Numerical Investigation of Micronozzle Performance for Various Nozzle Geometries : A Simulation with COMSOL

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Motivation

- *Micropropulsion systems are indespensible part of space mission these days due to the miniaturization of satellites to small size. The need to miniaturize the propulsion system has attracted worldwide attention since this aspect is applicable to areas like*
  - *space missions.*
  - *Micro Aerial Vehicles (MAV).*
- *Methods for creating thrusters with very low thrust using micronozzles have been actively developed over last decade.*
- *So far a number of micropropulsion systems have been made. Vapourizing liquid microthruster (VLM) seems to be very promising concept due its simple design.*
- *Modelling of high speed micro flows is required to get a clear understanding of the flow behavior, since experiments are difficult at micro scales.*

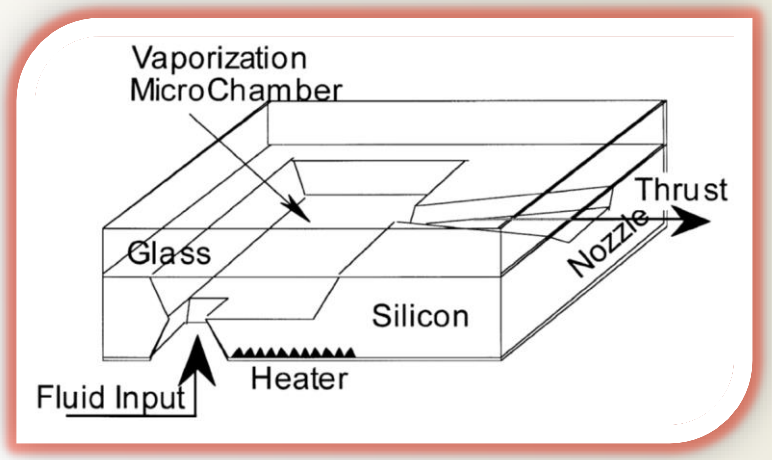
Micropropulsion Systems

- Cold gas system
- Bi-propellant thruster
- Mono-propellant thruster
- Plasma pulsed thruster

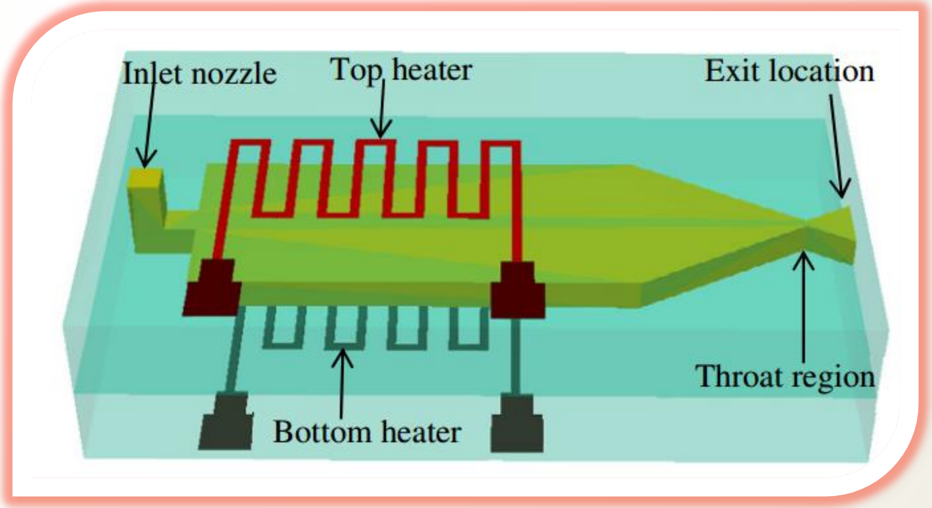
- Laser plasma thruster
- Micro solid propellant thruster
- **Vaporizing liquid thruster**

Vaporizing Liquid Microthruster

- *The change of phase (liquid-gas) is exploited to produce a thrust*
  - *Micro Channel*
  - *Propellant Inlet*
  - *Vaporizing Chamber*
  - *Heating Resistor*
  - ***Micro Nozzle***



Side exit microthruster, Structure Proposed by University of California



In-Plane VLM Proposed by Pijus kundu et.al [6]

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- *Over the last few years, the concept of VLM have been widely studied by different researches [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.*

Objectives

- *To quantify and analyse the effect of boundary layer on micronozzle performance.*
- *To Calculate the Thrust force at the exit of nozzle at constant inlet temeperature for various mass flow rates.*
- *Compare the performance of pyramidal nozzle and conical nozzle.*

Methodology

- *Numerical examinations of the flow of steam in a micronozzle is done by solving Navier stoke's equation with no slip wall condition and Heat equation using High Mach No Module of* ***COMSOL Multiphysics*** *4.3b.*
- *Simulations were done for two different geometries of micronozzle by varying the mass flow rates at constant inlet temperature.*

Governing Equations

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

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

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

ρ is the density (SI unit: $\mathrm{kg/m^3}$)

$\mathbf{u}$ is the velocity vector (SI unit: m/s)

p is pressure (SI unit: Pa)

τ is the viscous stress tensor (SI unit: Pa)

$\mathbf{F}$ is the volume force vector (SI unit: $\mathrm{N/m^3}$)

C_p is the specific heat capacity at constant pressure (SI unit: J/(kg·K))

T is the absolute temperature (SI unit: K)

$\mathbf{q}$ is the heat flux vector (SI unit: $\mathrm{W/m^2}$)

Q contains the heat sources (SI unit: $\mathrm{W/m^3}$)

$\mathbf{S}$ is the strain-rate tensor:

$$\mathbf{S} = \frac{1}{2}(\nabla \mathbf{u} + (\nabla \mathbf{u})^T)$$

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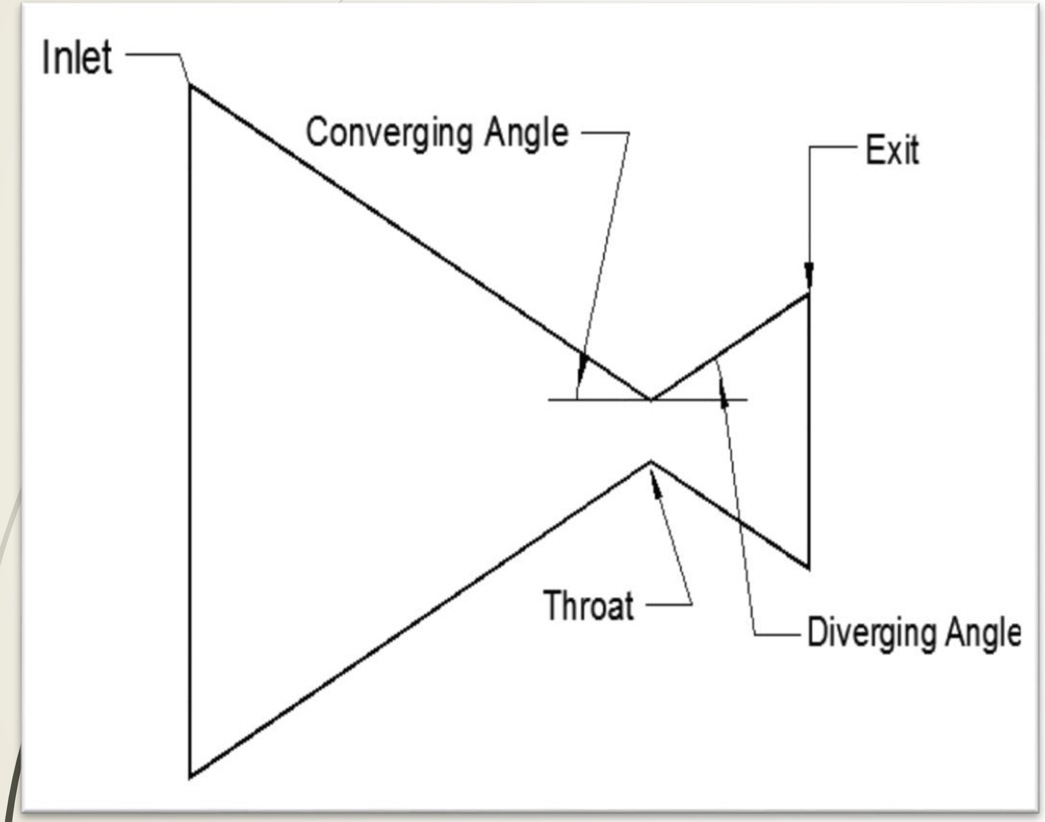
Numerical model



2D Schematic View of the Micronozzle

Parameter	Value
Inlet Area	0.23 sq.mm
Throat Area	0.01 sq.mm
Exit Area	0.05 sq.mm
Converging Angle	28[deg]
Diverging Angle	28[deg]

Parameters of numerical model

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Thrust force equation

$$T_f = m^*{}_* v_e$$

Inlet Pressure:

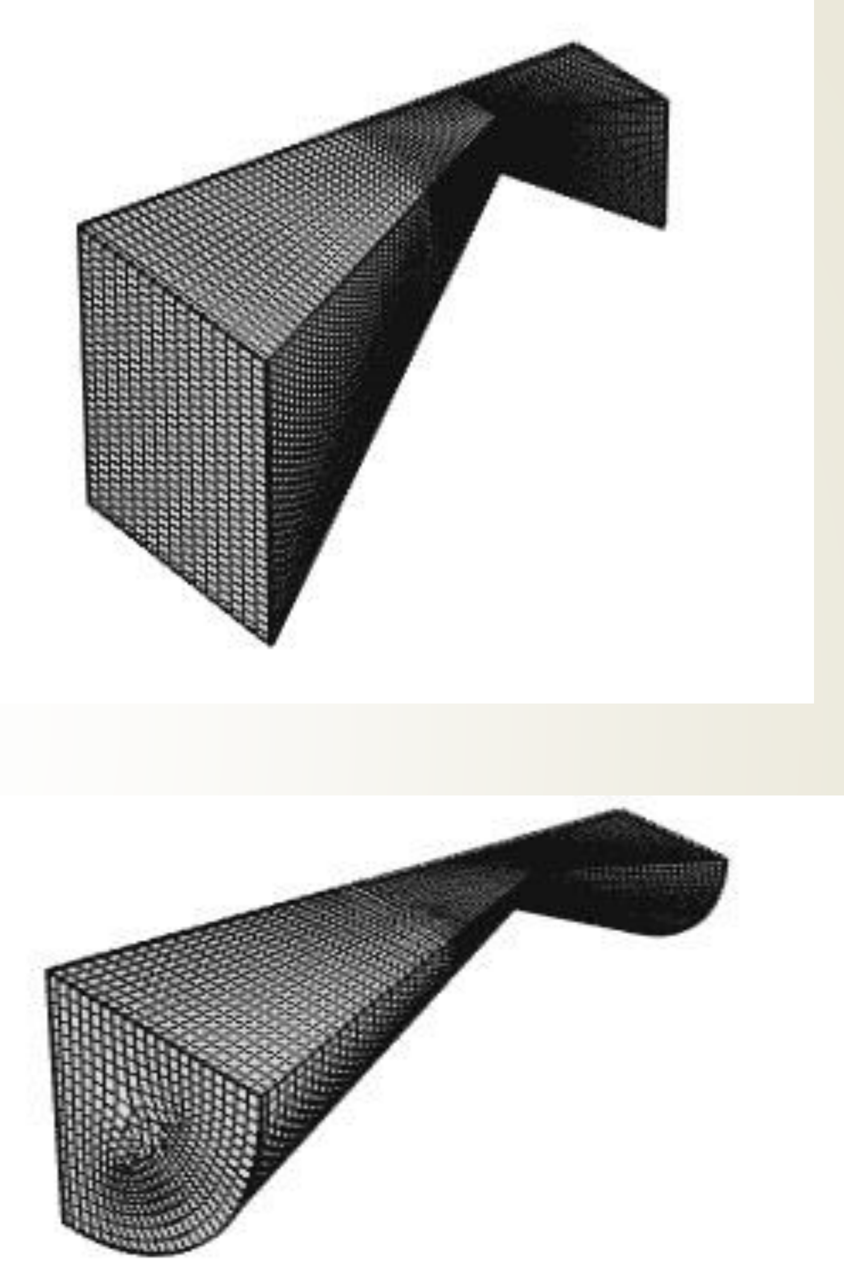
$$P_{in} = (m^{*} * Rs * Tin) / (A_{in} * U_{in})$$

Inlet Velocity:

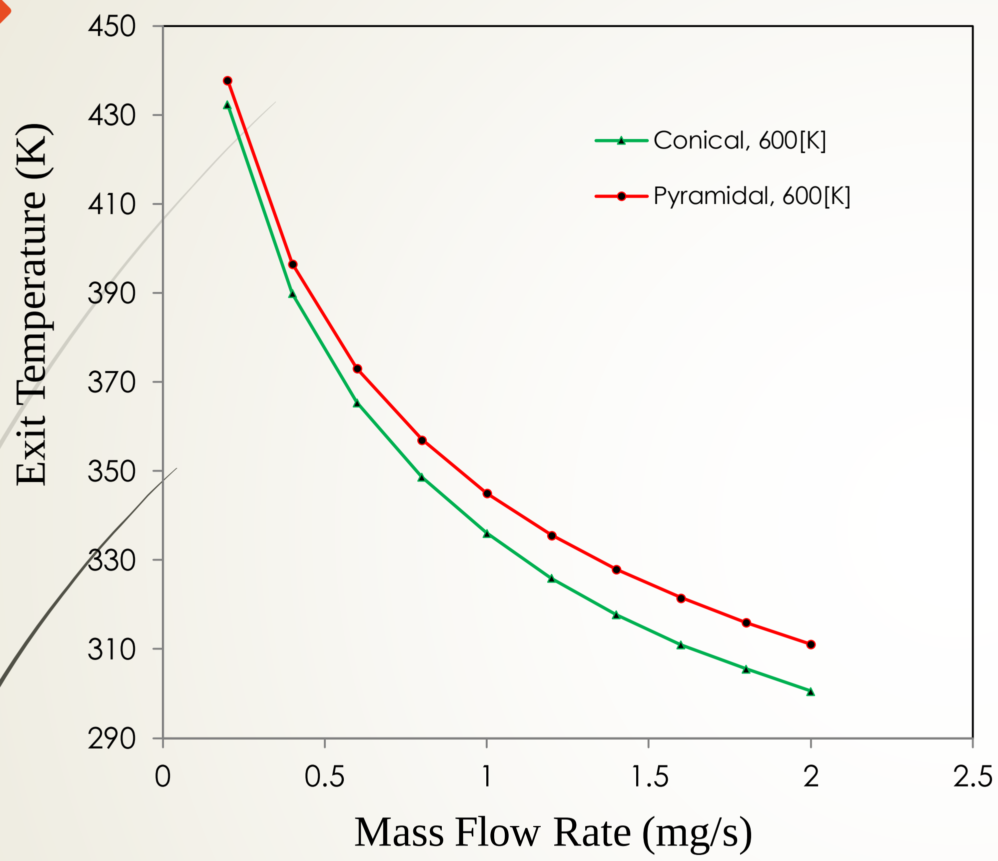
$$U_{in} = M_{in} * \sqrt{\gamma * Rs * T_{in}}$$

Assumptions

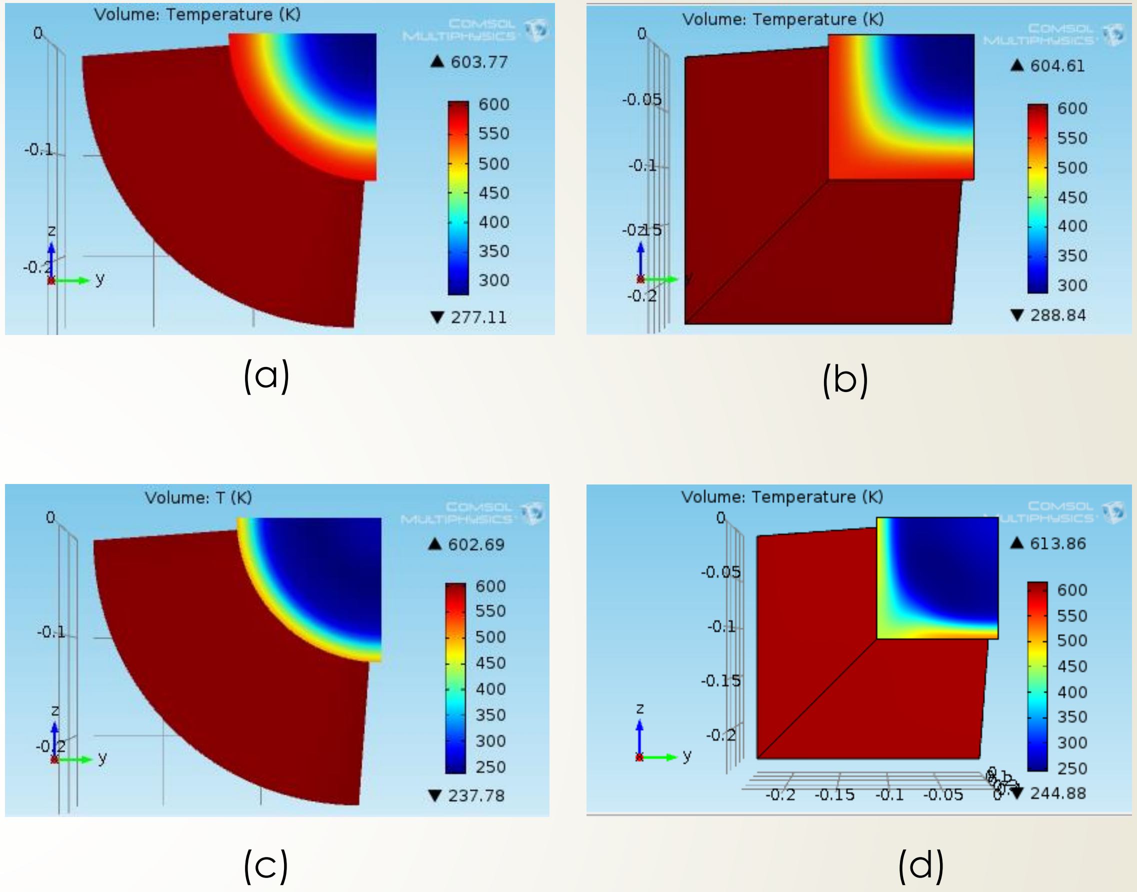
- *Propellant is in single phase (gaseous) inside the nozzle.*
- *Flow is isentropic, gas dynamics relations can be applied*



Results and Discussion



Mass flow rate versus Nozzle Exit Temperature



Temperature Profiles micronozzle
(a) Conical at 0.2 mg/s
(b) Pyramidal at 0.2 mg/s
(c) Conical at 2 mg/s
(d) Pyramidal at mg/s

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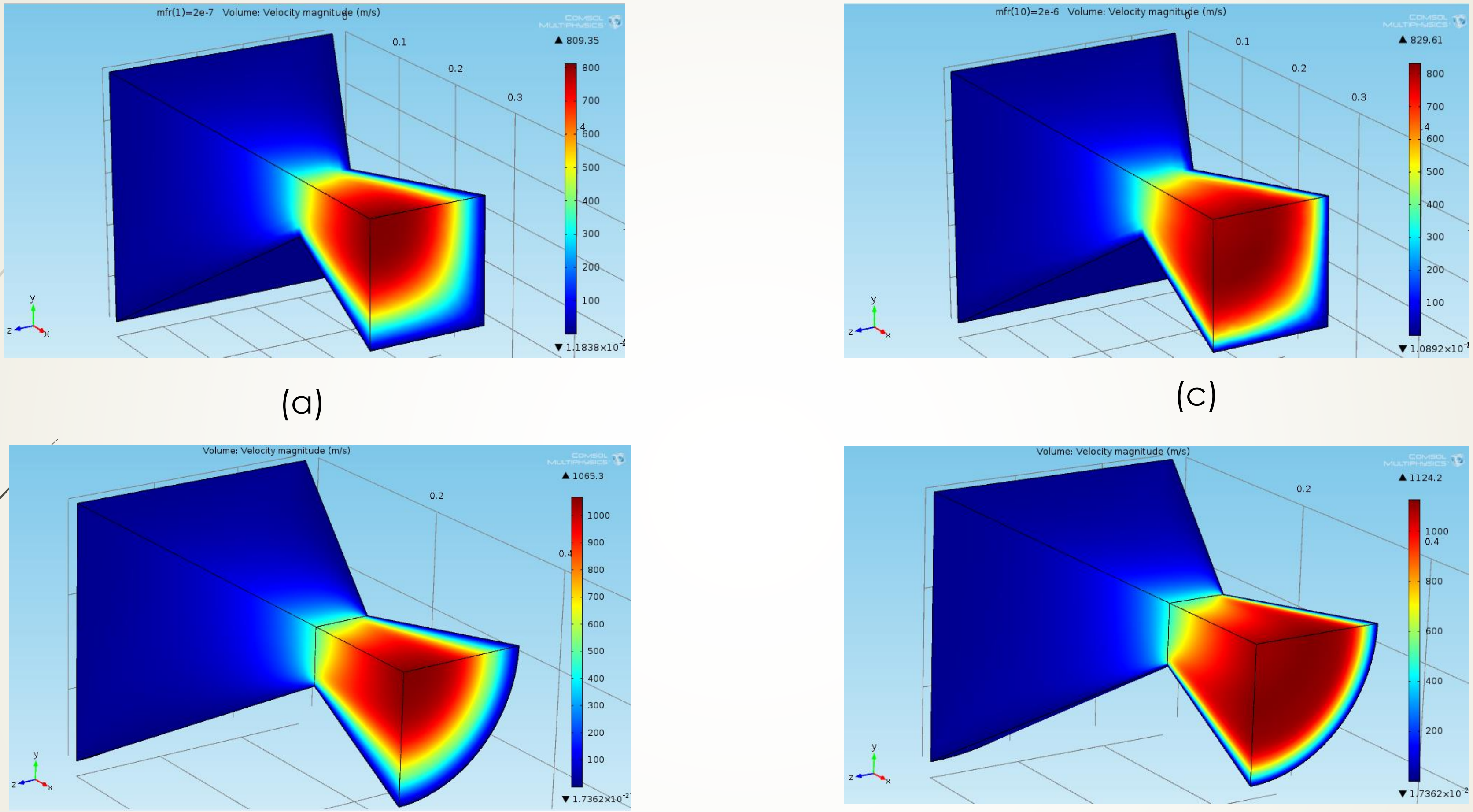
Results and discussion cont…



(a)

(c)

(b)

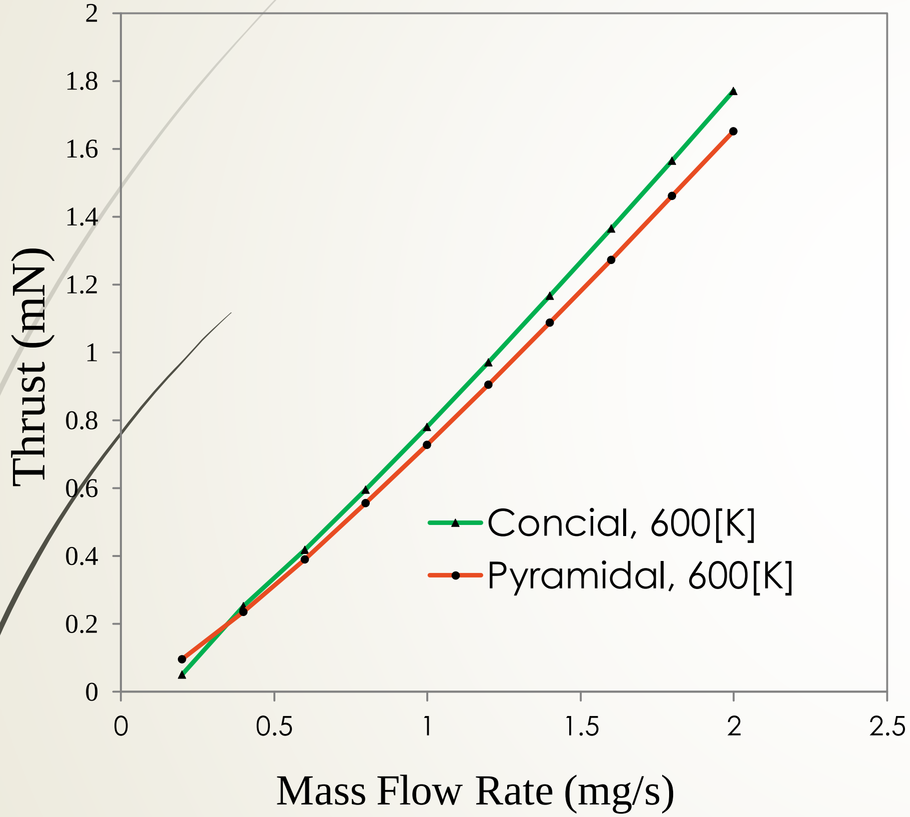
(d)

Vapour Velocity distribution of quarter section model of micronozzle.

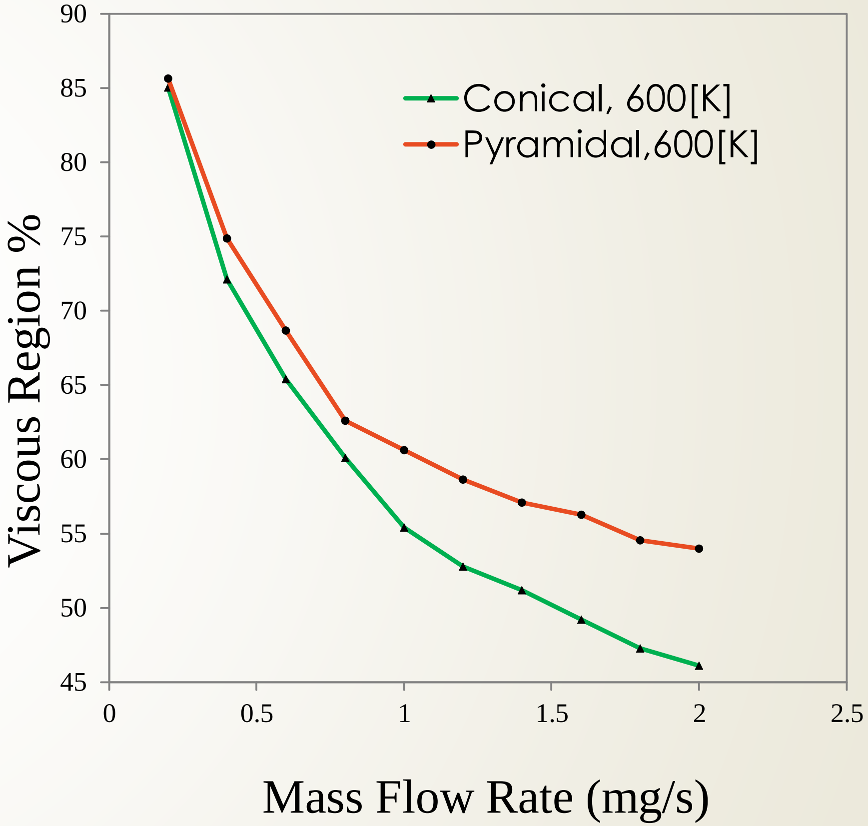
(a) Pyramidal Nozzle at 0.2mg/s (b) Conical Nozzle at 0.2 mg/s

(c) Pyramidal Nozzle at 2.0 mg/s (d) Conical Nozzle at 2.0 mg/s

Results and discussion cont….

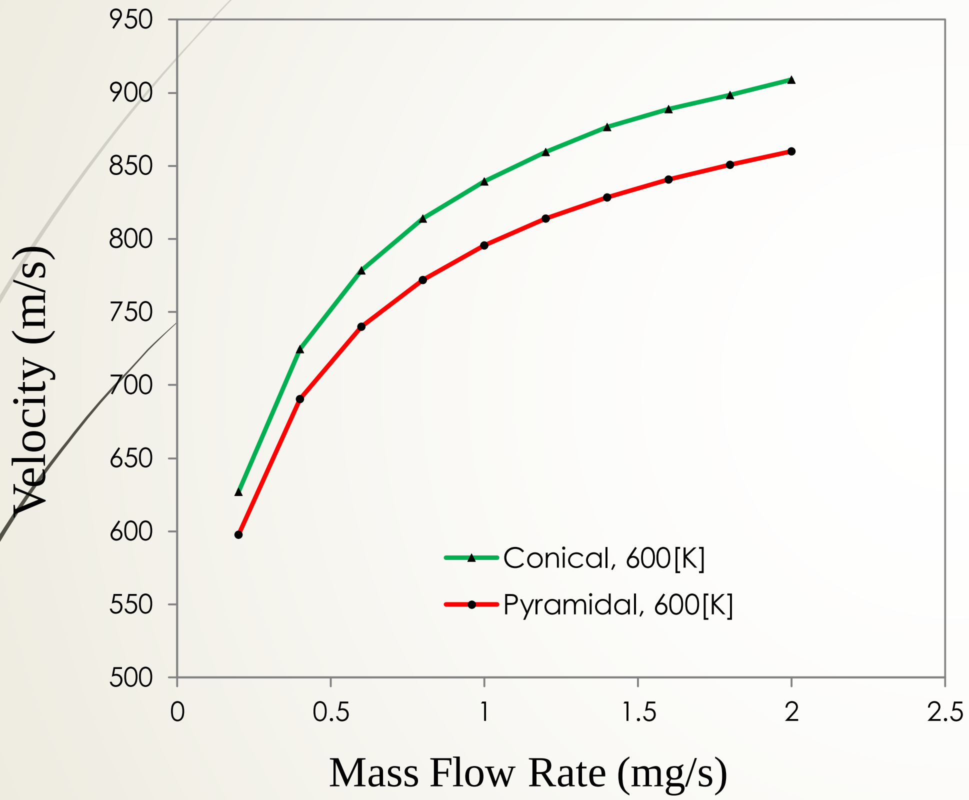


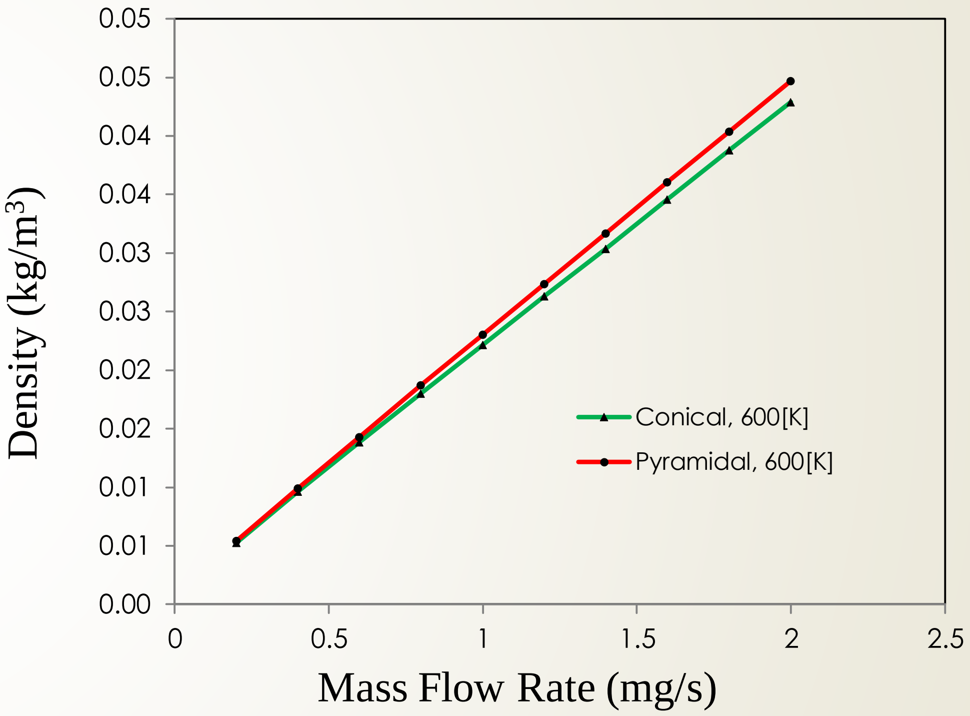
Mass flow rate versus Thrust force



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

Results and discussion cont….





Mass flow rate versus Velocity

Mass flow rate versus Density

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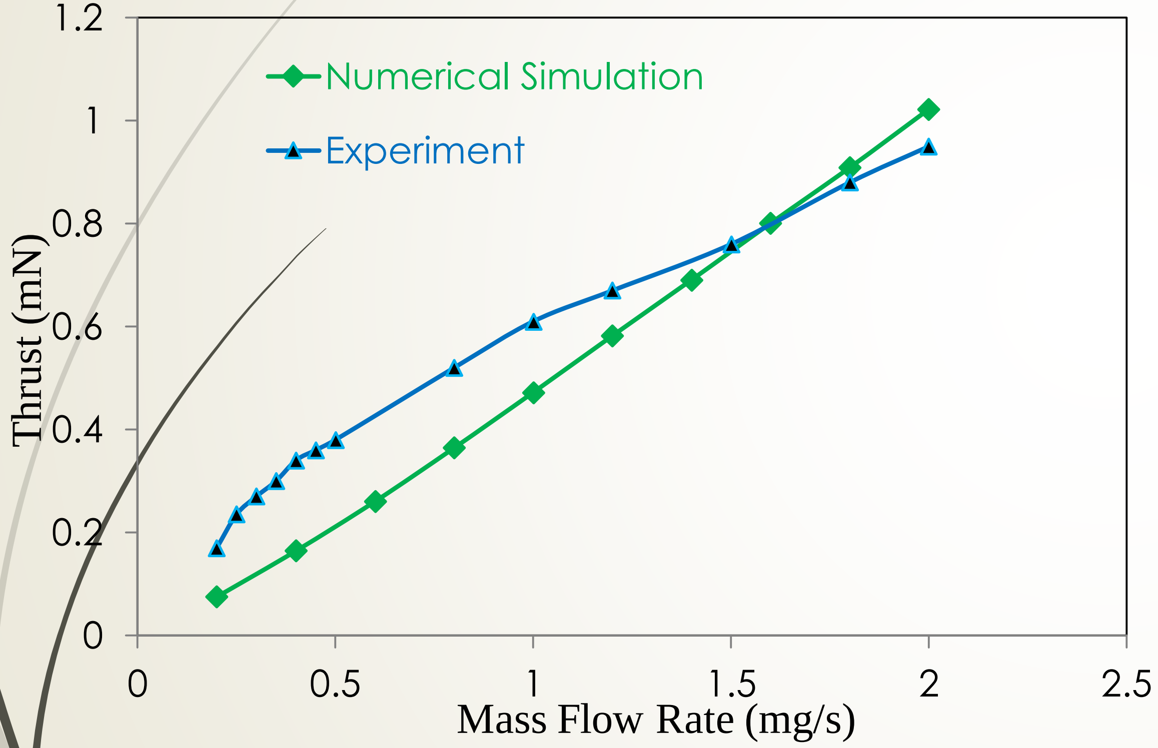
Validation of the CFD Code

The validation of steam flow in micronozzle is done by comparing the experimental results in Pijus kundu et.al [6]



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

Parameters of numerical model

Parameter	Value
Inlet Area	0.3 mm^2
Throat Area	0.013 mm^2
Nozzle Exit Area	0.065 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]

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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 lower 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 to make the thruster more energy efficient it is recommended to operate at suitable inlet temperatures.

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