

Numerical Study of Flow Characteristics in a Monopropellant Vapourizing Liquid Microthruster

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ABSTRACT- Methods for creating thrusters with very low thrust using micronozzles have been actively developed in the last decade. The nature of propellant flow in such micronozzles is different compared to macro nozzle. In micronozzles viscous effect dominates, hence the flow is always in laminar regime with high viscous losses. Due to condensation of vapour at exit of the nozzle, the thrust is reduced. Objective of this paper is to address these issues in micronozzle flow of vapour and also to compare the performance of thruster using two different propellants such as water and ethanol. In this paper a numerical study on the flow of water and ethanol as propellants in vapour phase inside a 3D pyramidal micronozzle by solving Navier stoke's equation with no slip boundary condition and equation of energy conservation is carried out. The computational model is validated with available experimental data in the literature. The computations are performed for different mass flow rates and inlet vapour temperature and is increased until the exit temperature reaches the saturation temperature of the vapour. Different output parameters of both propellants such as velocity and vapour density are compared and the boundary layer effects are also quantified.

KEYWORDS: Micro nozzle, Micro thruster

I. INTRODUCTION

In 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 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 etc [1-9]. 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. In this paper a 3D computational fluid dynamics (CFD) analysis was carried out to determine the minimum operational temperature of micronozzles, to maintain a single phase flow inside it. When the mass flow rate is increased, the inlet propellant temperature decreases, this leads to decrease in temperature of the vapour at the nozzle exit. If the nozzle exit temperature is below the saturation temperature of the vapour, the vapour will condense and thrust force reduces, called 'super cooling' [6]. In this study such an attempt is made by numerically analyzing the flow through a pyramidal shaped converging diverging nozzle using Comsol multiphysics R 4.3b.

II. NUMERICAL MODEL

Table1 Parameters of numerical model

Parameter	Value
Inlet side length	0.48 mm
Throat side length	0.1 mm
Exit side length	0.22 mm, 0.26 mm, 0.3mm
Converging Angle	28[deg]
Diverging Angle	28[deg]
Inlet Mach No	0.0254
Inlet to exit Pressure ratio	40.34, 66.08, 94.96
Mass Flow Rates	0.2[mg/s] – 2[mg/s]

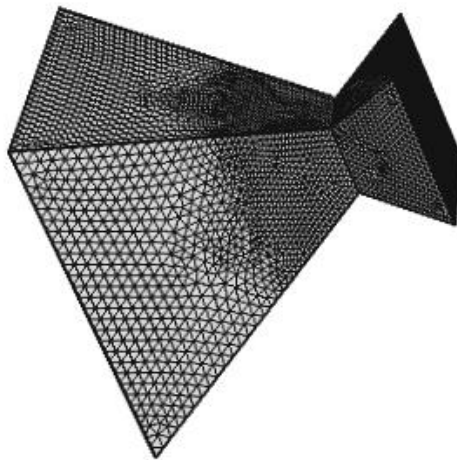


Fig.1. Meshed model of micronozzle using tetrahedral mesh

The 3-D model of the micronozzle is discretized using tetrahedral unstructured mesh, as for fluid flow analysis tetrahedral mesh is more suitable and easy to be meshed. Refinement in the mesh is made at the diverging section of the nozzle, since both velocity and temperature gradients are 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.

III. RESULTS AND DISCUSSION

The figure.2. presents the effect of mass flow rate on boundary layer, at low mass flow rate the boundary layer effect is more significant as compared to higher mass flow rates. This is due to increase in average temperature of vapour flowing through the nozzle, which leads to decrease in viscosity of the vapour. Hence, it is proved that the micronozzle performs more efficiently at higher mass flow rates

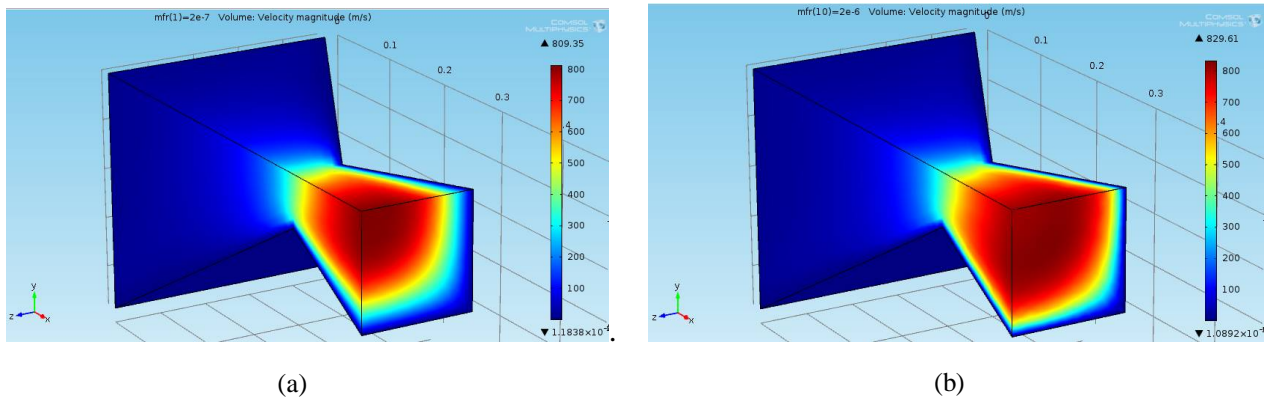


Fig.2.Vapour Velocity distribution of quarter section model of micronozzle with ethanol as propellant (a) At mass flow rate = 0.2 mg/s and (b) At mass flow rate = 2 mg/s

.Determination of minimum inlet temperature of Vapour

To determine the minimum inlet temperature of vapour, a series of simulations are performed by varying the mass flow rate of vapour (0.2 mg/s to 2 mg/s) and inlet temperature. The inlet temperature for which vapour temperature at the exit of nozzle become same as the saturation temperature corresponding to the exit pressure of vapour was set as the minimum inlet temperature for that particular mass flow rate. Fig.3 shows the comparison of minimum inlet temperatures of water vapour and ethanol vapour at various mass flow rates. The inlet temperature for ethanol is lower than water due to its lower specific heat value.

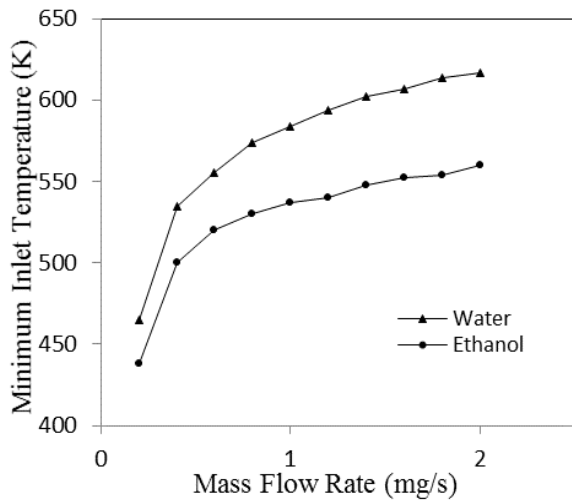


Fig.3 Plot of Mass flow rate versus minimum inlet temperature

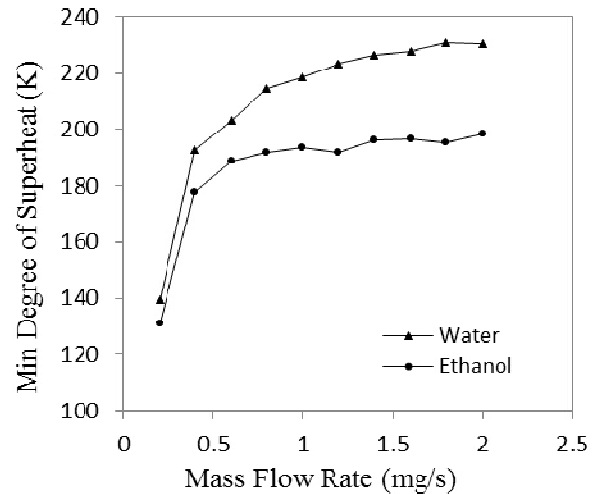


Fig.4 Plot of Mass flow rate versus minimum Degree of Superheat

In Fig.4 it is observed that the variation of degree of superheat of vapours to be maintained at inlet of the nozzle so as to get a superheated vapour flow throughout the micronozzle length. The propellant after vapourization in the vapourizing chamber should be raised to the minimum required inlet temperature by superheating before expanding in the micronozzles, otherwise the vapour at the outlet may get condense and reduces the thrust force.

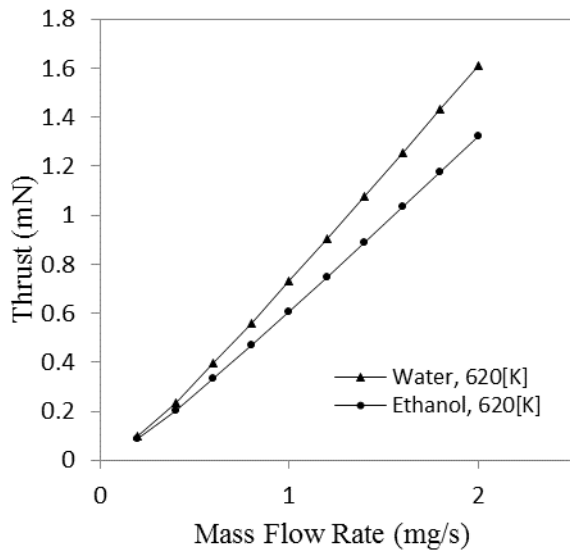


Fig.5 Plot of Mass flow rate versus Thrust force

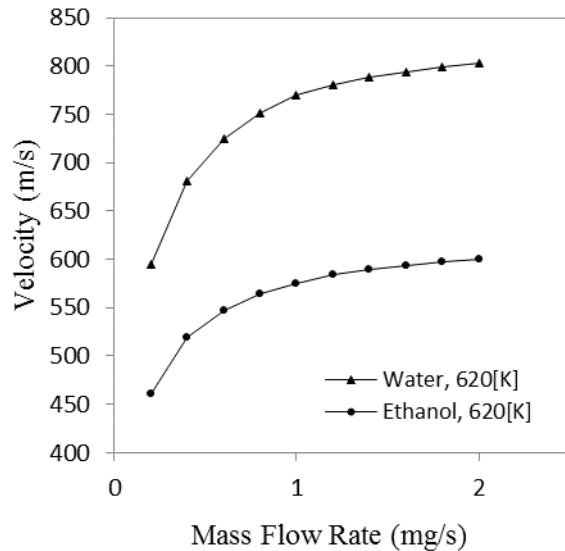


Fig.6 Plot of Mass flow rate versus velocity of vapour at the exit of micronozzles

Fig.5 presents the variation of thrust force at different mass flow rates at constant inlet temperature of 620 K. For same mass flow rate, the thrust force for water vapour is more than that of ethanol vapour. At lower mass flow rates, the variation is small, due the dominance of viscous boundary layer effect in the diverging section, which is shown in Fig.8, in which viscous region area percentage at the exit of nozzle is plotted against mass flow rate. The graph shows a steep decrease in viscous effect as mass flow rate is increased and found to be constant at higher mass flow rates.

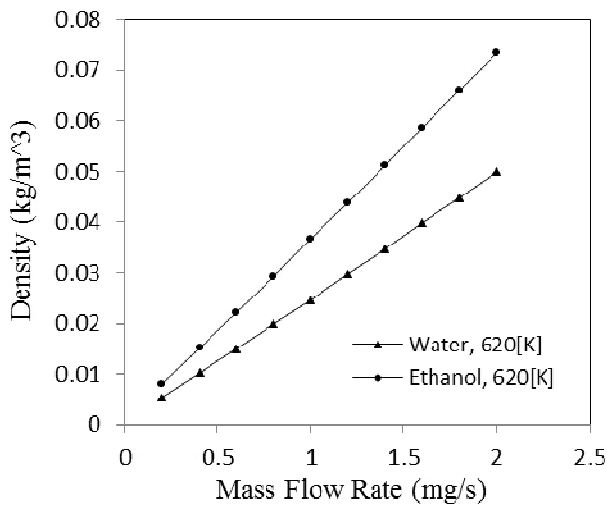


Fig.7 Plot of Mass flow rate versus Density at micronozzle exit

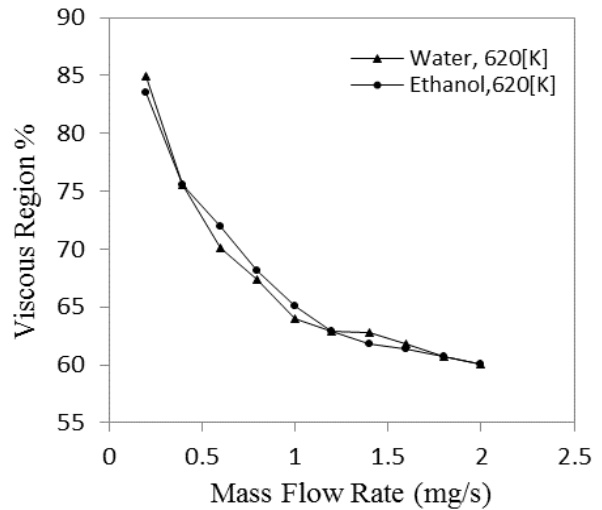


Fig.8 Plot of Mass flow rate versus percentage of viscous area at exit of the micronozzle.

The variations of velocity with respect to the mass flow rate is illustrated in Fig.6. Both the propellants show similar trends, but significant variation in the velocity values can be observed. This is due to higher pressure drop of water vapour than ethanol vapour. The water vapour at the inlet will have more pressure than ethanol vapour due its higher specific heat capacity value.

III. VALIDATION OF THE CFD CODE

The validation of steam flow in micronozzle was accomplished with the experiments conducted by Pijus Kundu et.al [6]. The validation details for the micronozzle is shown in Fig.9. 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. The numerical simulation results are in good agreement with the experimental results of the converging-diverging micronozzle.

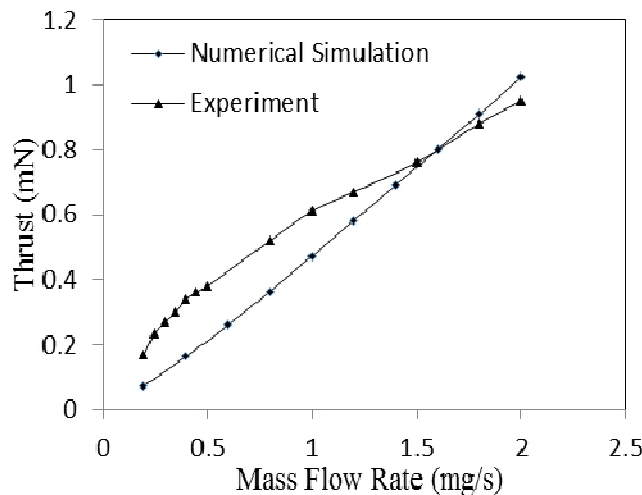


Fig.9. Plot of measured thrust numerically and experimentally versus mass flow rate at Ar =5 Inlet Temperature of 435.15 K

IV. CONCLUSIONS

In this research the performance analysis of a micronozzle steam flow is done by numerical simulation. Based on the study following conclusions can be made:

- (1) Maximum thrust force of 1.61 MN is achieved for water as propellant and 1.32 MN for Ethanol.
- (2) Less heater power is required to avoid supercooling when ethanol is used as propellant. For low level thrust operation, ethanol have got more advantage than water.
- (3) Since the variation in thrust value is more significant in higher mass flow rates, water as propellant can perform more efficiently.
- (4) The viscous losses are higher at lower mass flow rates in order to have efficient performance of the micronozzle, it is suggested to operate the thruster at higher mass flow rates to achieve an expected expansion of vapour.

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