

NUMERICAL ANALYSIS ON THE FLOW FIELD CHARACTERISTICS OF A MICRO THRUSTER

M.K. Choi¹, J.W. Lee¹, Sejin Kwon²

¹ Pohang University of Science and Technology, Pohang, KOREA

² Korea Advanced Institute of Science and Technology, Daejeon, KOREA

Abstract: In micro-thrusters flow field and thrust are strongly dependent on the boundary layer development and heat loss, so empirical formulas and equations used for the design of macroscopic thruster nozzles are not applicable to micro nozzles. In this study the flow field in a micro-thruster nozzle is analyzed with various factors such as boundary layer growth and heat loss through the nozzle wall taken into account, and as a result obtained important primary factors in the optimal design of a micro nozzle maximizing the momentum thrust. Navier-Stokes equation was directly solved using the commercial software, FLUENT6.3, for a 2D-planar of 200 micron throat diameter.

Key Words: Micro solid propellant thruster, Micro Nozzle, Optimum angle

1. INTRODUCTION

In a variety of micro systems, micro thrusters operating on a variety of propellants provide motion power for main propulsion and attitude or orbit control to micro satellites or micro UAV [1]. A micro thruster using a solid propellant is the commonest type with a number of advantages over other types of micro thrusters: flexibility in propellants, easy size enlargement or reduction, no need for fuel tank/tubing or valves, and no leakage problem. The utmost advantage, however, will be the simple structure, with just four stationary components of simple shapes – propellant, combustion chamber partially filled with propellants, igniter, and the nozzle.

The supersonic nozzle is the key element in every thruster. In a micro thruster, the thruster nozzle is small with the throat diameter of a few hundred microns and the overall length of a few mm. In such a small nozzle, the boundary layer occupies a substantial portion of the cross section, and the heat loss through the nozzle wall is also substantial because each propulsion is maintained for just a very short duration. Then the empirical formulas obtained for macro thrusters do not hold good for the micro thrusters, and the most fundamental energy equation assuming an isentropic expansion is no more valid. The anisotropic condition due to heat loss should affect the boundary layer growth and the free stream velocity.

Since the thrust of a micro thruster nozzle is thought to vary quite sensitively to small changes in geometric parameters, a number of studies have investigated the characteristics of flow field and thrust for micro thruster nozzles. However, most studies considered only either of the viscous or heat loss effect, and it is the objective of this study to analyze the flow characteristics in a micro thruster nozzle from the view point of obtaining the optimum nozzle shape with both the viscous boundary layer and heat loss effects considered.

2-D planar with a straight wall were analyzed using FLUENT 6.3, the commercial software. Nozzle throat diameter was fixed at 200 microns, and the expansion angle and length were varied

2. NUMERICAL METHODS

Computation domain was taken at least 15 times as large as the nozzle after trying a number of different domain sizes, in order to minimize the potential errors coming from the domain boundaries. The number of grid points ranged 18,000~30,000 depending on the nozzle used, and grids were made more densely populated near the throat and nozzle wall so that the boundary layer and the supersonic velocity development could be accurately simulated. Schematic of the grids near the throat is shown in Fig. 1, and air was used as the working fluid.

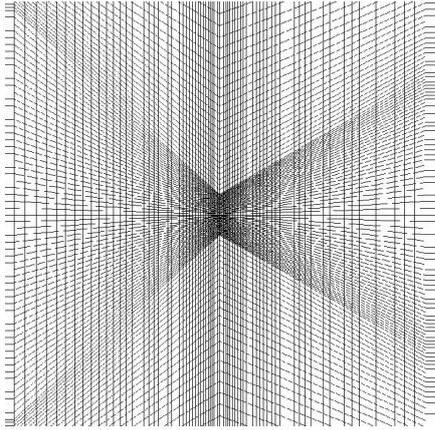


Fig. 1: Schematic of the grids near the nozzle throat.

3. RESULTS AND DISCUSSIONS

3.1 Effective Throat Area

When a constant mass influx was imposed at the chamber inlet, the stagnation pressure varied, decreasing with increased nozzle angle by as much as 10% at 45°. (Fig. 2) Same trend is observed both for viscous and inviscid fluid, and it is caused by the change in the effective throat area, A^* .

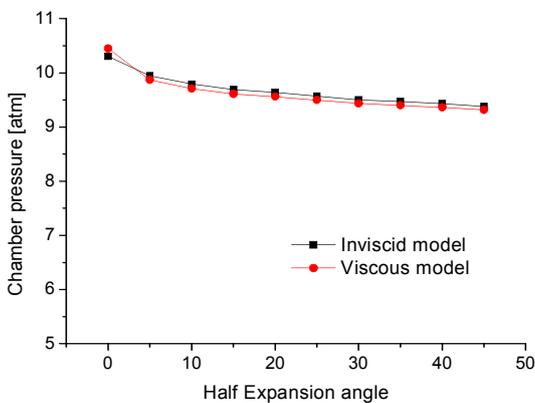


Fig. 2: Variation of the chamber pressure with nozzle angle at the same mass influx condition.

When the position of the throat ($M = 1$) on the nozzle axis is plotted, it was always formed in the divergent section and moved closer to the geometric throat with the increase of nozzle angle. (Fig. 3) Mach number contours for the subsonic and sonic regions (Fig. 4) clearly show the shape of the sonic plane and the change of its position at different nozzle angles.

The effective throat area A^* is larger than the geometric throat, the larger for the larger angle. Then the chamber pressure becomes smaller, and decreased A_e/A^* will result in a decreased Mach number at the exit. (Fig. 5)

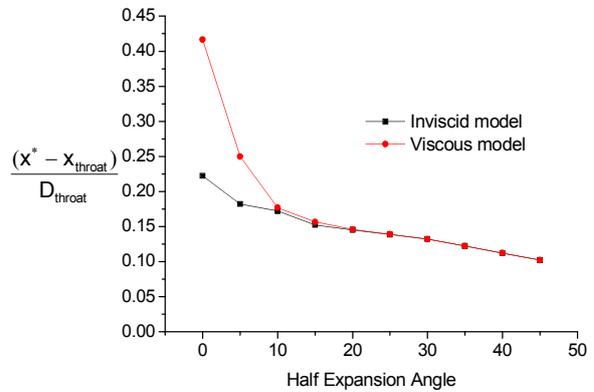


Fig. 3: Choking position on the centerline.

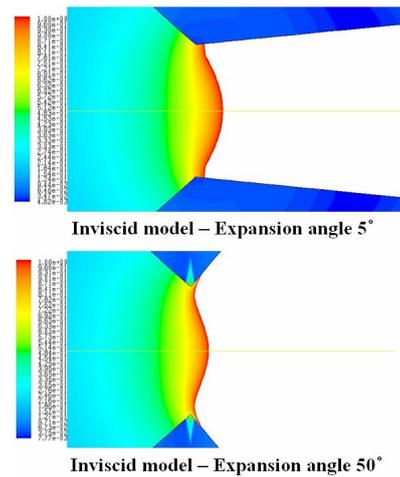


Fig. 4: Mach contours for the subsonic and sonic regions at two different nozzle angles.

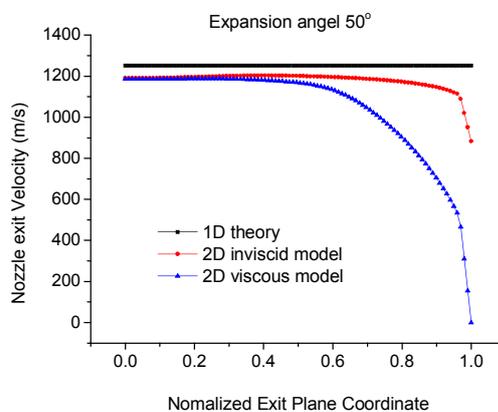


Fig. 5: Velocity profile at the nozzle exit.

3.2 Correction factor α (average flow direction)

Of various 2D effects on thrust the effect of flow angle at the exit can be reflected using a correction factor as shown in Eq. (1). Conventional theory for a macroscopic nozzle adopted $\alpha = 0.5$, Eq. (2). [2]

$$\text{Thrust} = \left[\int_{\text{exit}} \rho V_x^2 dA \right] = \cos^2(\alpha\theta_w) \left[\int_{\text{exit}} \rho V^2 dA \right] \quad (1)$$

$$\lambda = \frac{1}{2}(1 + \cos \theta_w)$$

$$\cos^2(\alpha\theta_w) = \frac{1}{2}(1 + \cos 2\alpha\theta_w) \quad (2)$$

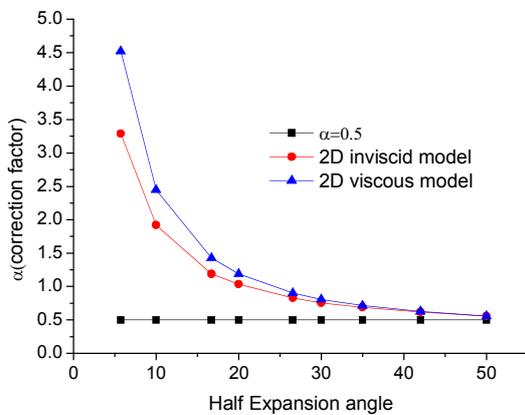


Fig. 6: Correction factor for a micro nozzle.

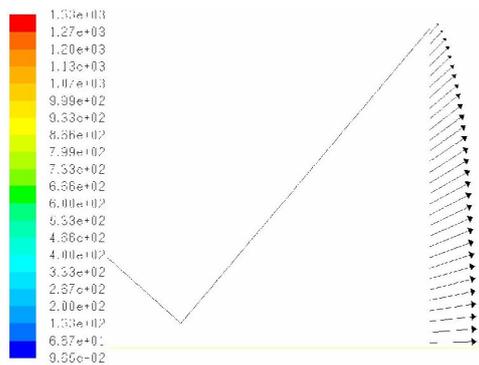


Fig. 7: Distribution of flow direction at the exit of a nozzle with 50° .

When α is calculated from the thrust obtained by a 2D simulation for a micro nozzle, however, it is always larger than 0.5, approaching the conventional value only at a very large angle of 50° . (Fig. 6) The discrepancy observed for a micro nozzle can be attributed to two factors: 1)

decreased Mach number compared to the 1D theory due to the decreased A_e/A^* , and 2) real flow direction at the exit is larger than is expected based on the wall angle as is shown in Fig. 7. The flow angle at the exit becomes larger in the presence of the boundary layer, and this discrepancy is larger at the smaller angles.

3.3 Effect of heat loss

The effect of heat loss may be substantial to a micro nozzle. While existing studies defined wall temperatures [3], we defined wall material and environmental temperature, instead. As is clearly shown in Fig. 8, the effect of viscous boundary layer on thrust is very small, but the effect of heat loss is quite large, amounting up to 6~10% depending on the ambient temperature.

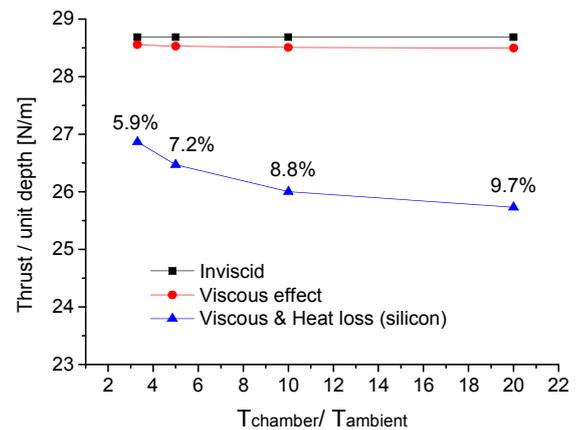


Fig. 8: Effect of heat loss on thrust.

3.4 Optimum nozzle shape

Thrust consists of two terms, one from the momentum efflux of propellant flow and the other from the pressure difference between inside and outside of the nozzle.[4] Of the two contributions, the momentum thrust is the dominant one.

In this study the optimum nozzle expansion angle was sought using a number of different approximations. Optimization was tried in two steps: first, the ratio of the exit area to the throat area (A_e/A_t) was varied at a fixed length to optimize the flow direction and then nozzle length was varied again to take into account the secondary effect of the boundary layer growth on the flow direction.

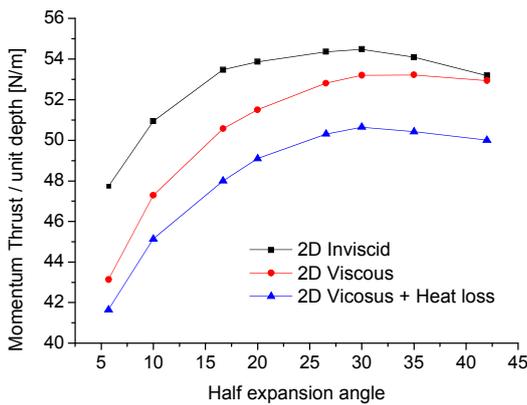


Fig. 9: Momentum thrust versus nozzle angle for a 2D-planar nozzle.

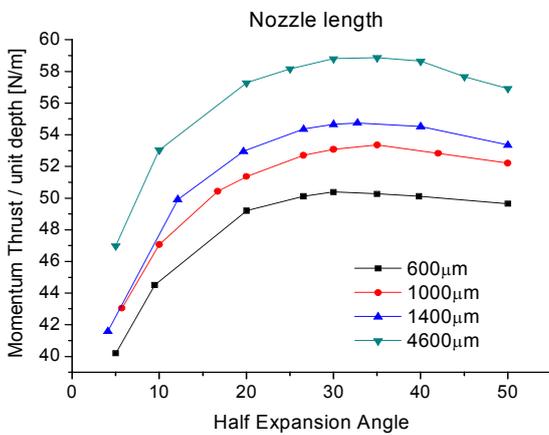


Fig. 10: Momentum thrust for various nozzle angles and lengths for a 2D planar nozzle.

Thrust obtained by a 2D Inviscid model is still overestimated due to the negligence of the boundary layer. The discrepancy between the “2D Inviscid” and “2D Viscous” comes from the existence of the boundary layer. From the figure it is implied that the effect of flow direction is the major cause of error in the estimation of thrust for a micro nozzle. The use of correction formula obtained for the macro nozzle overestimates the thrust by 15%, and the negligence of the boundary layer gives an additional 5%. The effect of heat loss is almost negligible.

Various effects on thrust result in changes to the optimum nozzle expansion angle. 2D Inviscid model gave 30° as the optimum angle for the 2D-planar nozzle, but the 2D Viscous model gave a little larger value of 35° . The larger angle required for a maximum thrust with the viscous model

looks reasonable, because the boundary layer occupies a larger fraction of the nozzle in a micro thruster, thus a larger angle is needed to maintain a required degree of effective expansion. When the nozzle length was varied, the optimum expansion angle remained almost the same over a wide range of nozzle length and total area ratio (A_e/A_t), in so far as the flow remained fully attached to the nozzle wall. (Fig. 10).

4. Conclusions

(1) In a micro thruster nozzle, the position and area of the effective throat varies with nozzle expansion angle, resulting in a decreased area ratio and mach number at the exit, the more at the larger angle.

(2) Correction factor for the thrust is always larger than that for a macro nozzle.

(3) Effect of heat loss is substantial, amounting up to 6-10% reduction in thrust.

(4) There exists an optimum nozzle angle, which is about 35° for a 2D planar nozzle.

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