

Estimation and Comparison of Thrust for Self-field MPD Thrusters

Mohd Ussama Ahmer

Abstract— Self-field Magnetoplasmadynamic Thrusters are special type of thrusters which consists of two metal electrodes separated by an insulator: a central rod-shaped cathode, and a cylindrical anode that surrounds the cathode. A high current electric arc is driven between the anode and cathode so as to ionize a propellant gas to create plasma. A magnetic field is generated by the electric current returning to the power supply through the cathode. This self-induced magnetic field interacts with the electric current flowing from the anode to the cathode (through the plasma) to produce the electromagnetic Lorentz force that pushes the plasma out of the engine, creating thrust. This document presents analytical estimation and comparison of thrust produced by two different propellants i.e. Argon and Nitrogen, in a Self-field Magnetoplasmadynamic Thruster. The estimation of thrust was done with the empirical model presented by Choueiri. Thrust estimation was performed for two different gases, Argon and Nitrogen, by varying the input parameters like mass flow rate and current. Thrust produced by the Nitrogen gas as propellant was found to be more than the thrust produced by the Argon at same current levels.

Index Terms— Argon, Electric propulsion, Magnetoplasmadynamic Thrusters, Nitrogen, Self-field

1 INTRODUCTION

Electric propulsion is based on the simple principle of separating the energy source and mass source in the thrust of an engine/craft. It is of common knowledge that chemical rockets use the energy stored in the propellants to create hot gas, which then becomes the working fluid in the engine, and is expelled out to generate the thrust. But this entire process also have a simple and fundamental limitation, occurred due to combining of energy and mass sources at one place. Due to this no more energy can be put into the system than that which is already stored in the propellant. The arrival of space age turned into a want of more thrust, this was provided by stretching the capability of chemical rockets to its theoretical best by multi-staging and near perfect efficiencies. But future space conquests require more powerful propulsion system for our ambitious programs like manned mission to the Mars, these type space missions involve large velocity increments, which would result in the requirement of large mass ratio of propellant to be carried by spacecraft, resulting in the heavy weight penalty. The solution is if somehow the capability of existing engine be improved such that the exhaust velocity of the rockets are increased then there may be a solution. But we know that due to chemical limitations, the chemical rockets cannot produce any more exhaust velocity than what it is already producing. The solution to this problem is given in the concept that – is to separate the energy input source from the propellant flow. Then the energy available in the system won't be dependent upon the mass flow rate of the

propellant and more amount of energy can be supplied to a kilogram of propellant than what it can produce from its chemical reaction.

Based upon the form of energy supplied to the propellant, the electric propulsion is now divided into following types

- Electro-thermal propulsion system
- Electro-static propulsion system
- Electro-magnetic propulsion system

The basic electro-thermal engine or otherwise called as resisto-jet, consists of a nozzle with high expansion ratio connected to the thrust chamber where gaseous propellant is heated by passing the propellant through the hot wires conducting electricity. This type of electric thruster uses the same thermodynamic effects to generate a high velocity exhaust stream as does a chemical rocket.

The most basic type of electrostatic thruster is the Arc-jet thrusters, here the propellant gas is heated by passing the propellant gas through an electric arc. A neutral gas is exposed to the electric field produced by the two electrodes, the propellant fluid initially resists the electricity but later on it starts to conduct the electricity as more and more ions are ionized and potential across it is increased. This ionized gas is expelled out in the form of thrust.

If we wish to exceed the exhaust velocities achievable using electrical heating of the propellant, it is necessary to abandon thermodynamic effects and act directly upon the atoms of the propellant by using the electromagnetic field. This implies that the propellant has to be ionized which is already happening in the arc-jet, where it is a nuisance and reducing the efficiency. If the propellant is fully ionized, then direct acceleration of the ions by electric and magnetic fields can produce a very high bulk velocity indeed. Based on operation Electromagnetic thrusters are divided in two categories:

- Ion-thrusters

• Author Mohd Ussama Ahmer is currently pursuing bachelor's degree program in Aeronautical Engineering from Mahaveer Institute of Science and Technology, India. E-mail: m.uahmer88@gmail.com

- Plasma thrusters

Ion-thrusters is the simplest concept where propellant is ionized, and then enters a region of strong electric field, where the positive ions are accelerated. Passing through a grid, they leave the engine as a high velocity exhaust stream.

The low thrust and very high exhaust velocity of ion engines are a disadvantage for many applications where the efficiency of electric propulsion would be beneficial. These disadvantages are attributable to the fact that only the positive ions contribute to thrust. The principle is simple, an ionized gas passes through a channel across which are maintained orthogonal electric and magnetic fields. The current, carried by electrons and ions, which develops along the electric field vector, interacts with the magnetic field to generate a propulsive force along the channel. The force acts in the same direction for both electrons and ions, and so the whole plasma is accelerated.

The lack of efficiency shown in the electrostatic models lead to the constant improvement of existing models. During one such arc jet-related activity that the evidence of an acceleration mode differing from the expected conventional gas dynamic mechanism was gathered, quite serendipitously, by Adriano Ducati at the Giannini Scientific Corporation of Santa Ana, California. In an empirical series of experiments with a conventional short arc jet device it was found that by drastically reducing the propellant gas flow. The exhaust velocity of the hydrogen flow could be increased to values of the order of 100 000 m/s, and the overall efficiency reached 50%.

In its basic form, the MPD thruster consists of two metal electrodes separated by an insulator: a central rod-shaped cathode, and a cylindrical anode that surrounds the cathode. A high-current electric arc is driven between the anode and cathode so as to ionize a propellant gas to create plasma. A magnetic field is generated by the electric current returning to the power supply through the cathode. This self-induced magnetic field interacts with the electric current flowing from the anode to the cathode (through the plasma) to produce the electromagnetic Lorentz force that pushes the plasma out of the engine, creating thrust.

Only self-field MPD thruster acceleration has been successfully modeled analytically, the analytical model for the estimation of thrust of self-field MPDT was given at first by Macker, followed by Tikhonov, and later an empirical model derived by Choueiri.

The first major MPD thruster flight test occurred in 1980 on the Japanese MS-T4 spacecraft. The thrusters were mounted so as to generate torque on the spacecraft and permit measurement of the thruster impulse bit via changes in the satellite spin rate. The second MPD thruster flight test involved using a thruster as a plasma source to study charging of the Space Shuttle. This experiment, part of the Space Experiment with Particle Accelerator (SEPAC) series, was launched in 1983 into a 245 km orbit as part of Spacelab 1. While the system elements were the same as for the earlier

flight; their configuration and qualification testing were changed significantly to accommodate the requirements for mounting on a manned spacecraft.

2 REVIEW OF LITERATURE

A study was done by R.J. Jahn in the year 1968, which resulted in the formulation of the Maecker's formula. The maecker formula is given as

$$T = \frac{\mu_0}{4\pi} \ln \left(\frac{r_a}{r_c} + \frac{3}{4} \right) J^2$$

Where T is thrust, ra is radius of anode, rc is radius of cathode and J is Current driven between electrodes.

The study further states that the total thrust is the combination of the blowing contribution and pinching contribution of the thrust. Electro thermal and electromagnetic effects both contribute to accelerate the gas. Unsteady electromagnetic field effects may produce beneficial spatial non-uniformities in the discharge pattern. The generation of thrust depends upon the efficiency of conversion of electrical energy into the kinetic energy.

A study was conducted by R.J. Sovie and D.J. Connolly in the year 1970 over the effect of background pressure in the thrust generation of the MPDT. The effect of the environmental pressure on the MPDT was studied. Spectroscopic data indicated no significant effect for pressures below 2E-04 torr. Above this pressure, the effects of collisions between the propellant and background gas were detected; i.e. the exit velocity of the primary propellant was reduced. The entrainment and the acceleration of background gas were detected above this pressure. Both effects increased with increase in the tank pressure. It can be seen from the data that in least one case the entrainment seemed to contribute a majority of the thrust at a pressure of 0.2 torr.

A study was presented by A.C. Mallairis ET. Al over the performance of the quasi-steady magnetoplasdynamic thruster. The familiar axisymmetric model was considered with the conical tungsten tip cathode, and the copper plate anode orifice. The performance of the thruster was evaluated with the milliseconds of pulses. The five noble gases were used as propellants, with mass flow rates ranging from 0.1-100 gm/sec. Input currents with 5-50 KA were employed. Result was that the efficiencies vary from 30% to 10% approximately, also based on the other MPD conditions.

A dissertation was submitted by the David and ET. Al for the completion Ph.D. Thesis over the Magnetoplasdynamic Channel Flow for Design of Coaxial MPD Thrusters in the year 1982. The current, mass flow, and electrode geometry of self-field, coaxial MPD thrusters are related to terminal characteristics such as voltage, specific impulse and thrust efficiency by both experiment and a simple 1-D model. For high power, magnetically accelerated flows, analysis shows that the gas is subsonic near the inlet, and that the terminal voltage has a strong dependence on the electrode geometry up to and

including the sonic location. The electrode configuration in the downstream, supersonic portion strongly affects the exit Mach number, which for argon propellant can be as high as 6 or more. Experiments show that terminal voltage-current characteristics remain unchanged within the error bar, when the downstream 9/10th of a long cylindrical thruster is flared to a 3:1 expansion ratio. Thrust efficiency however, is improved in the flared thruster and is 1.5 that of the cylindrical thruster. The 1-D model, with an equilibrium argon state equation, compares favorably with experiments in that the parametric behavior of computed and measured electric fields is the same for current and mass flow variations. By relating the thermodynamics of heat and energy addition to plasmadynamic quantities, the model shows that the thrust efficiency has an asymptote of 0.70, large magnetic Reynolds numbers. Ignoring electrode losses, the model predicts thrust efficiencies of 65% at 1500 secs and 70% above 3000 secs specific impulse. Previous experiments have shown that thrust efficiency and specific impulse are limited by severe erosion which is accompanied by voltage oscillations. Experiments in this thesis show that this limit is improved for both longer electrodes and anodes of smaller diameters. The model shows that axial profiles of the Hall parameter are reduced for these geometry changes. Thus, longer electrodes and smaller anode diameters postpone the occurrence of large and perhaps critical Hall parameters.

A report was presented by M. Martinez Sanchez ET. Al. in the year 1988, with the title of fluid mechanics in magnetoplasmdynamic thruster. In the study both theoretical and experimental results were presented to demonstrate a) the effects of electrode geometry on the operation of the magnetoplasmdynamic arc jet, b) the onset phenomenon was calculated. Several mechanisms for onsets were postulated.

A research was conducted by V.B. Tikhonov in the year 1993 on the plasma acceleration process in self-field and applied field thrusters. Interconnection of flow parameters and magnetic field, defining plasma acceleration processes were established. A coefficient of thrust dependent upon the current driven between the electrodes was given. New formulation was presented in the paper to predict the thrust of the both Self-field and applied field MPD thrust. The new formed relation was,

$$C_T = \frac{\gamma + 1}{2} + \frac{\alpha_0^{-2}}{2}$$

Where CT is the coefficient of thrust, α_0 is the dimensionless parameter.

Edgar Choueiri presented a paper later in the year 1997, on the thrust of self-field MPD thruster. The Maecker formula has long been used to explain the scaling of the thrust of self-field magnetoplasmdynamic thrusters (MPDTs) with the total current. But the Maecker's model is too simplistic and over predicts the thrust, while Tikhonov model under predicts the thrust. Gasodynamic behaviors of plasma are different at lower and higher current levels. So, a

formula was proposed to predict the thrust of self-field MPD thrusters.

3 METHODOLOGY

To compare the analytical model of thrusts for nitrogen and argon, Choueiri's empirical mathematical model was employed. The model successfully interrelates various parameters like thrust, mass flow rate, current, etc.

Choueiri's scaling formula is based on establishing a simple, though semi empirical formula, for coefficient of thrust (CT) as the function of current driven between electrodes (J). A formula that will hold well for different propellants and at different mass flow rates (m.). Central to this model is a dimensionless current ξ also defined as Critical ionization velocity, obtained by

$$\xi = J / [m^{1/2} \left(\frac{2\epsilon_i}{m_a} \right)^{1/4} / \left(\frac{\mu_0}{4\pi} \ln \frac{r_a}{r_c} \right)^{1/2}]$$

Where, m_a is the mass of the neutral atom, and ϵ_i is the first ionization potential of the neutral atom.

Plasma instabilities in the MPDT, and also the acceleration of propellant are due to the action of current, the energy sink equipartition is stated as

$$\frac{1}{2} T u_{ex} = \dot{m} \frac{\epsilon_i}{M}$$

Where, u_{ex} is the exhaust velocity of the plume.

From the Maecker's model we have relation,

$$T = (\mu_0 / 4\pi) C_T J^2$$

By substituting in above relation we get,

$$\frac{\mu_0}{4\pi} C_T J^2 u_{ex} = \dot{m} u_{ci}^2$$

Where, $u_{ci} = \left(\frac{2\epsilon_i}{m_a} \right)^{1/2}$ and is known as critical ionization velocity.

The current that produces exhaust velocity equal to the critical ionization velocity is called as critical ionization current.

$$J_{ci} = \left(\frac{\dot{m} u_{ci}}{\frac{\mu_0}{4\pi} C_T} \right)^{1/2}$$

And also,

$$\xi = \frac{J}{J_{ci}}$$

The coefficient of thrust CT is given as $\ln \left(\frac{r_a}{r_c} + \xi^2 \right)$

For $\xi = 1$, $J = J_{ci}$

$$T = \left(\frac{\mu_0}{4\pi} \right) C_T \xi^2 \left(\frac{\dot{m} u_{ci}}{\frac{\mu_0}{4\pi} C_T} \right)$$

Data was analyzed based on the equations presented above. The table below shows various parametric dependencies.

Table 1: Parametric Dependencies

System Performance Parameter	Dependency	Variation
ξ_r	Assumed	0.2 units/step
r_a, r_c	Assumed	Constant
C_T	Dependent on ξ, r_a, r_c	From corresponding relations
J_{ci}	Dependent on \dot{m}, u_{ci}, C_T	
J	Dependent on ξ, J_{ci}	
T	Dependent on C_T, J	

4 RESULTS

Based upon the equations presented in chapter 3, estimation of thrust for Argon and Nitrogen Gas as propellant was performed using Excel and related graphs were produced.

Calculations were performed for varying mass flow rates (1-10) gm/sec, and by varying the dimensionless current parameter ξ (0-5) with steps of 0.2 units/step.

The graphs were plotted for thrust T vs current J and also for the thrust T vs dimensionless current parameter ξ .

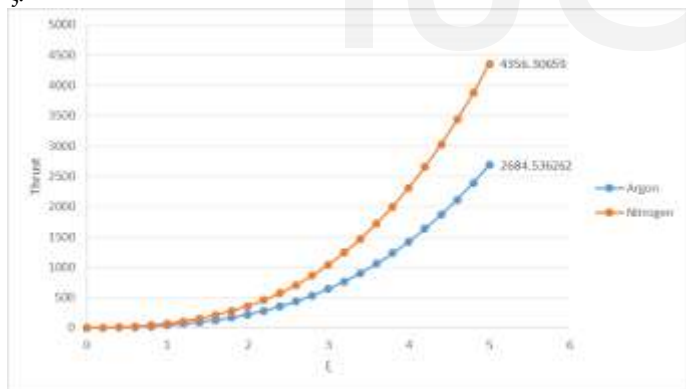


Fig 1: Thrust vs ξ at $\dot{m} = 1 \text{ gm/sec}$

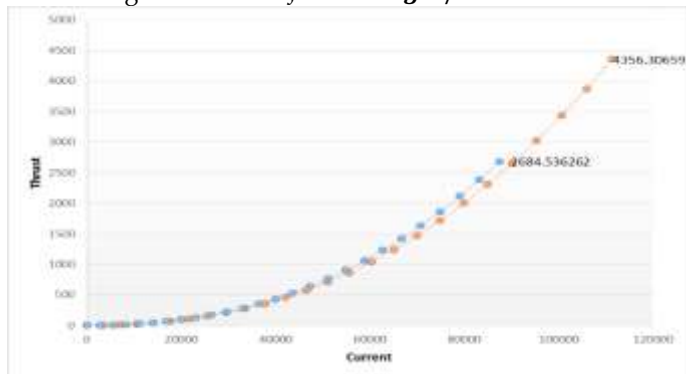


Fig 2: Thrust vs Current at $\dot{m} = 1 \text{ gm/sec}$

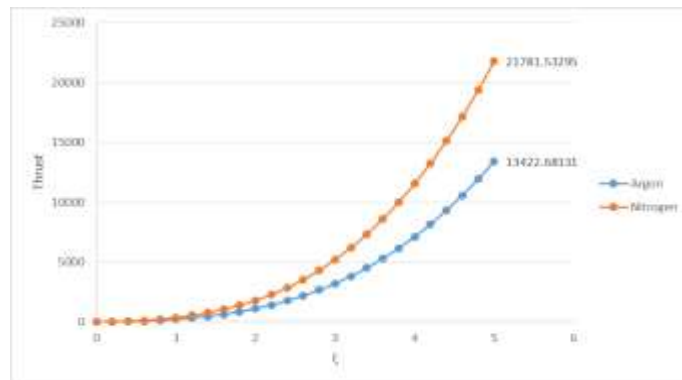


Fig 3: Thrust vs ξ at $\dot{m} = 5 \text{ gm/sec}$

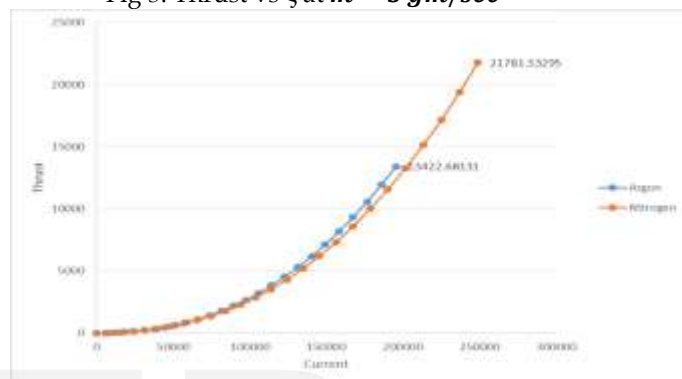


Fig 4: Thrust vs Current at $\dot{m} = 5 \text{ gm/sec}$

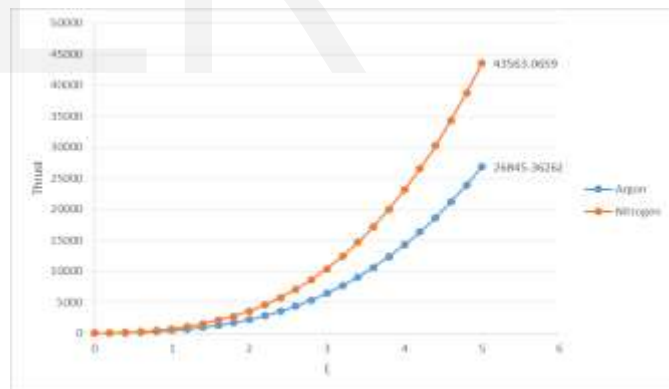


Fig 5: Thrust vs ξ at $\dot{m} = 10 \text{ gm/sec}$

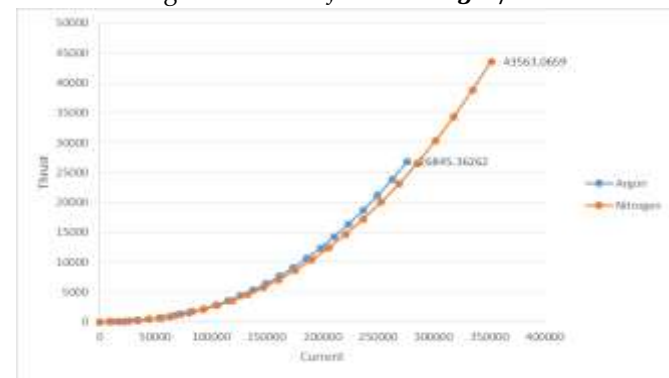


Fig 6: Thrust vs Current at $\dot{m} = 10 \text{ gm/sec}$

5. CONCLUSION

Comparison of thrust was done for Argon and Nitrogen gas as propellants. Nitrogen produced more thrust than argon for same level of ξ . It is evident from the data that the thrust depends on mass flow rate m , critical ionization velocity of the propellant u_{ci} , and the current driven between the electrodes J . Thruster operating at same value of ξ show similar characteristics, and a similar pattern was found in the T vs J graphs. In overall result, the Nitrogen was found to be a better propellant than the Argon.

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