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NUMERICAL SIMULATION STUDIES ON THE INFLUENCE OF ARGON AND XENON IN MAGNETOPLASMA DYNAMIC THRUSTERS

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ABSTRACT
Numerical simulation of Magnetoplasmadynamic Thrusters (MPDT) using COMSOL Multiphysics, focusing on the impact of electromagnetic fields on plasma behavior and thrust generation. MPDTs, which accelerate ionized plasma via Lorentz forces, hold significant potential for long-duration space missions. Propellant gases like Argon a Xenon are used in the plasma module to assess electron density, and electron temperature along with this Electric current and Creeping Flow are used for electric potential velocity and pressure contours. The inlet mass flow rate is 15 kg/s and a voltage of 3 kV was carried out. Such discoveries provide the basis for developing more innovative MPDT models for space missions.

Keywords: Magneto Plasma Dynamic Thruster, MPDT, Electric Propulsion, Electromagnetic Propulsion, Etc.

I. INTRODUCTION

Plasma, or ionised gases, are used in plasma rockets, an advanced type of thruster, to push spacecraft around. Plasma rockets are fundamentally different from conventional chemical rockets which operate according to combustion principles to create high velocity exhaust products, plasma rockets make use of electric and magnetic fields to accelerate plasma particles [1] [5]. These particles are sat to incredibly velocities and are made up of ions and electrons. They make them ideal for a long-duration program such as interplanetary flights as it allows them to get significantly higher exhaust speeds without having to use biospheres and other natural resources [2]. Most of the time the plasma is formed by ionizing a neutral gas like Argon, xenon etc. Electromagnetic fields then used to accelerate the hence the charged particles whereby forming a propulsion system. Plasma rockets are ways more efficient to chemical rockets because there is no need for combustion. Ion thrusters, Magnetoplasmadynamic thrusters, hall thrusters, VASIMR and so on are some of the most familiar examples of Plasma propulsion system [3].

As for plasma rockets, potential power specifications are given with a greatly decreased mass flow rate but an increased exhaust velocity. Most of them use plasma, which is a more energy state, to achieve greater exhaust velocities ranging from 5 to 50 kilometers per second [4].

The plasma thruster can be categorized into three types:

- Electrothermal Propulsion
- Electrostatic Propulsion
- Electromagnetic Propulsion

This can be further having sub parts which are shown in table below:

Table 1: Types of Plasma Rockets

Electrothermal Propulsion	Electrostatic Propulsion	Electromagnetic Propulsion
Resistojet	Ion thrusters	Magnetoplasmadynamic Thrusters (MPDT)
Arcjet	Field Emission Electric Propulsion Thrusters (FEEPT)	Hall Effect Thrusters
Electrothermal Hydrazine	Microwave or Radio-frequency Ions	Variable Specific Impulse Magnetoplasma Rockers (VASIMR)
Microwave	Plasma Separator Ions	Helicon

Electrothermal		
Pulsed Electrothermal	Electrohydrodynamic Thrusters	Induced Pulse

The idea on which MPDTs rely is based on the Lorentz force wherein force is applied on plasma, charged particles when they are moving through electric as well as magnetic field. The thruster, in many cases, includes the central cathode and the annular anode that comprises coaxial geometry [5] [7]. Between the electrodes it is necessary to introduce a gas propellant, often an inert one such as argon or xenon. Ideally, when current density is high in the plasma, discharge between anode and cathode interacts with the magnetic field: either self-magnetic or external. Interaction within this system increases plasma velocity to very high velocities creating thrust [6].

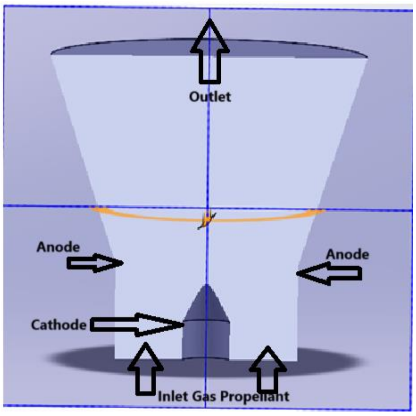

Figure 1.1: Schematic design of MPDT.

Magnetoplasmadynamic Thrusters (MPDT) are chosen to offer the high thrust to power ratio and versatility for achieving mission objectives in multiple profile scenarios [8]. MPDTs employ electromagnetic fields both to accelerate plasma and as a result, exhaust velocities and, as a result, efficiency of accelerating are impressive. This makes them optimal for deep-space missions in that high-performance propulsion systems are obligatory [9]. It consists of components like Anode, Cathode, Insulator, Propellant gas Inlet and Outlet show in Figure 1.

A high-power MPDT (200 kW to 1 MW) with long-lasting capabilities has not yet been demonstrated. The lifespan of these thrusters is primarily constrained by cathode erosion, which lasted 500 hours at 30 kW [10] [11]. Current efforts focus on understanding power loss mechanisms, identifying key acceleration processes in applied fields, and reducing electrode erosion [23].

The applied-field MPDTs compared to self-field devices, their scaling characteristics remain largely unexplored. Testing was conducted at an argon propellant flow rate of 15 kg/s and discharge currents ranging from 8, 10 and 12 kA. Various factors limit MPDT performance, including electrode power dissipation, frozen flow losses, and the "onset" phenomenon, which encompasses a range of issues such as high-frequency voltage fluctuations, anode spot formation, and increased erosion in the chamber [12] [15].

II. THEORETICAL MODEL (0D)

MPD thrusters main operate through the use of electromagnetic acceleration. Here, acceleration of a body of ionized gas is accomplished through the action of currents passed through the gas and the magnetic fields either generated by those currents or externally imposed [24]. Suppose we have a flow of ionized gas, which experiences Electromagnetic fields which both act perpendicular to both E and u [13] [16]. If the gas has scalar conductivity, σ, then current density, $j = \sigma(E + vB)$ will flow across the gas parallel to E interacting with magnetic field B to get a distributed body force density $f_b = j \times B$.

III. ANALYTICAL MODE (1D)

The Governing equations for MPDT model which includes:

(a) Continuity Eq.

$$\frac{\partial(\rho A)}{\partial t} + \frac{\partial(\rho U A)}{\partial z} = 0$$

(b) Momentum (with Lorentz Force)

$$v\frac{dv}{dz} = -\frac{1}{\rho}\frac{dp}{dz} + \frac{1}{\rho}jB$$

(c) Energy

$$\frac{j^2}{\sigma} - Q_{loss} = \rho v c_p \frac{dT}{dz} - v\frac{dp}{dz}$$

(d) Ohm's Law

$$j = \sigma(E - vB)$$

(e) Eq. of the state

$$p = \rho Rt$$

(f) Maxwell's Eq.

$$j = -\frac{1}{\mu_0}\frac{dB}{dz}$$

(g) Thrust

$$T = \dot{m} \cdot V_e$$

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Table 2: Collisions and Reaction Modeled for Ar

Reaction	Formula	Type	Energy loss(eV)	Reaction Rate coefficient
1	e+Ar=>e+Ar	Elastic	0	0
2	e+Ar=>e+Ars	Excitation	11.5	5e-9
3	e+Ars=>e+Ar	Super elastic	-11.5	1e-11
4	e+Ar=>2e+Ar+	Ionization	15.8	1e-8
5	e+Ars=>2e+Ar+	Ionization	4.24	4e-8
6	Ars+Ars=>e+Ar+Ar+	Penning ionization	-	6.2e-10
7	Ars+Ar=>Ar+Ar	Metastable quenching	-	3e-15

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Table 3: Surface Reactions for Ar

Reaction	Formula	Sticking Coefficient
1	Ars=>Ar	1
2	Ar^{+}=>Ar	1

Table 4: Collisions and Reaction Modeled for Xe

Reaction	Formula	Type	Energy loss(eV)	Reaction Rate coefficient
1	e+Xe=>e+Xe	Elastic	4.2	1e-9
2	e+Xe=>e+Xes	Excitation	8.31	5e-9
3	e+Xes=>e+Xe	Super elastic	-8.31	1e-11
4	e+Xe=>2e+Xe+	Ionization	12.13	1e-8
5	e+Xes=>2e+Xe+	Ionization	3.8	1e-8
6	Xes+Xes=>e+Xe+Xe+	Penning ionization	-	6e-10
7	Xes+Xe=>Xe+Xe	Metastable quenching	-	3e-15

Reaction	Formula	Sticking Coefficient
1	Xes=>Xe	1
2	Xe^{+}=>Xe	1

IV. RESULT AND DISCUSSION

Three physics modules are used for both Argon and Xenon in this paper which are Plasma, Electric Current, Creeping flow (Laminar Flow) that gives an output for Electron Density, Electron Temperature, Electric Potential and Velocity and Pressure Flow.

It is generated by using the reactions for Argon, Xenon propellant gas which are shown in tables above (Table 2 to 5).

(a) Electron Density $(1/m^3)$

Electron Density stands for free electrons per unit volume of plasma which is immensely helpful in determining the conductivity or ionization concentration in plasma used for Magnetoplasmadynamic Thrusters (MPDT). Improved densities are indeed good for conductivity and propulsive efficiency [17]. It has helped monitor the ionization and energy usage enabling improved thrust production.

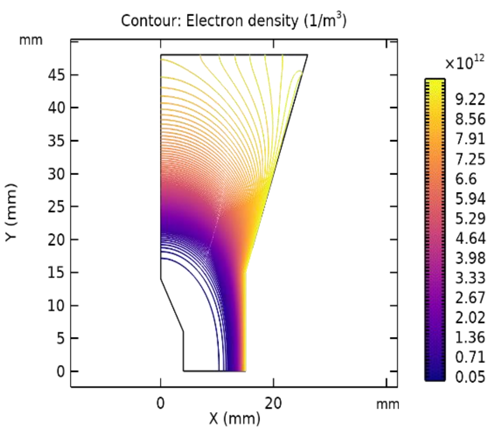

Figure 4.1: Electron Density contour for Argon.

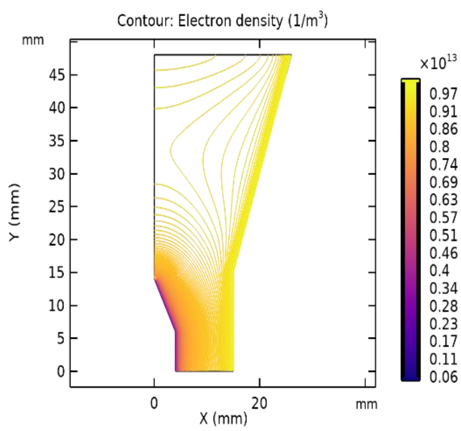

Figure 4.2: Electron Density contour for Xenon.

Discussion: For Figure (4.1) in terms of force, argon has got higher electron density and is more preferred in applications that demand high thrust with small energy. For Figure (4.2) although xenon has a lower electron density, it is far more efficient and has a longer lifetime than the others, particularly in applications where continuous push is being utilised.

(b) Electron Temperature (eV)

Electron Temperature in pertinent to the average kinetic energy of electrons in plasma and has the unit of electron volts (eV) [18] [19]. It represents the amount of energy available for ionisation, and as well reveals that a high temperature is preferable for ionising the neutral gas, which is important in Magnetoplasmadynamic Thrusters (MPDT). Understanding it contributes with shaping the desired rates of ionization and raising the thrust-to-power ratio for stable plasma.

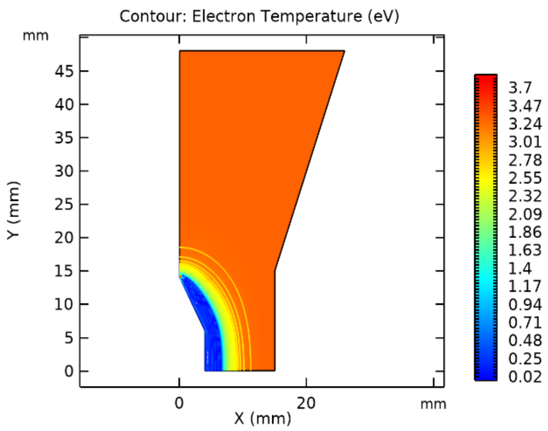

Figure 4.3: Electron Temperature contour for Argon.

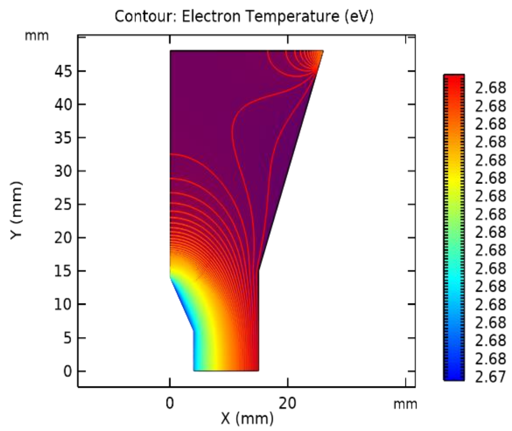

Figure 4.4: Electron Temperature contour for Xenon.

Discussion: For Figure (4.3) Argon is effective at moderate temperatures in achieving ionization, but For Figure (4.3) Xenon demands more energy at a lower temperature, yet electron temperatures remain higher for the same duration of ionization. Argon is suitable for high thrust at the moderate level of power, the contrary of which is Xenon that has high efficiency in longer missions maintaining the stability of the plasma.

(c) Electric Potential (V)

Electric Potential, given in volts (V) determines how charged influx of plasma is motivated through a field of energy/charge for both ions and electrons. Although a higher potential is useful in managing ion acceleration in Magnetoplasmadynamic Thrusters (MPDT) because a higher kinetic energy results in increased thrust [20]. It describes the method on how well efficiencies in ion acceleration are achieved and propulsion is effectively provided.

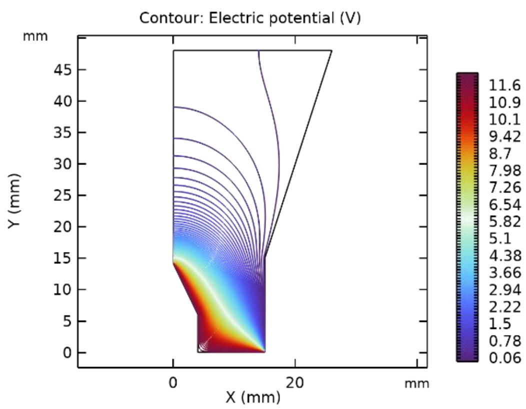

Figure 4.5: Electric Potential contour for Argon.

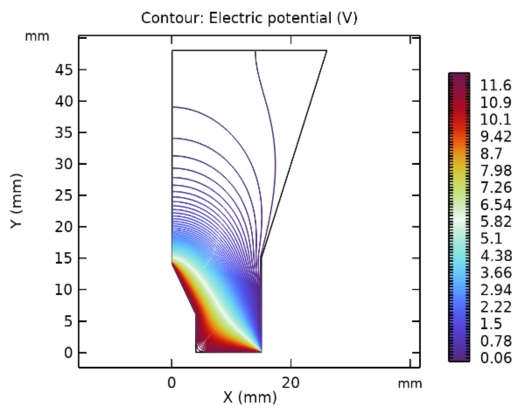

Figure 4.6: Electric Potential contour for Xenon.

Discussion: For Figure (4.5) and Figure (4.6) they are same because of their roles as ionized propellants during the interaction with electric or magnetic fields. These two gases when ionised, produce plasma that reacts to these fields in a manner that is highly dependent on charge/mass ratio. Despite the fact that the ionization

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process occurs at xenon has an atomic mass greater than argon, the electrical potential difference of the process at lowest retouring to the operating conditions of the thrust revolve around. This has generated similarities for the electric potentials when used as propellants because the dynamics and the thrust of the plasma and the thrust generation depend on the charges and mobility of the ions rather than the gases themselves.

(d) Velocity (m/s)

Velocity, ejected per frame from the thruster are quantified in meter per second, m/s [21]. It directly influences the thrust in Magnetoplasmadynamic Thrusters (MPDT), with higher the exit velocity, suggesting higher the thrust and specific impulse required for efficient propulsion.

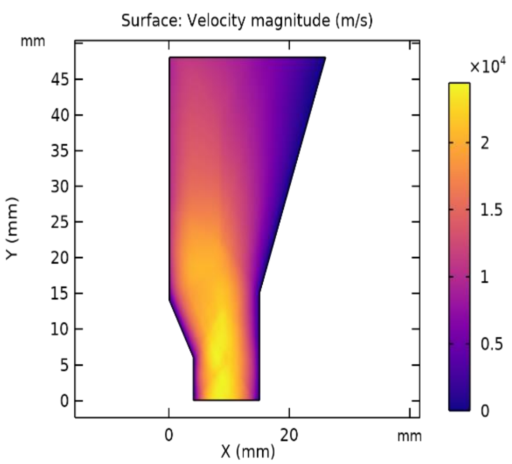

Figure 4.7: Velocity contour for Argon.

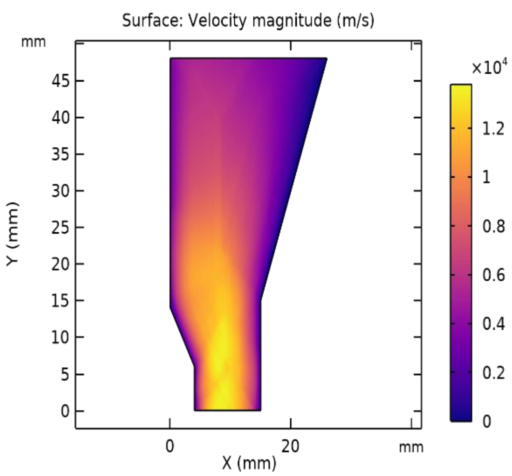

Figure 4.8: Velocity contour for Xenon.

Discussion: For Figure (4.7) due to higher velocity of ejection Argon yields higher thrust and is suitable for applications that involve a quicker acceleration. For Figure (4.8), the lower velocities obtained in Xenon are coupled with a higher mass flow rate giving long duration thrusts, good for missions which require longer thrust than acceleration.

(e) Pressure (pa)

Pressure is expressed in Pascals (Pa) and is equal to the force applied to unit area of plasma and exhibits its density and thermal energy. It affects Plasma stability and the thrust distribution within Magnetoplasmadynamic Thrusters (MPDT) [22]. Monitoring Pressure is in the role of sustaining the plasma density, and energy distribution stability, maintaining constant thrust and reliability of thruster parts.

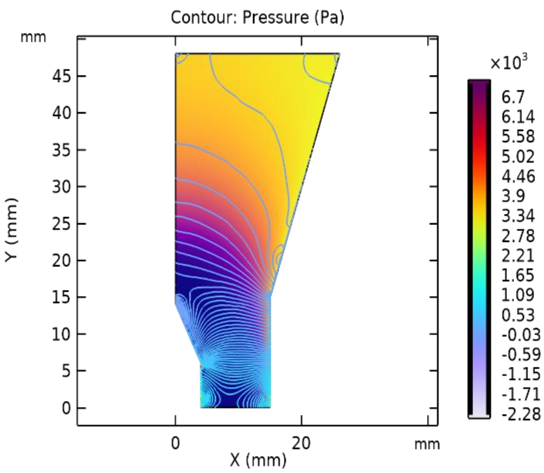

Figure 4.9: Pressure contour for Argon.

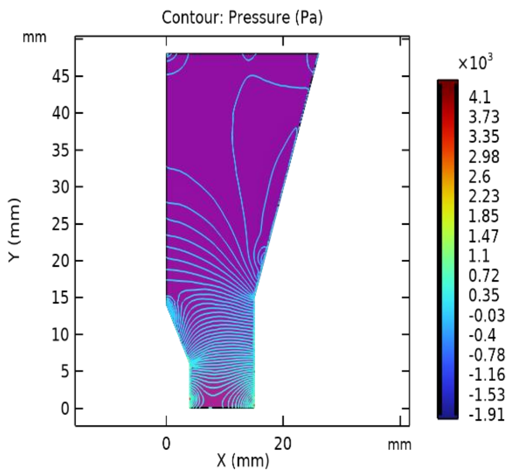

Figure 4.10: Pressure contour for Xenon.

Discussion: For Figure (4.9) due to the higher and more uniform pressure distribution of Argon, the thrust is tenable and produced quickly at higher acceleration for missions requiring Agile acceleration. For Figure (4.10) pressure distribution especially on Xenon side is low but concentrated in that it provides for efficient, controlled thrust for long durations and this make it proper for missions which require endurance and energy conservation.

NOMENCLATURE

T: Thrust (N)

Ve: Exit velocity (m/s)

m: Mass flow rate of the propellant (kg/s)

σ: Conductivity (S/m)

J: Current density (A/m^2)

B: Magnetic field (T)

E: Electric field (V/m)

ρ: Plasma density (kg/m^3)

v: Velocity of the plasma (m/s)

p: Pressure (Pa)

T_e: Electron temperature (K)

n_e: Electron number density ($1/m^3$)

V: Electric potential (V)

V. CONCLUSION

Comparative analysis of the use of Argon and Xenon in the MPDTs analysis shows that both gases offer major strengths depending on the specific mission needed. Argon, having a higher electron density and attracted with higher ejection velocity is suitable for applications where higher thrust and acceleration are required over a less duration. This makes it suitable for missions that require high speed as with conventional rocket guidance systems. However, it is characterized by less electron density and ejection velocity but greater resource saving and longer service life. Hence, Xenon is suitable in long duration space missions in which steady, regulated power is required for generating a specific thrust.

The computer simulations indicate that Argon has a higher thrust-to-power ratio at mid to low power levels, so will be suitable for highly manoeuvrable missions. Compared to the previous generation arc-jet engines, xenon is preferred for deep space missions due to higher efficiency for sustained thrust, while maintaining stability. Therefore, the decision whether to fill Argon or Xenon shall be shaped by the mission, energy, and thrust to accommodate in relation to MPDTs always as a versatile solution for all demands concerning space exploration propulsion systems.

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