THRUST PERFORMANCE EVALUATION OF CHEMICAL ROCKET ENGINE BY THERMAL AND FLUID DYNAMIC ANALYSIS FOR EXHAUST GAS FLOW SUBJECTED TO COOLING

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ABSTRACT

Chemical rocket engines play an important role in space travel as they produce high thrust, required for initial lift- off of the rocket. Deep space exploration mission is very expensive, as most of the engines in use are chemical rocket engines and they operate with low efficiency. Even if electric propulsion systems are used, they cannot replace the solid or liquid propellant rocket engines, as only they are capable of generating high thrust. The thrust is essentially generated by combustion process of fuel and oxidizer. But the thrust is fundamentally a function of mass flow rate, pressure and velocity of the exhaust gas and the temperature gained due to the combustion does not contribute to the generation of thrust. By the conversion of a property, such as exhaust gas temperature, which cannot contribute to increase of thrust into a useful property such as the exhaust gas pressure, the efficiency of thrust generated by the rocket engine at the nozzle chamber exit can be improved. The cooling systems that are currently in use mainly focus on prevention of overheating of rocket engine structure but do not serve to cool the exhaust gas.

This paper studies the feasibility of achieving isenthalpic flow of exhaust gas in the engine nozzle chamber to convert temperature of the exhaust gas into exhaust pressure. This is achieved by cooling the exhaust gas. Thermal analysis of the temperature distribution is performed to evaluate the thrust characteristics before and after cooling of exhaust gas. The design requirements for the cooling mechanism as well as the effect of geometric modifications are discussed. Fluid dynamic analyses for flow regimes of subsonic, sonic and supersonic conditions are done for geometries to evaluate the thrust performance. Improvement of thrust efficiency can greatly reduce the cost of space travel.

NOMENCLATURE, ACRONYMS, ABBREVIATIONS

ρ	Density, kg/m^3
v	Specific volume, m^3/kg
A	Cross- sectional area, m^2
F_T	Thrust force, N
g	Acceleration due to gravity, m/s^2
h	Specific enthalpy, KJ/kg
LH2	Liquid Hydrogen
LOX	Liquid Oxygen
$\dot{m}$	Mass flow rate, kg/s
M	Mach number
$\dot{Q}$	Heat flow rate, KJ/s
u	Specific internal energy, KJ/kg
$\dot{W}$	Work rate, KJ/s
V	Velocity, m/s
z	Potential head, m

Subscripts

1 – Inlet condition

2 – Outlet condition

e- Nozzle exit

o- Atmospheric condition

INTRODUCTION

Propulsion system is a key subsystem of the rocket which is responsible for the momentum control of the rocket. The propulsion system can be broadly classified into mass – based propulsion system and non – mass propulsion system. The most commonly used propulsion system is a chemical rocket propulsion system which is a mass – based system. The chemical propulsion system is very essential in the lift – off stage, where large amount of thrust is required[1]. The thrust is generated by expulsion of the exhaust gas. The exhaust gas is generated due to the combustion process of fuel and oxidizer. The combustion leads to generation of exhaust gas at high temperature and pressure. The exhaust gas is pushed out the rocket engine nozzle chamber with pressure and high velocity. Thus the rocket is pushed forward as reaction to the expulsion of mass. Thrust is fundamentally dependent on mass flow rate, exit velocity and exit pressure of the rocket[2].

New propulsion systems like electric propulsion system are much more efficient compared to chemical rocket engines. But they cannot replace the chemical rocket propulsion as they cannot produce high thrust required for initial stages of the rocket[3]. Hence it is important to improve the thrust capacity of chemical rocket engines. The exhaust gas of the chemical rocket engine has a high temperature and pressure. The temperature of the exhaust gas does not actively contribute to the thrust generated by the rocket engine. If the pressure of the exhaust gas can be increased at the expense of the temperature then the thrust of the rocket can be improved. The feasibility of conversion of temperature into pressure by cooling of the exhaust gas is studied. The cooling of the exhaust gas can be done with the help of a two phase cooling system such as the cryogenic loop heat pipe[4].

DESIGN OF NOZZLE AND EFFECT OF GEOMETRIC PARAMETERS

A rocket nozzle model is designed based on a convergent – divergent nozzle. The nozzle has 3 sections viz., convergent section, throat section and the divergent section. The throat section is significantly longer compared to other rocket nozzles. This is to accommodate the cooling system. The nozzle is designed for high mass flow rate and large thrust. The geometry of nozzle has a significant effect on thrust performance of the nozzle. The area ratio of divergent to throat has to be optimal to achieve high exit velocity and prevent formation of normal shock. The formation of the normal shock decreases the ideal thrust that can be achieved. The area ratio of the convergent has to be designed in such a way that sonic velocity condition is achieved at the throat of the nozzle. It is also important to prevent the drastic rate of change of cross – sectional area as it will lead to back pressure and reversed flow. The overall size of the nozzle has a significant effect on the structural mass of the rocket.

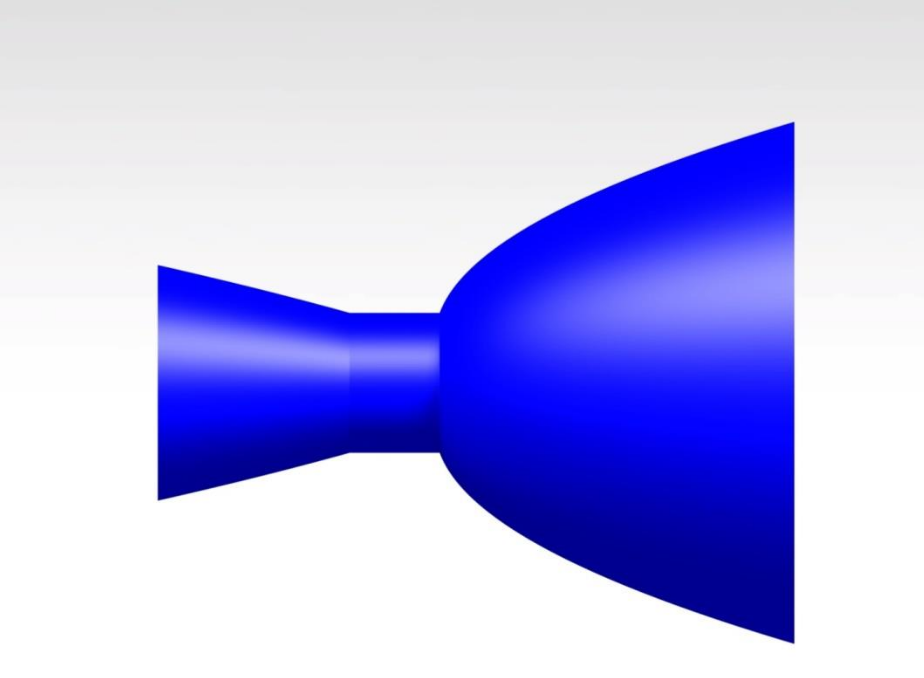

Figure 1. Orthographic view of rocket nozzle.

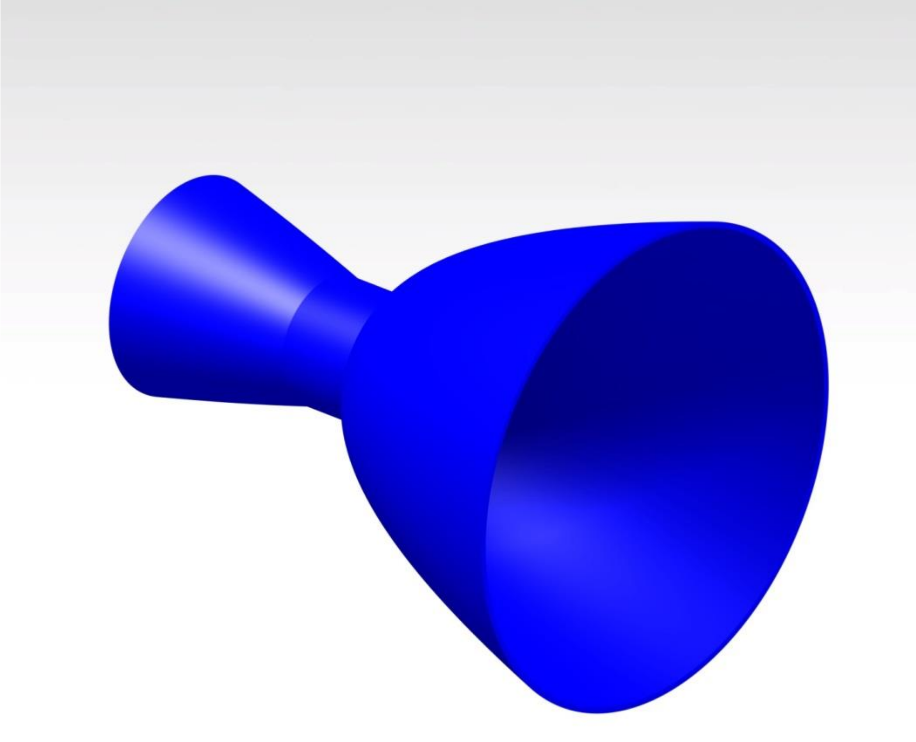

Figure 2. View of divergent section of rocket nozzle.

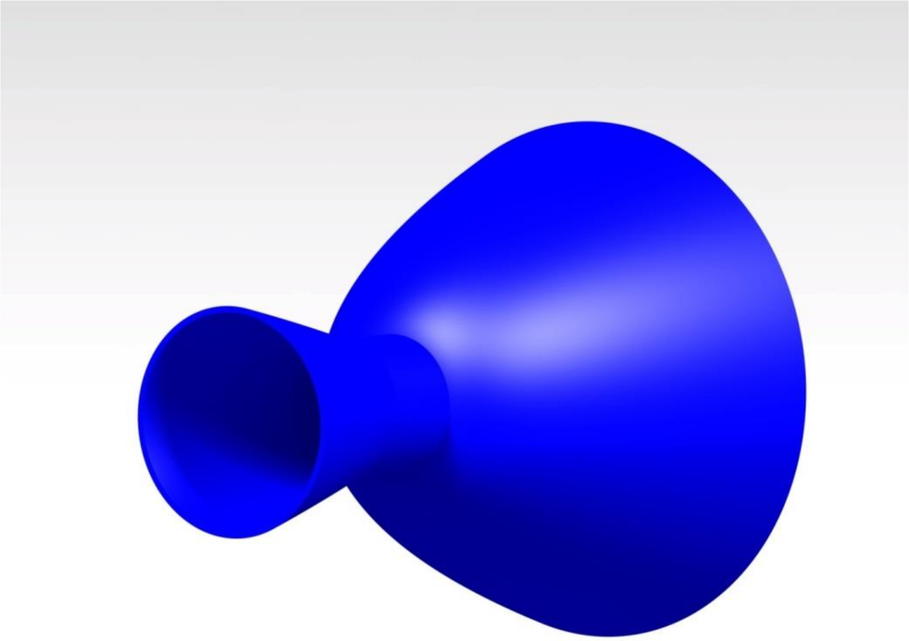

Figure 3. View of convergent section of rocket nozzle.

COOLING SYSTEM REQUIREMENTS

The rocket nozzle is designed based on LOX/LH2 propelled liquid rocket engine. The exhaust gas is H_2O (superheated steam). The rocket is designed for a high mass flow rate; hence a heat dissipation rate of 10^6 to 10^7 Watts is required. The fluid in the cooling system must be reusable as the single time use systems are expensive and heavy. Cooling systems such as loop heat pipe, cryogenic loop heat pipe are preferred over dump cooling and film cooling systems.

The fluid should have high heat capacity and high density. This can reduce the overall structural mass of the cooling system. High structural mass of the cooling system increases load on the rocket and thereby requires more fuel. The freezing temperature of the cooling fluid should as low as possible to avoid freezing on reaching higher altitudes during the flight.

Loop heat pipes offer great flexibility with heat loads. The main component of loop heat pipe is the evaporator chamber and it consists of a wick system. The primary wick when manufacturing using 3D printing techniques offers a great control of porosity thereby aiding in better design of the cooling system[5].

NOZZLE PARAMETERS AND OPERATING CONDITIONS

The flow analysis of the rocket nozzle is done based on the following geometric parameters, operating conditions and exhaust gas.

Table 1. Nozzle parameters and operating conditions

Parameter/ Operating condition	**Value/ Name**	**Units**
Total length	5000	mm
Convergent inlet diameter	1750	mm
Divergent exit diameter	4000	mm
Throat diameter	1000	mm
Convergent length	1500	mm
Throat length	750	mm
Divergent length	2750	mm
Chamber pressure	70	bar
Chamber temperature	1800	Celsius
Mass flow rate	1970	Kg/s
Exhaust gas	Water vapour (Superheated)	-
Temperature drop while cooling	10	Celsius
Method of cooling	Two phase cooling system	-

FLOW ANALYSIS BY STEADY FLOW ENERGY EQUATION

The fluid dynamic analysis is done based on equation of continuity and flow regimes in the nozzle section. The exhaust gas flow remains subsonic in the convergent section and it is modelled to be incompressible in this region. In the throat section, the flow is sonic and the velocity and density remain constant, when the exhaust gas is not cooled. The flow in the divergent section is supersonic and it is modelled to be a compressible in this region. The mass flow rate is constant and the flow is modelled to be steady. The flow is vertical and gravitational potential energy is taken into account.

$$\dot{m} = \rho_1 A_1 V_1 = \rho_2 A_2 V_2 \; - \text{ Equation 1}$$

$$\frac{dA}{A} = (M^2 - 1) * \frac{dV}{V} \; - \text{ Equation 2}$$

The thermal analysis for the flow is done using steady flow energy equation. This equation is particularly useful for a general flow condition. The equation is solved based on boundary conditions and flow regimes. The parameters are calculated using XSteam.m, which a MATLAB function to calculate different properties of steam for given two initial values with combinations of properties like pressure, temperature, density, enthalpy etc. The inlet conditions of the nozzle are found with chamber temperature and pressure. The properties at the rest of the nozzle regions are computed with the help of enthalpy of preceding position and velocity and density which are found using equation of continuity. Thus the pressure, temperature and velocity in all sections and found and the temperature distribution can be plotted.

$$\dot{Q} - \dot{W} = \dot{m}((h_2 - h_1) + (\frac{{V_2}^2 - {V_1}^2}{2}) + g(z_2 - z_1)) \; - \text{ Equation 3}$$

$$h = u + P.v \; - \text{ Equation 4}$$

To achieve an isenthalpic flow in the convergent and divergent section, heat energy has to be added to compensate for the kinetic energy gained by the gas. The flow in the throat section is approximately an isenthalpic flow, as the enthalpy gain due to drop in potential energy is negligible. The flow is assumed to be inviscid and pressure losses due to friction, expansion or contraction are not taken into account. The thrust can be calculated based on the exit pressure, exit velocity and the mass flow rate.

$$F_T = \dot{m}(V_e) + (P_e - P_o)A_e \; - \text{ Equation 5}$$

RESULTS AND DISCUSSION

Pressure, Velocity and Temperature plots without cooling

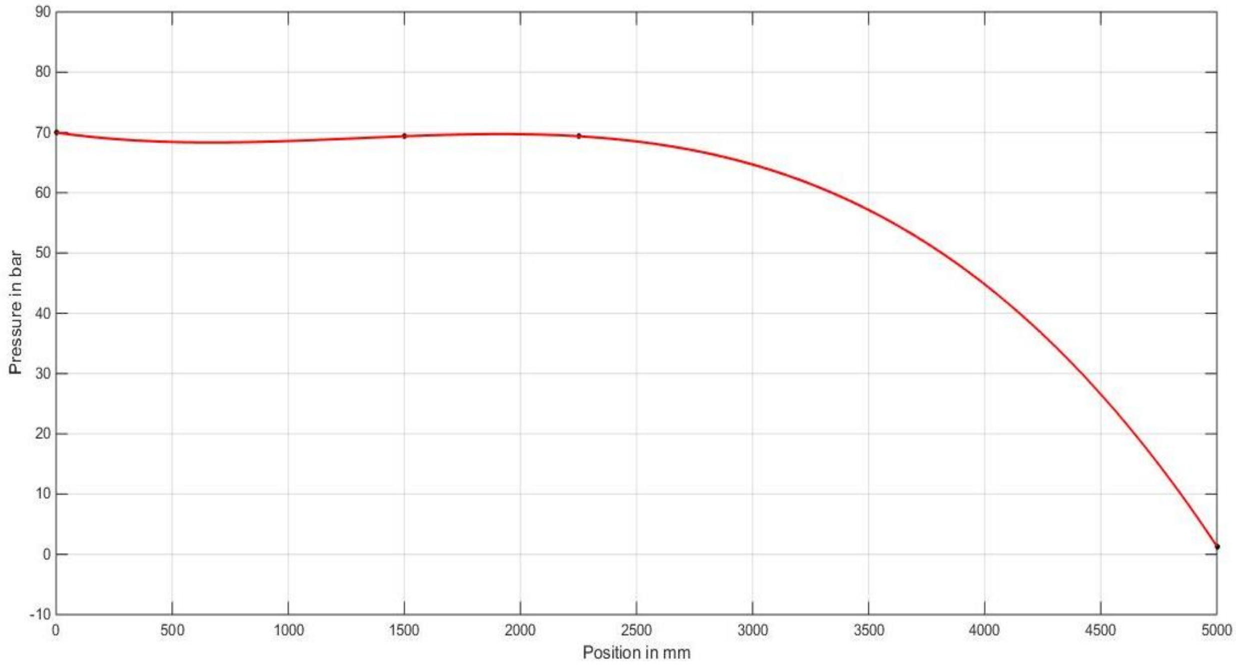

Figure 4. Pressure vs. Position plot - No cooling condition.

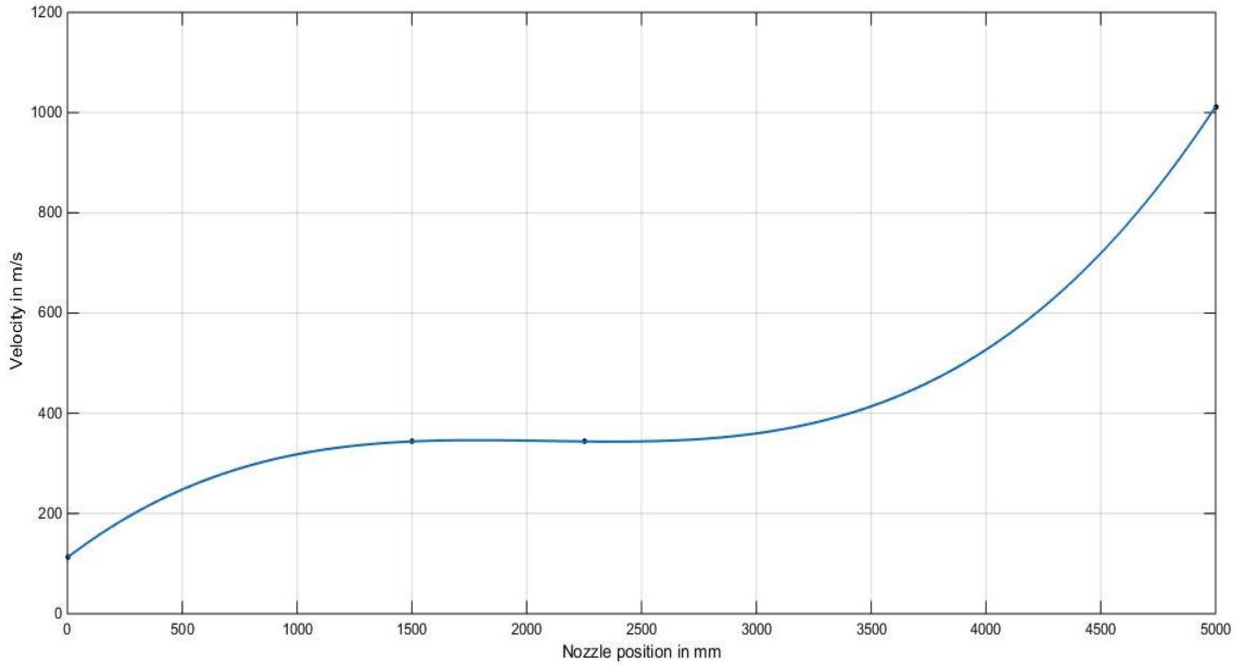

Figure 5. Velocity vs. Position plot - No cooling condition.

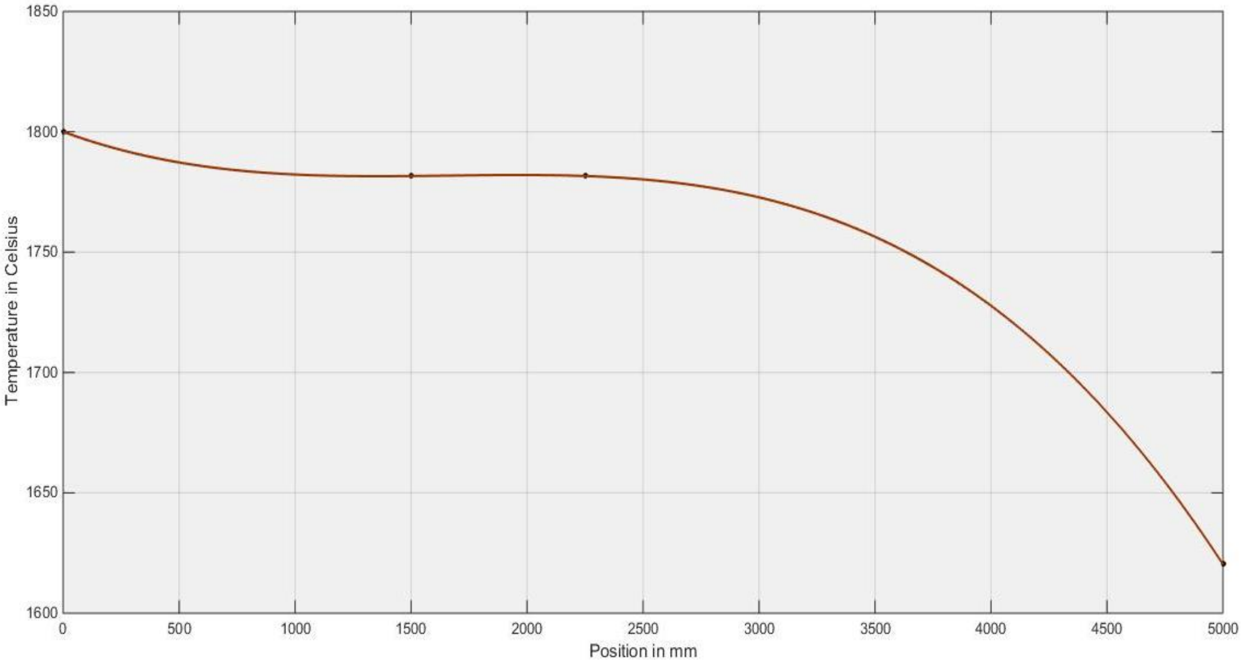

Figure 6. Temperature vs. Position plot - No cooling condition.

Pressure, Velocity and Temperature plots with cooling

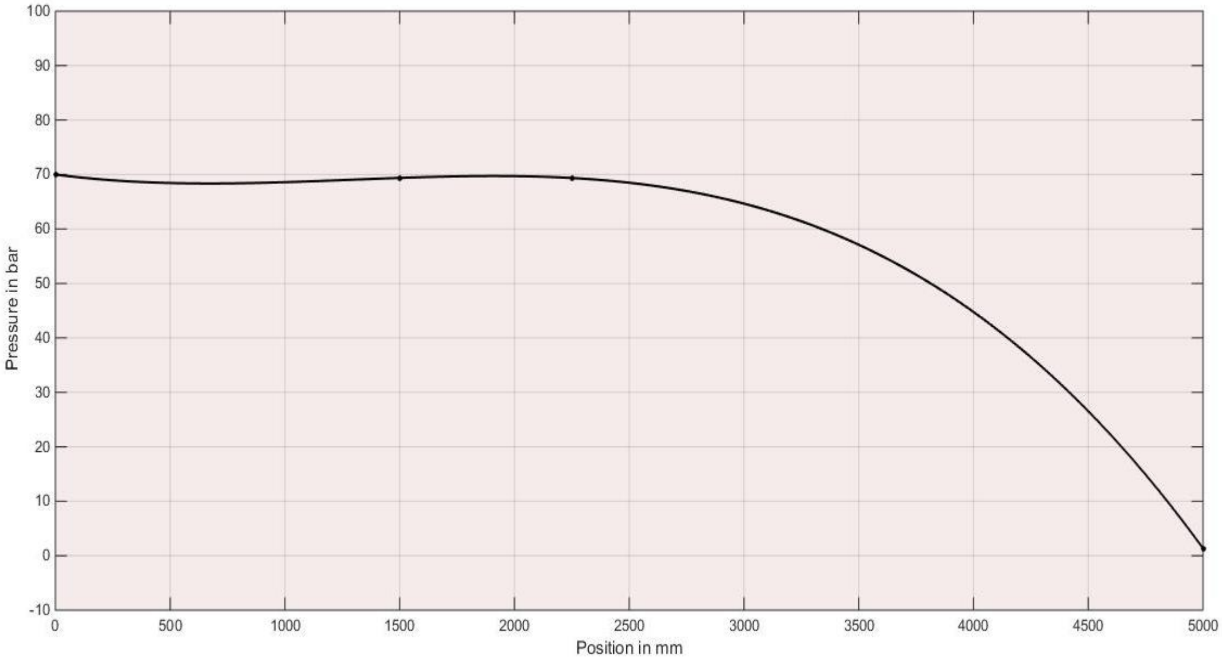

Figure 7. Pressure vs. Position plot – With cooling condition.

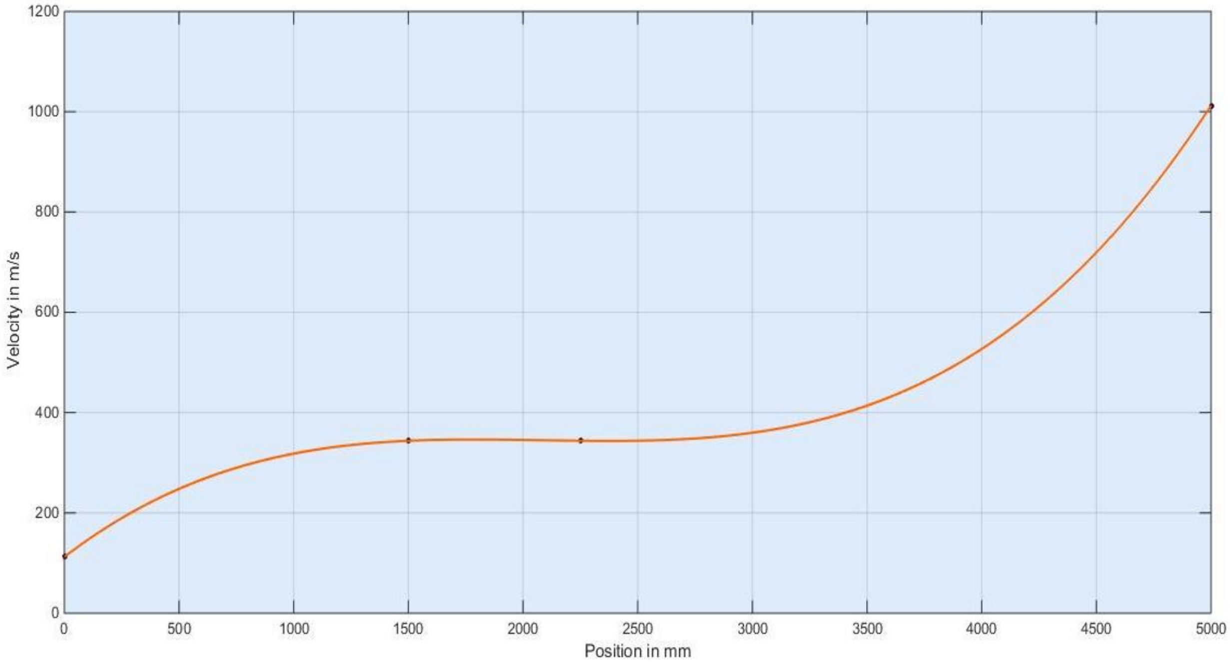

Figure 8. Velocity vs. Position plot – With cooling condition.

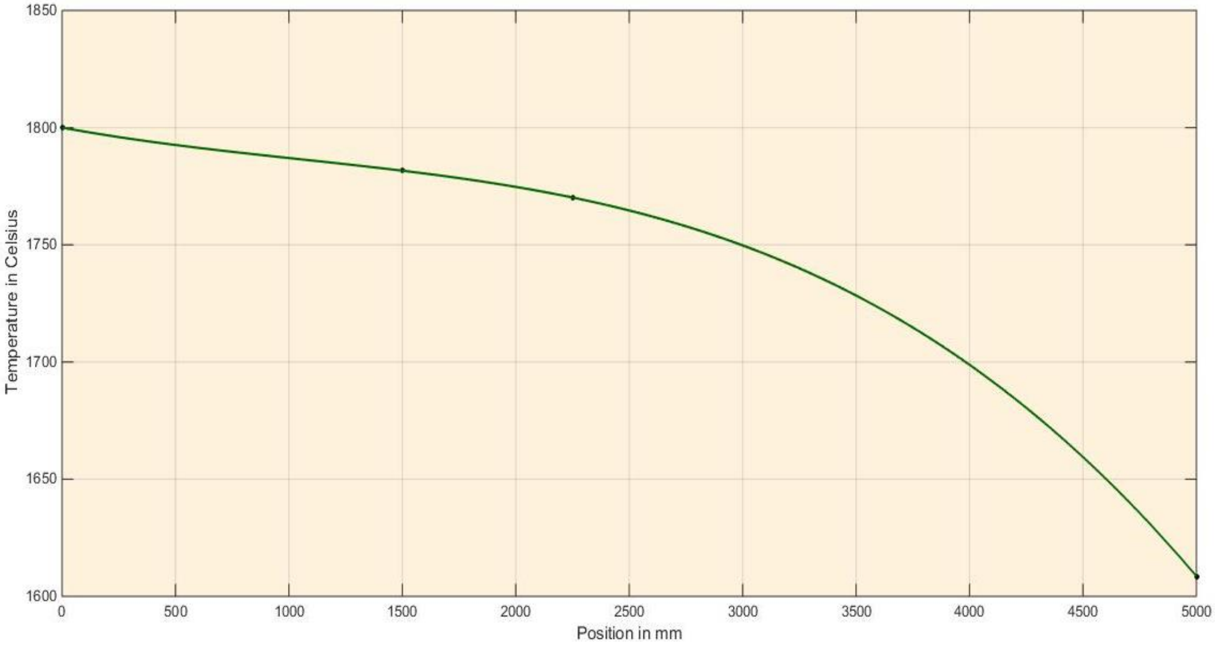

Figure 9. Temperature vs. Position plot – With cooling condition.

It is observed that the cooling of exhaust gas at throat leads to an increase in the density of the gas thus leading to a decrease in the kinetic energy of the gas and thrust generated. The pressure at the throat is nearly constant and it observed that a high reduction in the temperature can lead to a subsonic flow in the throat region, thus further reducing the thrust of the rocket engine. The exhaust gas cooling is done to an extent where the velocity nearly remains sonic in order to have a supersonic flow in the divergent section.

It is also observed that the exhaust gas cooling leads to a decrease in the pressure and enthalpy of the gas at the exit. This also leads to the reduction of the pressure and thrust generation. On the other hand if the exhaust temperature is increased by heating, the density is decreased and the kinetic energy increased thereby an increased the thrust of the rocket. It is important to note that the presence of any throttling device will only reduce the pressure and kinetic energy of the exhaust gas.

The addition of heat energy is not an energy efficient method but it can improve the thrust of the rocket. In outer space, energy can be absorbed by either solar radiation or ambient radiation in space. Even if the combustion energy of the propellant components cannot be extracted to its full potential, the thrust generating capacity of the rocket engine can be in increased in this manner. The heating of the exhaust gas is difficult to achieve as the exhaust is at a very high temperature and the system should be able to achieve even higher temperature to enable heat transfer. One of the methods is to use a plasma generator to increase the temperature of a gas. The generator need not produce an ionizing temperature but it can generate sufficiently high temperatures.

Table 2. Thrust comparison with and without cooling of exhaust gas

Operating condition (Ambient pressure is taken as 0.9 bar)	Exit pressure (bar)	Exit temperature (Celcius)	Exit velocity (m/s)	Thrust generated (MN)
No cooling condition	1.3467	1781	1012.3	2.555
With cooling condition	1.3384	1770	1012.3	2.545

CONCLUSION

In conclusion, thrust cannot be increased by the decreasing the temperature of the exhaust gas. Instead the thrust generated can be increased by increasing the temperature. The increase in temperature leads to an increase in internal energy and enthalpy and a decrease in density, which will be helpful in increasing the kinetic energy of the gas.

The heating of exhaust gas is difficult because the heating system must maintain higher temperature than the exhaust gas. The exhaust gas itself has a very high temperature. But the heating effect can be achieved using high power systems such as plasma generators. Plasma generators area capable of generating very high temperature but they consume lot of energy.
Improvements in the fields of battery technology and photovoltaic cells can lead into better absorption of ambient radiation energy from outer space and thus can support heating systems.

The downside of heating the exhaust gas is expansion of nozzle due to heating and development of wall stresses. The effect on nozzle structure when exhaust gas is subjected to heating should be assessed to achieve a safe and reliable heating mechanism.

ACKNOWLEDGEMENTS

I would like to thank Mr. G. Vinod Kumar, Asst. Prof., MED, KITSW and Ms. G. Sumithra, Asst. Prof., MED, KITSW for their support in this project. I would like to thank Mr. Magnus Holmgren for his open source XSteam MATLAB program. This MATLAB function was used to determine state properties at various locations in the nozzle.

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