Numerical Investigation of Micronozzle Performance for Various Nozzle Geometries

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Abstract— ***Design and manufacture of thrusters for producing very low thrust force in the range of milli or micro newtons using micronozzles have been actively developed in the last decade. The nature of propellant flow in such micronozzles are different compared to macro nozzles. In micronozzle viscous effect dominates, hence the flow is always in laminar regime with high viscous losses. Objective of this paper is to address these issues in micronozzle flow of vapour and also to compare the performance of micronozzle for two different nozzle geometries. In this paper numerical study of the flow of water as propellant in vapour phase inside a 3D micronozzle by solving Navier stoke's equation with no slip boundary condition and equation of energy conservation. The computational model is validated with available experimental data in the literature. The computations are performed for different mass flow rates with inlet vapour temperature kept constant as 600K. Different output parameters of both nozzle geometries are compared and the boundary layer effects are also quantified.***

Index Terms—**micronozzle, micro thruster**

Nomenclature

VLM	Vapourizing liquid microthruster
Ar	Ratio of nozzle exit area to throat area.
ρ	Density (kg/m^3)
u	Velocity Vector (m/s)
p	Pressure (Pa)
τ	Viscous stress tensor (Pa)
F	Volume force vector (N/m$^{3)}$
C_p	Specific heat capacity at constant pressure (J/(kg.K))
T	Absolute Temperature (K)
q	Heat flux vector (W/m^2)
Q	Heat Sources (W/m^3)
S	Strain-rate tensor
T_f	Thrust force (mN)
m^*	Mass flow rate (mg/s)
v_e	Exit velocity of vapour (m/s)
Rs	Specific gas constant (J/(kg.K))
P_{in}	Inlet Vapour Pressure (Pa)
U_{in}	Inlet Vapour Velocity (m/s)
M_{in}	Inlet Mach No
γ	Ratio of specific Heats
A_{in}	Inlet area of Nozzle (m^2)
Tin	Inlet vapour temperature (K)

Introduction

In the recent years significant studies have been conducted in the area of micro-propulsion systems. The need to miniaturize the propulsion system has attracted worldwide attention since this aspect is applicable to many areas like space missions, terrestrial, security and biomedical applications. In the case of space applications the micropropulsion systems are used to Position the space vehicle in particular orbital location. In the past few years a number of various micropropulsion systems were proposed and tested by many researchers around the world, Vapourizing liquid microthruster (VLM) attracted the research community the most due its simple design and operation. Over the last few years, the concept of VLM have been widely studied by different researches by using various propellants such as water, ethanol, hydrogen peroxide [1-9]. VLM consists of a microchannel, propellant inlet, vaporizing chamber, heating resistor, and micronozzle. The propellant in liquid phase is heated inside the vapourizing chamber using micro heater, which might be embedded or thin film coating on the surface of the thruster. The vapourized propellant is then expanded through a micronozzle to produce thrust in the opposite direction. Since the VLM does not contain any moving parts, its design seems to be very simple and is easy to fabricate. In almost all the papers published in the past, majority of the studies were experiments. Researches like D.K. Maurya et.al

[2] suggested analytical model of VLM in earlier stage of development of VLM, but the model fails to explain about viscous effect in micronozzle. Due to the dominance of viscous effect in micronozzle the actual thrust force will be slightly lower than the theoretical value. In this paper a 3D computational fluid dynamics (CFD) analysis was carried out to analyze the flow characteristics inside the micronozzle for different nozzle geometries such as pyramidal, conical using Comsol multiphysics R 4.3b.

Numerical Model

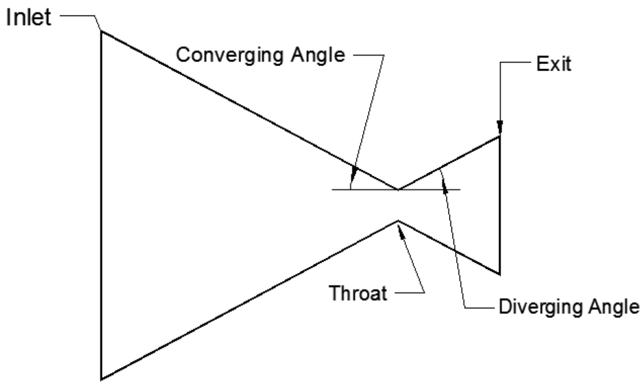


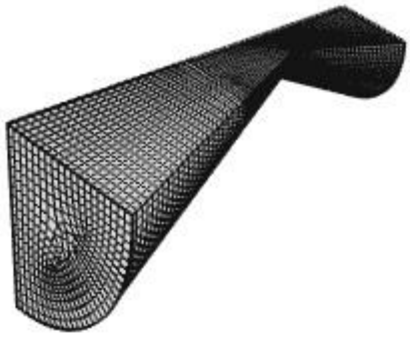
Fig.1 2D Schematic View of the Micronozzle

Table.1. Parameters of numerical model

Parameter	Value
Inlet Area	0.23 mm^2
Throat Area	0.01 mm^2
Exit Area	0.05 mm^2
Converging Angle	28[deg]
Diverging Angle	28[deg]
Inlet Mach No	0.0254
Inlet to exit Pressure ratio	40.34
Mass Flow Rates	0.2[mg/s] – 2[mg/s]
Inlet Temperature	600[K]

The 3-D model of the micronozzle is discretized using structured mesh, as for fluid flow analysis hexagonal structured mesh is more suitable. More refinement in the mesh is made at the diverging section of the nozzle, since both velocity and temperature gradient is very high in this region. If the meshing is not refined enough, the mass flux at different cross sectional areas will vary and this affects the accuracy of the results. Mesh convergence study was conducted by varying the number of elements across the model. The meshes have been refined to the point where simulations are independent of further mesh refinement. Complete mesh consists of 30212 domain elements. Water is used as the propellant, as it is the most commonly used propellant in VLM.

(a)



(b)

Fig.2. Meshed quarter models of micronozzles
(a) Pyramidal (b) Conical

The continuity equation is

$$\nabla \cdot (\rho \mathbf{u}) = 0 \quad (1)$$

Momentum Equation is as follows

$$\rho(\mathbf{u} \cdot \nabla)\mathbf{u} = \nabla \cdot [-p\mathbf{I} + \tau] + \mathbf{F} \quad (2)$$

Energy equation is as follows

$$\rho C_p \, \mathbf{u} \cdot \nabla T = -(\nabla \cdot \mathbf{q}) + \tau:\mathbf{S} - \frac{T}{\rho}\frac{\partial \rho}{\partial T}\bigg|_p (\mathbf{u} \cdot \nabla)p + Q \quad (3)$$

Thrust force equation

$$T_f = m^* * V_e * 10^3 \quad (4)$$

Inlet Pressure:

$$P_{in} = (m^* * Rs * Tin) / (A_{in} * U_{in}) \quad (5)$$

Inlet Velocity:

$$U_{in} = M_{in} * \sqrt{\gamma * Rs * Tin} \qquad (6)$$

Results and Discussions

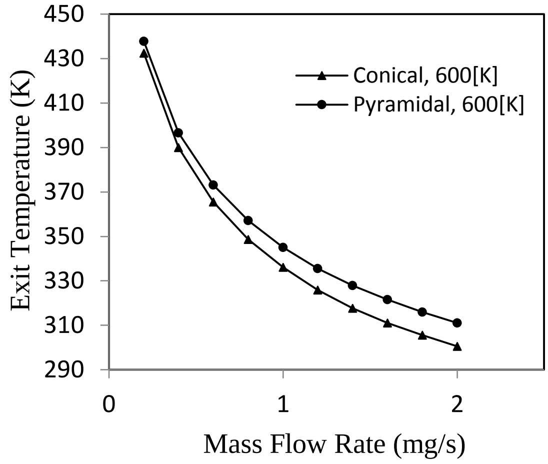


Fig.3. Plot of Mass flow rate versus Propellant temperature at the exit of the nozzle.

Fig.3 shows the propellant temperature at the exit of the nozzle. In the case of the conical nozzle the temperature is lower than that of pyramidal nozzle. The variation is due to the difference in the actual expansion ratio of the nozzle. The actual expansion will be sligtly lower than the theorectical value, since viscous effect is not taken in to account for theoretical calculations.

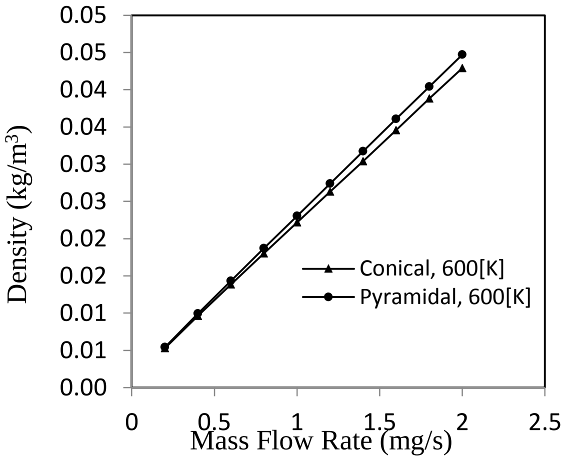


Fig.4 Plot of Mass flow rate versus Propellant density at the exit of the nozzle

Variation of density of the vapour at the exit of the nozzle is plotted in fig.4. The density value is more or less same for both the nozzles at lower mass flow rates, since there is not much difference in the nozzle exit temperature. At higher mass flow rates variation is observed, thus nozzle with higher vapour density can generate more thrust force.

Variation of velocity of the propellant vapour is significant even at lower mass flow rates. Velocity plot has got steep increase at the beginning due the effect of boundary layer which is illustrated in fig.9.

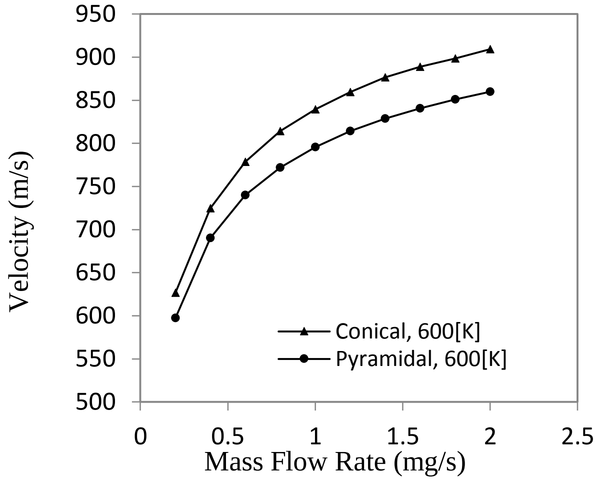


Fig.5 Plot of Mass flow rate versus velocity at the exit of the nozzle.

Fig.6 gives some idea about the variation of pressure and temperature of vapour at the nozzle exit. The third graph is the saturation curve of the water vapour. The portion of the graph below the saturation curve gives the indication of supercooling of the vapour propellant, ie lowering

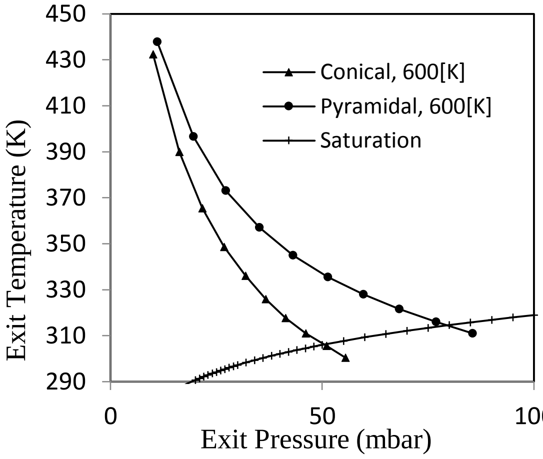


Fig.6 Plot of Exit Vapour pressure versus exit temperature of vapour

the vapour temperature below its saturation value without change in phase. But supercooling will reduce the thrust force. This happens as the adiabatic expansion in the diverging section of the nozzle occurred too rapidly and as such the steam undergo supercooling, causing the gas to condense and even produce ice [11]. This can be prevented by either increasing the inlet vapour temperature or operate the thruster at lower expansion ratio.

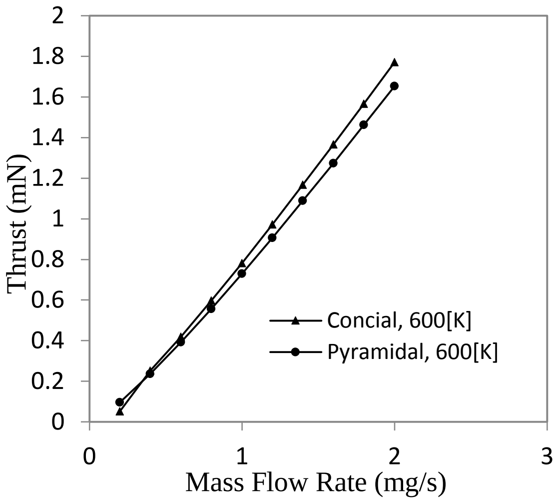


Fig.7 Plot of Mass flow rate versus Thrust force at the exit of the nozzle

The thrust force is calculated using the equation (4). The thrust force at low mass flow rates are almost equal in magnitude, but at higher mass flow rate variation can be observed due to the boundary layer effect, which is more for pyramidal nozzle.

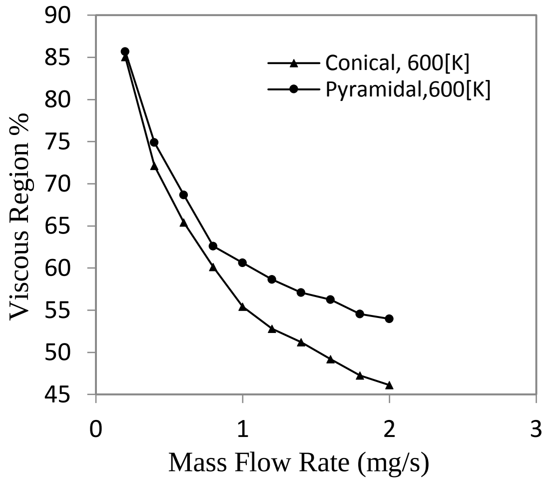


Fig.8 Plot of Mass flow rate versus Percentage area of viscous region at the cross section of nozzle exit

The variation in viscous boundary layer region is due to the variation in viscosity of the vapour. Since in gases viscosity depends on molecular momentum transfer, when the average temperature of the gas is reduced the viscosity of gas will decreases. Thus decrease in exit vapour temperature reduces the viscosity of the vapour at higher mass flow rates. The inviscid region is considered for the velocity range of 95% to 100% of the maximum velocity at the exit of the nozzle.

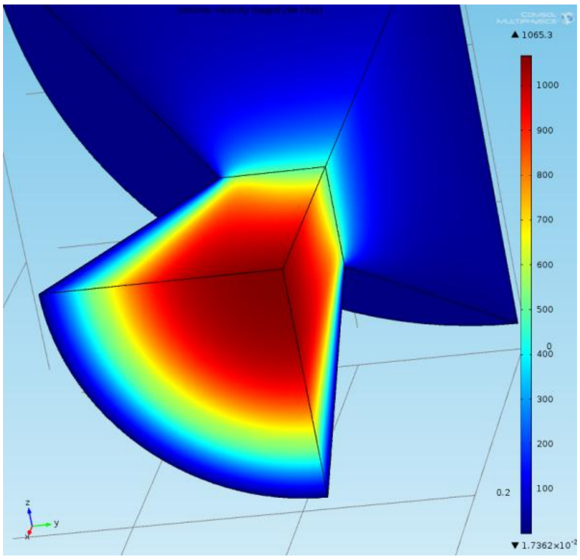


Fig.9 Velocity Profile of conical micronozzle at mass flow rate of 0.2[mg/s]

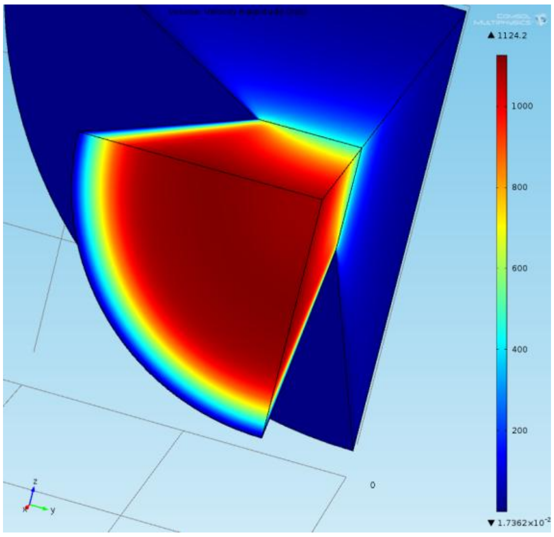


Fig.10 Velocity Profile of conical micronozzle at mass flow rate of 2[mg/s]

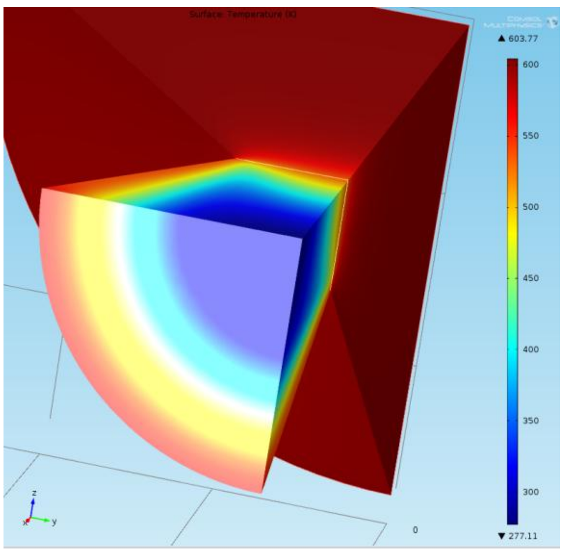


Fig.11 Temperature Profile of conical micronozzle at mass flow rate of 0.2[mg/s]

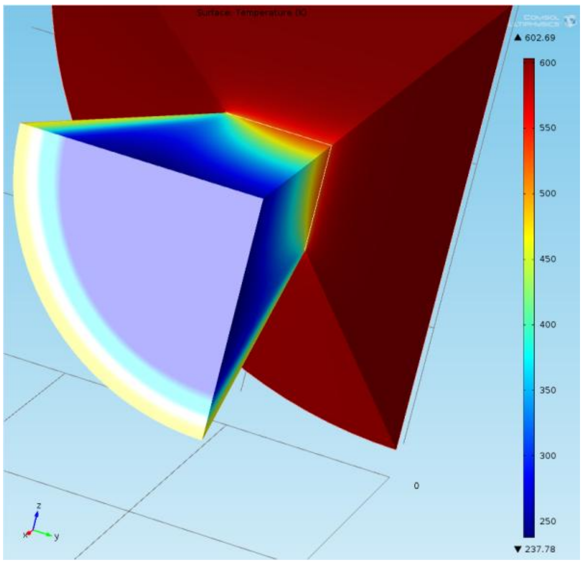


Fig.12 Temperature Profile of conical micronozzle at mass flow rate of 2[mg/s]

Validation of the CFD Code

The validation of steam flow in micronozzle is done by comparing the experimental results in literature [6] and solving the model using CFD code. The validation details for the micronozzle are shown in Fig.13.

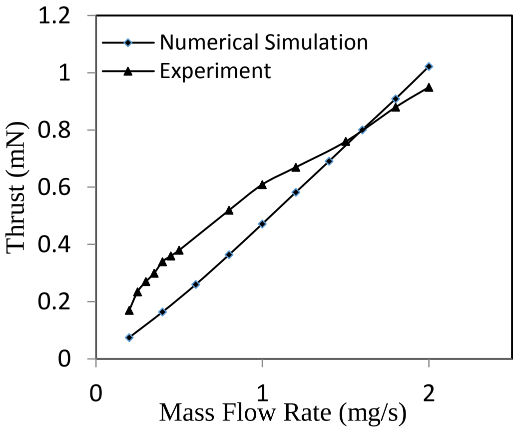


Fig.13. Plot of measured thrust numerically and experimentally versus mass flow rate at Ar =5 Inlet Temperature of 435.15 K

A 3D model of the in-plane converging diverging nozzle is numerically simulated with same boundary conditions used for experiment and by varying the mass flow rate in the range of 0.2 mg/s to 2 mg/s. Comparison of the values shows good agreement of the thrust value obtained by numerical simulations and experiments.

Conclusions

A numerical investigation of vapour flow inside a micronozzle has been presented here. Analyzing the flow of propellant vapour through nozzles of two different geometries, it is concluded that conical nozzle out performs the pyramidal nozzle. The maximum thrust force for conical is 1.77 mN and that for pyramidal is 1.65 mN.

For higher mass flow rate operations it is recommended to use propellant with lower viscosity, so that efficient expansion of the vapour can be achieved.
In order make the thruster more energy efficient it is recommended to operate at suitable inlet temperatures.

The nozzle can be fabricated by LTCC technology which is cheaper compared to other micro fabrication techniques.

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