STUDY GAS FLOW HEATING IN MICRO-NOZZLE THROUGH WALLS INSTEAD OF PREHEATING

Amar H. Hameed
Mechanical Engineering Department
KTO Karatay University
Konya, Turkey
E-mail: dr.eng.amar@gmail.com

ABSTRACT

Previously, Preheating has been established in micro-nozzles to increase the specific impulse of thrusters and increase thrust level. However, heating may cause higher viscous losses in micro-nozzles working at low Reynolds numbers. In this work, heating is combined with gas expansion by using heated walls for convergent-divergent micro-nozzle. The flow in 2D micro-nozzle with heat generation inside the side-walls has been numerically simulated and analyzed. A wide range of low Reynolds numbers flow is tested to investigate the effect of flow parameters. A range of diverse amounts of heat fluxes is also examined to study the effect of heat flux intensity and distribution. Heat evolving in a micro-nozzle wall shows improvement of thrust level and specific impulse due to an increase in both gas density and pressure generally. However, there is a loss in exit velocity and increase in the thickness of the subsonic boundary layer. It is observed that heat transfer can improve the performance of the nozzle as that happens in preheating, due to lower gas temperature at expansion region. The effect of heating looks more significant at lower Reynolds numbers flow investigated.

Keywords: low Reynolds number flow, Micro-nozzle, micro-thruster, micro-propulsion, MEMS-based thruster.

INTRODUCTION

Nowadays, the need of extremely precise impulse for maneuvering the new generation of micro and nano-satellites is growing. Micro-nozzles with throat size of few hundred microns or below were fabricated. The flow in a MEMS supersonic micro-nozzle can be substantially affected by viscous effects. For various microscale nozzles reported in the literature, the Reynolds numbers are relatively low; typical values are well below 1000 and some are less than 100. As such, the magnitude of viscous losses can be significant. In the diverging nozzle section, a viscous subsonic layer may extend a sufficient distance away from the wall so as to retard the bulk flow and reduce efficiency. Louisos, W. F. and Hitt, D. L. [1] investigated a steady viscous flow through a two-dimensional supersonic linear micro-nozzle, they conducted the numerical solution for range of Reynolds numbers and for expander half-angles of 10-50 deg, they found that using an expander angle larger than the traditional angle of macro-nozzle can compensate for the presence of the viscous subsonic layer.

Nomenclature

A	[m^2]	Cross section area
I_{sp}	[s]	Specific impulse
Kn	[--]	Knudsen Number
L	[m]	Characteristic length
M	[--]	Mach number
p	[N/m^2]	Pressure
R	[J/Kg.K]	Gas constant
Re	[--]	Reynolds number
T	[K]	Temperature
u	[m/s^2]	Velocity
Special characters		
γ	[-]	Specific heat ratio
ρ	[kg/m^3]	Gas density
$\dot{m}$	[kg/s]	Mass flow rate
μ	[N.s/m^2]	Dynamic viscosity
π	[-]	Constant ratio
τ	[N]	Thrust
Subscripts		
exit		Exit section
∞		Ambient

Improvements to the specific impulse were achieved through a combination of decreasing the nozzle length and increasing the nozzle expansion angle for low Reynolds numbers by [2]. The thick viscous layer growing from the sidewall in the micronozzle as the low Reynolds number effect in low-pressure measurement interacts with the shockwaves to induce a series of compression waves and a _-shock wave, as demonstrated by [3], instead of showing a pressure jump pass through a shock wave, the pressure gradually increases when passing through the _shock structure. They investigated that experimentally by the image visualization of supersonic flow at convergent-divergent micronozzle with various total pressure and Reynolds numbers. Xu, J. and Zhao, C. [4] stated that, the viscous boundary layer thickness relative to the whole nozzle width on the exit plane is increased but attains the maximum value around of 0.5 and oscillates against this value with the continuous increasing of the nozzle upstream pressures. Hitt, W. F. and Louisos D. L. [5][5][5] found that an inherent trade-off exists between viscous losses and losses resulting from non-axial exit flow at large expansion angles. They also found that, viscous effect are more pronounced in 3D owing to the flat plate side-walls in the depth dimension, they also found that, heat loss from the flow acts to reduce viscous effects and the corresponding size of the subsonic boundary layer thus increasing micro-nozzle performance. Alexeenko, A. A., et al [6] predicted the importance of wall temperature in the micronozzle system; they studied time dependent performance of a high-temperature MEMS-based thruster by a coupled thermal fluid analysis of gas and walls. They found that the temperature inside the solid material approximately increases uniformly with very small changes owing to Biot number smaller than unity. They also found that the predicted thrust and mass discharge coefficient of both two dimensional and three dimensional micronozzles decreases in time as the viscous losses increases for higher wall temperatures for two different chamber pressures in different outer thermal boundary conditions, their results of effect of wall temperature on performance are agreed with the results of [5][5][5]; heat losses from the high temperature gas decreases with time due to raising wall temperature and so viscous effects increases. This research is not repeating studying the relation between gas heat losses and nozzle performance, heat is supplied from nozzle wall toward gas and it increases the heat content of gas, heat is one form of energy may convert to momentum forces to increase the thrust. Current work is analyzing the performance of the nozzle in addition to changes in properties of flow when heat is generated within the wall and rejected to the gas during its expansion inside nozzle.

The intent of this study is to submit an expected solution to enhance the performance of micronozzle without increasing the pressure of the propellant reservoir. Increasing the chamber pressure requires a bigger and heavier system; however this is not desired in nano- and micro-satellites. The energy planned to be supplied to enhance the efficiency of the propulsion system is taking another form, in the space another forms of energy are more likely to be available, such as the solar energy and the generated electrical power from solar energy. Designing a system supplying thermal energy across side wall to gas in order to increase the thrust of micronozzle without increasing the stagnation pressure of the system is the aim of this research. In addition to that, heating fins used previously for preheating in micronozzles increase the friction losses of gas [7], however it seems to greatly improve the system performance as much as mass flow rate reduced [7]. Heating is studied here to be performed through side walls of the nozzle without using any heating fins. Many configurations of wall heating are tested, heating is supplied through the entire wall or through a portion of the wall of convergent-divergent micro-nozzle; the thrust and the properties of the flow are studied accordingly.

COMPUTATIONAL MODEL

The computational domains are based upon the typical nozzle geometries of the micro-thruster prototype developed at NASA GSFC and described by [5]. The expander half-angle is fixed at 15 deg. The two dimensional meshes have been developed using GAMBIT 2.4.6 grid generation software. The nozzle inlet, throat, and exit dimensions are 1103.1 μm, 90 μm, and 560μm, respectively, which yield an area expansion ratio of 56:9. The span from inlet to throat of the prototype is 506.5 μm. The mesh has been changed in size horizontally and vertically to find the better mesh size. All of the mesh elements within the nozzle are quadrilateral, and outside exit plane mesh elements are unstructured quadrilateral with a maximum skewness of 0.65. The planar symmetry is also used to reduce the computational expenditure as shown in Figure 1. In developing the final meshes, a systematic grid refinement study has been undertaken to ensure that all results are insensitive to further grid refinement. The refinement study examined grid insensitivity at both the centerline and near wall of the flow regime at the exit section as has been discussed in [8].

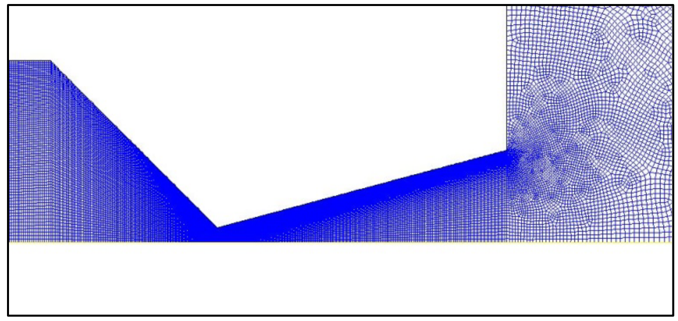

Figure 1 Typical mesh of modeled micro-nozzle.

Governing Equations and Boundary Conditions

The steady state conservation of mass, x-momentum, y-momentum, and energy coupled with an ideal gas state equation ($p=\rho RT$) are solved in the two-dimensional domain of micronozzle. The viscous dissipation term in the energy equation has not been considered. However it may have a significant role, principally in low Reynolds numbers. It has been ignored here to highlight the effect of wall heating and cooling on the main flow properties, yet its effect in our problem can be proposed for further studies. Owing to the significance of viscous losses in the hot gases, the monopropellant gas hydrogen peroxide (H_2O_2) decomposed at high temperature considered by [1] is considered here. The inlet gas temperature of the micronozzle is assumed to be that of the fully decomposed adiabatic flame temperature of 85% pure decomposed H_2O_2 (886 K). The decomposition of the H_2O_2 occurs upstream of the micronozzle in a catalytic chamber.

The molecular weight and other constant and variable thermo-physical properties for the resultant decomposed propellant, which is treated as a homogeneous mixture, are calculated using the mass fractions of each individual component found from the reaction formula [1]. Viscosity is assumed to be constant for some cases to distinguish the changes via temperature for the other properties rather than variable viscosity. The constant viscosity corresponds to the average of the inlet and the exit temperatures obtained from one dimensional flow analysis. The variable viscosity is calculated by the FLUENT software according to Kinetic-Theory for each individual component of the propellant, and then the mixture viscosity is calculated via the mass fraction of the gases.

The inlet static pressure is calculated from the proposed inlet stagnation pressure using the relations of one-dimensional flow analysis. Both static and total inlet pressures associated with the stagnation decomposition temperature compose the inlet boundary condition for the cases denoted by ‘specified stagnation pressure’ cases. For ‘specified mass flow rate’ cases, stagnation decomposition temperature and mass flux compose together the inlet boundary condition, while the software disregards the input value of static pressure for subsonic flow. The velocity has uniform distribution at the inlet section which is true physically if the inlet section is connected upstream to a relatively large chamber. The ambient pressure (p_{∞}) stands for the outlet pressure on the horizontal and vertical far fields which locate away from the exit section of the micronozzle. The no-slip condition at the wall is assumed for the present calculations. Knudsen number obtained according to the equation below shows values of *Kn* below than (0.01), where Mach number (*M*) and Reynolds number (Re) are obtained from the simulation.

$$Kn = \sqrt{\frac{\gamma\pi}{2}}\frac{M}{\mathrm{Re}} \qquad (1)$$

Reynolds number changes with mass flow rate $\dot{m}$, which is considered with the characteristic length *L*, dynamic viscosity μ, and flow area *A* to define the Reynolds number as;

$$\mathrm{Re} = \frac{\dot{m}L}{\mu A} \qquad (2)$$

Reduction of stagnation pressure or mass flow rate reduces Reynolds number, which subsequently increases *Kn* number to be higher than 0.01. However, the continuum assumption is not applicable to this order of *Kn* as the Knudsen number, based on the throat size, grows several order of magnitude at the nozzle exit, as stated by [9]. Louisos and Hitt (2008) proved that differences in the thrust between no-slip and first order slip condition for highly polished silicon are at most 1.5% at the extremely low Reynolds number of 15. They stated that the assumption of no-slip conditions is still applicable to (Re=15) even the average Kn, which has been computed along the length of the expander wall, reached 0.0548 arguing that in an actual device; the presence of surface roughness would reduce the impact of slip. The thermal boundary condition of the wall plays the most important role in this work. To inspect more realistic heat exchange technique, a uniform wall with heat source to be developed to the gas by forced convection is tested under different conditions of uniform power generation. The uniform power has fixed positive value along the x-axis which is denoted by ‘Heated sidewall’.

The motivations behind studying the heated side wall are;

- Heat may convert to beneficial momentum greater than the increased viscous losses.
- Subsonic layer near the wall occupies a large portion of the divergent wall, and it may be accelerated significantly by heating.
- The fabrication of electrical resistance as a side-wall is easier and cheaper than that for thermoelement.

Micronozzle Performance

In this section, we are concerned with calculating thrust production, mass flow rate, and nozzle specific impulse for the cases studied. The thrust is properly evaluated from the simulation data according to;

$$\tau = \int_{A,exit} \rho u (u.n) dA + \int_{A,exit} (p_{exit} - p_{\infty}) dA \qquad (3)$$

The specific impulse, I_{sp} represents the amount of thrust produced to the weight flow of the propellants. It is a measure of the fuel efficiency of a nozzle [10][9]. It can be obtained from:

$$I_{sp} = \frac{\tau}{\dot{m} g_o} \qquad (4)$$

Where; τ is the calculated thrust, *N*, $\dot{m}$ is the real mass flow rate reported from the simulation, kg/s, and g_o is the gravitational acceleration at sea level on earth equal to 9.807 m/s². The specific impulse efficiency is the ratio of numerical specific impulse I_{sp} calculated from equation (4) to the optimum (theoretical) specific impulse I_{sp}^{optim}, which is calculated from the one dimensional solution, [11][10];

$$\eta_{sp} = \frac{I_{sp}}{I_{sp}^{optim}} = \frac{\tau / \dot{m} g_o}{\sqrt{\frac{2\gamma R T_o}{g^2(\gamma - 1)}}} \qquad (5)$$

RESULTS AND DISCUSSION

Thrust is calculated at the exit section of the nozzle for many values of Reynolds number. For each Reynolds number four diverse amounts of heat generation rates are tested to examine the effect of increasing heat generation rate on the performance of micro-nozzle. Figure 2 shows the thrust results for Reynolds numbers 400, 600, 800, and 1000. For each Reynolds number flow, heat generation rate is selected to be; 0, 3, 5, and 10 to cover wide range of wall heating. The results show generally little increase of thrust level between 2.75% to 3.70%. By the definition of thrust as in equation (3), thrust can be broken into two parts; momentum thrust which is a function of exit velocity and pressure thrust which is a function of exit static pressure. However the changes in total thrust are not significant, but the changes in exit static pressure seem to be more significant especially at high Reynolds numbers as shown in Figure 3. Static pressure increasing extents over than 1300 *pa* for the flow of 1000 Reynolds number due to the raising of static temperature of the flow. At low Reynolds number 400, the static pressure fluctuates between decreasing due to overcoming of friction losses and increasing due to dominating of molecules movement. High changes in static pressure have been conflicted by the reduction of exit velocity due to the effect of thicker boundary layer. So, the changes in total thrust have not been got the expected impact. The specific impulse is in contrast with total thrust shows important changes with heating rate especially for low Reynolds numbers. Specific impulse is generally improved by wall heating, while further heating is not always improve the specific impulse for low Reynolds number of (400) as shown in Figure 4.

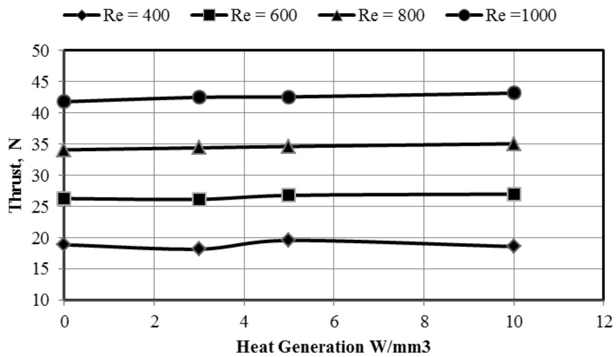

Figure 2 Thrust level at nozzle exit section for different Reynolds numbers and different heat generation rates.

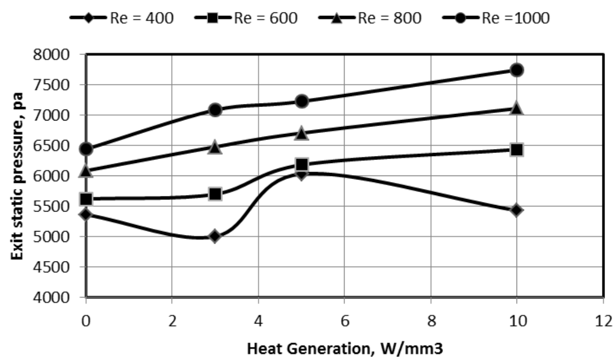

Figure 3 Exit static pressure for different Reynolds numbers and different heat generation rates.

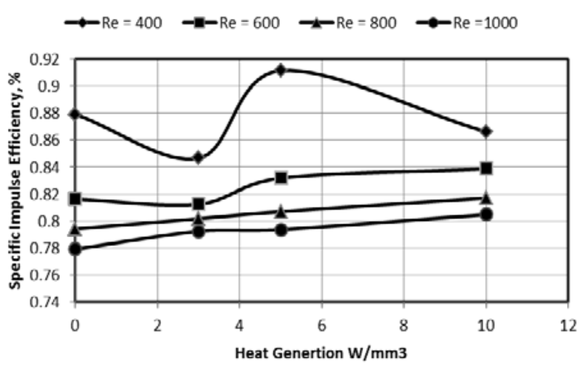

Figure 4 Specific impulse efficiency for different Reynolds numbers and different heat generation rates.

CONCLUSIONS

The results prove that not only the preheating can increase the thrust, but the heating of the entire wall can improve the thrust and specific impulse. Heat can be added more effectively through the divergent wall of the nozzle due to high temperature drop at the expander and higher temperature difference. Several amounts of transferring heat to gas through the wall are tested for several Reynolds numbers. Thrust levels generally improved fairly with increasing wall heating generation rate. Exit static pressure knowingly increases with heating rate for flow with high Reynolds number. The main measurement of nozzle performance; specific impulse is improved with heating rate. Specific impulse efficiency increases by about 2.5% in high Reynolds number.

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