal intensity [5]. The step scheme was chosen in this study. In this method, the radiation cannot be directly transferred to adjacent element contacting at each corner of the control volume of interest, and thus a certain amount of errors could exit.

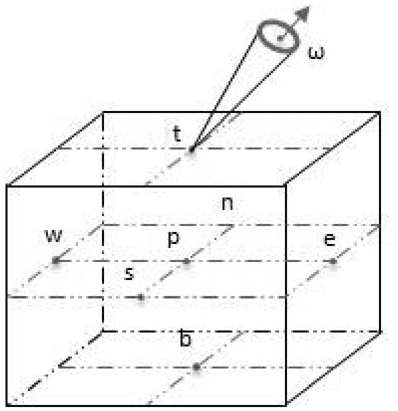

Fig. 3 A control volume in Cartesian coordinates

Using the step scheme, the above equation can be recast into the following general discretization equation for an arbitrary radiation direction

$$a_p' I_p' \lambda = a_I' I_{I\lambda}' + b \tag{6}$$

where

$$a_p' = \sum_{i=1}^{NA} \max(A_i D_i', 0) + [k_{a\lambda} + k_{s\lambda}] \triangle V \triangle \Omega'$$
$$a_I' = \max(-A_i D_i', 0)$$
$$D_i' = \int_{\triangle \Omega'} (s \cdot n_i) d\Omega$$
$$b = S_\lambda' \triangle V \triangle \Omega \tag{7}$$

In the Equation (6), the subscripts $i = w, e, n, s, t, b$ respectively denote the points of control surface. The subscripts $I = W, E, N, S, T, B$ also denote center points of control volume. These discretization equations were calculated by CGSTAB[6].

3. THE CHARACTERISTICS OF THE EXHAUST PLUME FIELD

The temperature flow field of two-dimensional exhaust plume was shown in Fig. 4 for the detective wavelength with $2.7\mu m$.

The scattering phase function $\Phi(s, s')$ was denoted by a finite series of Legendre polynomial. Dispersed scattering phase function was defined as follows:

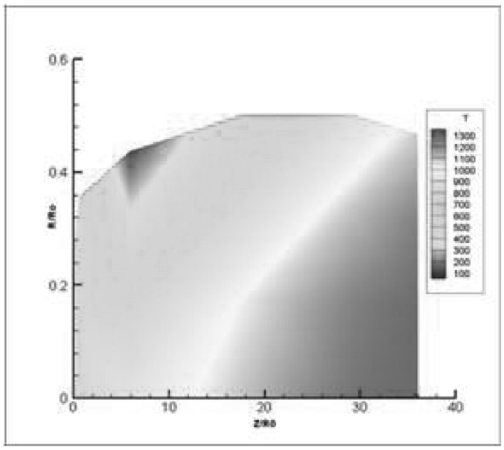

Fig. 4 Temperature distribution of the plume (R_0: nozzle exit radius)

$$\Phi(s, s') = \Phi(\cos\Psi) = \sum_{j=0}^{J} C_j P_j(\cos\Psi) \tag{8}$$

where Ψ is the scattering angle between incident direction, s' and scattered direction s. C_j are the expansion coefficients that depend on the size and refractive index of the scattering particle.

The calculation domain is discretized into $N_x \times N_y = 56 \times 25$ uniform control volume in the x and y directions. The total solid angle 4π is divided into $N_\theta \times N_\phi = 8 \times 10$ directions, where ϕ is the azimuthal angle and θ is the polar angle, ranging from 0 to 2π and 0 to π, respectively. For the case of wall emissivity $\epsilon_w = 0.9$.

4. RESULTS AND DISCUSSION

4.1 THE RADIATION FIELD OF EXHAUST PLUME

The sketch of the calculation zone is given in Fig. 5 where θ is the detective angle between the detective direction and z axial.

The maximum value of the radiation occurs at the nozzle exit because of the high temperature and concentration of Al_2O_3. As the location is further away from the nozzle tip, the value of the radiation is increased. However, after reaching around $30z/R_0$, the value of the radiative intensity does not change significantly because the particles are non-symmetrical along the exhaust plume. The large particles are congregated in the middle region and small ones are

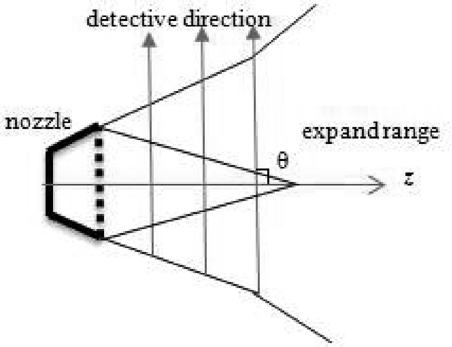

Fig. 5 The sketch of calculation zone of exhaust plume radiation and the direction of detection

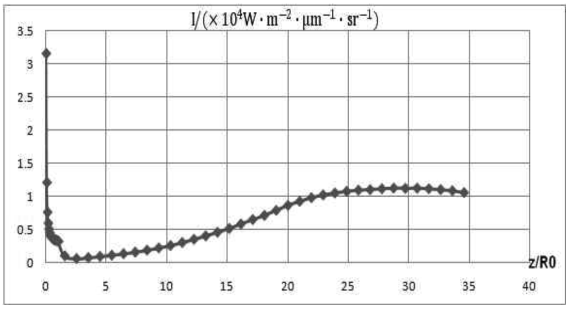

Fig. 6 Radiation field of exhaust plume at $2.7\mu m$

dissociated to the outside region where the temperature is lower than melting point of the aluminium. Those small particles distributed in the outside region are dominant in the infrared signature. In the Fig. 6, the radiative intensities at the end of the exhaust plume are bigger than the region around the nozzle exit. This is due to a secondary ignition (afterburning) where the temperature is higher than that region. Another investigation for different detective angles is conducted as shown in Figs. 7 and 8. As the detective angles θ vary from 30°, the uniform property that the directional radiation is the same at every location was observed.

5. CONCLUSION

The finite volume method has been used to analyze the infrared radiation of high temperature gas flow. The exhaust plume is considered to absorb, emit and scatter radiant energy isotropically as well as anisotropically. The effects of plume cone angle, scattering phase function and boundary conditions are examined in the exhaust plume flow. The particles of the aluminium turn out to be distributed in the outside region. As the location is further away from the nozzle tip, the value of radiation is increased. However, after reaching around $30z/R_0$, the value of the radiative intensity does not change significantly.

ACKNOWLEDGEMENT

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