 ICCES, vol.15, no.1, pp.1-7

Influence of thrust vectoring on radiative heat flux from plume flow

S.N. Lee[1], S.W. Baek[1], K.M. Kim[2], M.J. Yu[3]

Summary

A finite volume method with nongray gases is applied to examine the radiative base heating due to plume which is changed by mechanical deflection. Numerical approaches are made to predict the effect of TVC. The radiative properties within plume flow are modeled with the weighted sum of 4 gray gases. The exhaust plume is considered as an absorbing and emitting medium with no scattering. Flow field is molded with using Preconditioned Navier-Stokes(N-S) algorithms with multi-block. The Geometric Conservation Law(GCL) is considered to compute the nozzle moving mechanism. The radiative base heating is changed by the nozzle deflection angle.

Keywords: Radiation, WSGGM, TVC, AUSM$^+$-up, SST, GCL, Preconditioned

Introduction

While a rocket or a missile is in mission, it is sometimes needed to control its flight path due to indispensable outside disturbance or for a specific purpose.

Thrust Vector Control is a technique to change direction of flight path of the propulsion system. There are some kinds of TVC method. Many researches have been studying to find out the most effective mechanisms. Among them, the adoption of rotating vanes is to directly guide the exhaust gas direction. However, in this case the vanes are openly exposed to the very hot gas. Moreover, it can change the radiative heat flux due to rotation of plume shape. The base heating from rocket exhaust plumes are important and have been widely studied to investigate the radiative effect. While Tien and Abu-Romia[1] considered the exhaust plume as a semi-infinite cylindrical absorbing and emitting gas body, Morizumi and Carpenter[2] developed a scheme to predict rocket base and spacecraft heating. Beak and Kim[3] and Tan et al.[4] researched the base heating due to searchlight and/or plume emission with finite volume and backward Monte Carlo methods. In this report, the base heating is simulated to know the effect of vector control. The exhaust plume is considered an absorbing and emitting medium with no scattering. A numerical simulation was modeled to predict the ability of the thrust vectoring and

[1]KAIST, Daejeon, S. Korea.
[2]ADD, Daejeon, S. Korea.
[3]KARI, Daejeon, S. Korea.

radiative heat flux. To examine the flow field, the preconditioned N-S scheme is used to solve effectively both incompressible and compressible area. AUSM$^+$-up scheme is applied to get a cell face inviscid flux. The grid change by rotating nozzle is simulated using the geometric conservation law.

Schematic of Rocket Nozzle

The schematic of TVC nozzle examined in this work is illustrated in Fig. 1. Nozzle is a submerged shape and consisted of 8 multi-blocks.

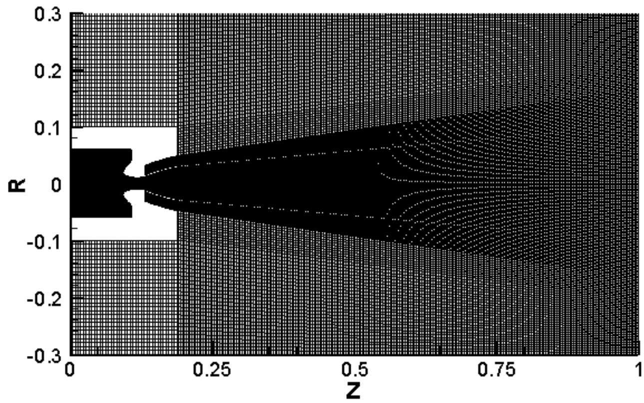


Figure 1: Schematic of Submerged TVC Nozzle

Numerical Formulation

Two-dimensional nozzle is examined here.

The governing equations include the Navier-Stokes, energy and turbulence equation for the gas phase. The gas phase equation for 2-D flow is cast in the following form following Weiss and Smith [5] and Shuen et al [6]

$$\Gamma\frac{\partial Q}{\partial t}+\frac{\partial(E-E_v)}{\partial x}+\frac{\partial(F-F_v)}{\partial y}=S \tag{1}$$

Γ represents the preconditioning matrix which controls the eigenvalues. While E and F are flux terms, E_v and F_v are diffusive terms. S is a source term for turbulence modeling.

$$\Gamma = \begin{pmatrix} \rho_p & 0 & 0 & \rho_T & 0 & 0 \\ \rho_p u & \rho & 0 & \rho_T u & 0 & 0 \\ \rho_p v & 0 & \rho & \rho_T v & 0 & 0 \\ \rho_p H - 1 & \rho u & \rho v & \rho_T H + \rho C_p & 0 & 0 \\ \rho_p \kappa & 0 & 0\rho_T \kappa & \rho & 0 & \\ \rho_p \omega & 0 & 0\rho_T \omega & 0 & \rho & \end{pmatrix}$$

Moreover, to model the rotation of nozzle numerically, geometric conservation law(GCL) is applied into the Preconditioned N-S equation[7]. Ω, means the control volume and v_{gn} is the grid velocity. The S_f is the cell face area. The change of volume is equivalent to the cell face movement rate.

$$\frac{\Omega^{n+1} - \Omega^n}{dt} = \sum_f v_{gn} dS_f \tag{2}$$

1) Inviscid Flux

To get the cell face mass flux and pressure, Advective Upwind Splitting Method(AUSM)$^+$-up[8] is applied here.

AUSM$^+$-up scheme

$$\dot{m}_{1/2} = a_{1/2} M_{1/2} \begin{cases} \rho_L \\ \rho_R \end{cases} \tag{3}$$

$$M_{1/2} = \mu^+_{(4)}(M_L) + \mu^-_{(4)}(M_R) - \frac{K_P}{f_a} \max(1 - \sigma \bar{M}^2, 0) \frac{P_R - P_L}{\rho_{1/2} a^2_{1/2}}$$

$$P_{1/2} = P^+_{(5)}(M_L) P_L + P^-_{(5)}(M_R) P_R - K_u P^+_{(5)} P^-_{(5)} (\rho_L + \rho_R) f_a a_{1/2} (u_R - u_L) \tag{4}$$

3) Radiative Transfer Equation

For a nongray mixture of gases, the radiative heat flux measured on the base plane is defined as the summation of the kth gray band intensity such as

$$q_z = \sum_k^K \int_{\Omega = 4\pi} I_k(r_w, s)(s \cdot n_w) d\Omega \tag{5}$$

Where $I_k(r_w, s)$ is the kth gray band radiative intensitiy at position r_w in the direction s. n_w is the unit normal vector on the base plane and Ω is the solid angle. To predict radiative heat flux for nongray gases, the radiative intensity at the kth gray bands at any coordinate r along a path s through absorbing and emitting can be obtained by the following radiative transfer equation(RTE)[9]

$$\frac{\partial\mu}{r}\frac{\partial}{\partial r}(rI_k)-\frac{1}{r}\frac{\partial}{\partial\phi}(nI_k)+\xi\frac{\partial I_k}{\partial z}=-(k_k+\sigma)I_k+w_k(T)k_kI_b+\frac{\sigma}{4\pi}\int_{4\pi}I_k(s')\phi(S',s)d\Omega' \tag{6}$$

Numerical Simulation

The three cases which nozzle rotation angle is 0, 4° and 8° are compared to predict the radiative heat flux by the TVC performance.

Nozzle inlet condition is set to 20atm, 2500K and 0.025 of mach number. An ambient pressure and temperature is 1atm and 300K. The free stream mach number is assumed to be 0.6. The base is set to constant 300K to get radiative heat flux.

The far field boundary condition is defined by Riemann invariant.

$$R^{\pm}=U\pm\frac{2a}{\gamma-1}$$

$$\bar{U}=\frac{1}{2}(R^{+}+R^{-}),\quad \bar{a}=\frac{(\gamma-1)}{4}(R^{+}-R^{-})$$

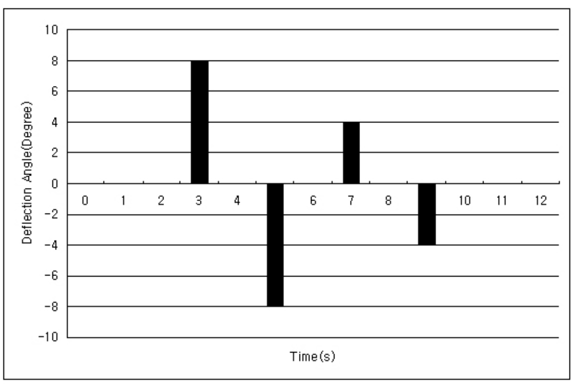


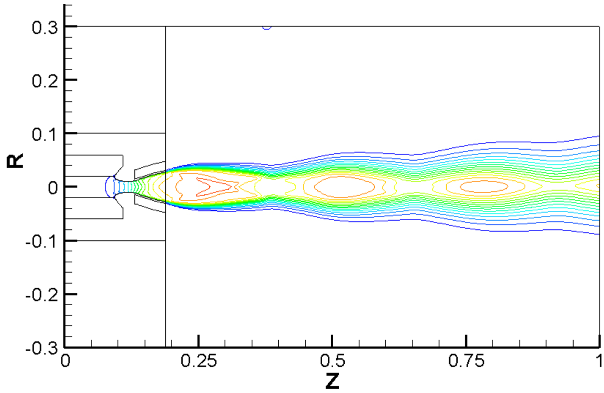
Figure 2: Nozzle deflection signal

The flexible nozzle rotates by input data as time change in Fig. 2.

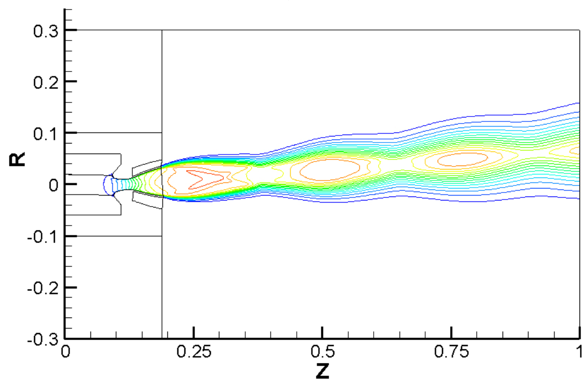
Numerical Result

The plume and base heating by the flexible nozzle is drawn in Fig. 3 and 4.

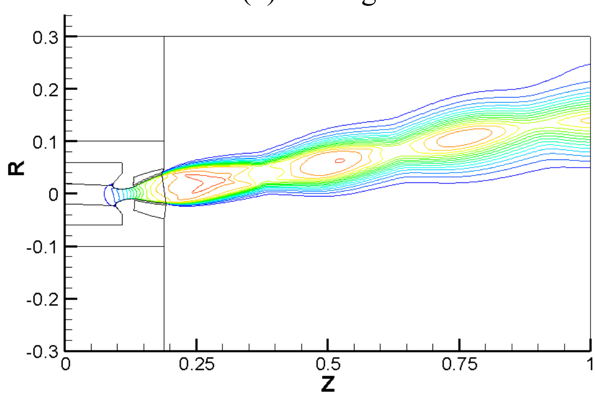
The plume by mechanical deflection in Fig. 3 is changed quickly and equally to the rotation angle of nozzle and there is no change for plume shape.



(a) steady state



(b) + 4 degree



(c) + 8 degree

Figure 3: Plume change by nozzle deflection

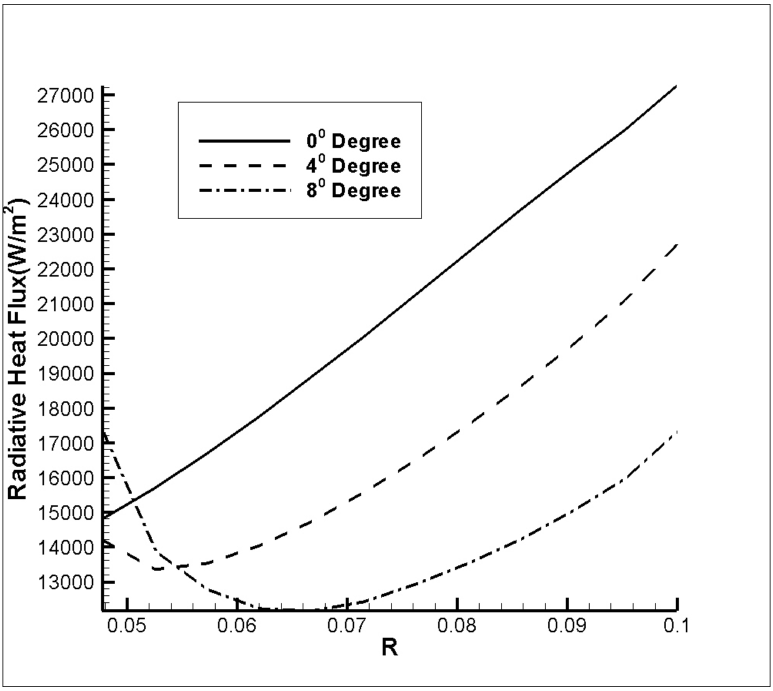


Figure 4: Radiative heat flux by plume change

As shown in Fig. 4, the radiative heat flux is varied by the nozzle rotation angle. As the angle is larger, the heat flux near bottom of base is larger, but it is smaller from middle of base due to change of plume shape.

Conclusion

The preconditioned N-S equation with finite volume method using WSGGM is used to examine the radiative heating by the TVC. The flexible nozzle changes the motion by mechanically. So, thrust also change directly by the deflection angle of nozzle. The radiative heat flux is varied by the angle of nozzle. Average heat flux becomes smaller when the nozzle deflects upward. However, depend on the position of base, the base heating is slightly different. The heat flux at the bottom of base in case of 8odegree is higher than 0° degree as the hot plume gases reach to the bottom closer.

Acknowledgement

This work was supported by grant of System Integration and Development of the Third KOREA Multi-Purpose SATellite of Korea Aerospace Research Institute

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