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Basic MATLAB simulation of ion propulsion rocket by chlorine as propellant via negative ion pair thrusting

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Ion propulsion rocketry is increasingly becoming popular by ion-ion pair thrusting concept, because they need low propellant, and design thrust around 1.5 N with low electric power and high efficiency. Basic MATLAB simulation of negative ion-negative ion pair propulsion has been explained in this article. Negative ion plasma has been obtained from electronegative gas, e.g. chlorine, by attachment of electron. Formation of large stable negative ion is achievable due to high electron affinity of chlorine. Electron affinity is a measure of energy exchange due to the addition of electron to a neutral atom to form a negative ion. When the neutral chlorine picks up electrons and forms chloride (Cl^-) ion, the energy released due to exothermic reaction is -349 kJ/mol (i.e., -3.6 eV/atom). Mechanism of attachment of electron to chlorine involves the formation of intermediates. Due to that, the high repulsive force is created between the same negative ions. Average distance between any neighbouring ions is important for rocket thrust calculation, and is determined by propellant exhaust velocity. Mass flow rate of propellant is assessed from the ratio of total mass of propellant needed for operation to time periods. This accelerates negative ions to a high velocity in the thrust vector direction with a significantly intense magnetic field and the exhaust of negative ions through nozzle. On comparing with theoretical value and earlier method (xenon ion-electron), this method is capable of achieving required thrust with low electric power (1 kW).

Keywords: Ion propulsion rocket, Negative ion pair thrusting, MATLAB, Simulation, Aerospace

1 Introduction

In general, a rocket is a vehicle to carry satellite to space. It includes satellite launch vehicle, space shuttle[1], etc. Operation of rocket is based on Newton's II law of motion. Ion propulsion rocket needs only $1/10^{th}$ of fuel used in chemical rockets[2]. But, thrust generated is relatively low; and hence this propulsion cannot be used to lift up from earth, or to leave from earth's gravitational pull. However, ion propulsion can provide a large velocity needed for long interplanetary mission, and will take a lead role in the future of rocketry[3]. This propulsion method reduces the total mass of the rocket, and reaches far-off targets at low thrust[1,4].

In ion propulsion, ionization chamber produces the ions with the help of RF power. While producing ions, the internal temperature and internal pressure of the chamber increases rapidly. The high pressurized ions are ejected through ion acceleration chamber. The ion acceleration chamber enhances the thrust of the ions[5]. The required thrust is produced with the help of high RF power (electric power). The Recombination between ions and electrons is rather a slow process and the presence of electrons downstream adds to the ionization in this region. Hence, even if charge neutrality is ensured, the downstream plasma with charged particles exists outside the thrust body. This plasma is known as the plasma plume[6]. One of the major problem with this plume is the accelerated ions might undergo charge exchange collision with the slow neutrals, which in turn produces slow ions that can backscatter and deposit on the thruster body, solar panels, and scientific instruments[1].

Reaching the Mars orbit is time consuming travel, and takes around 9 months for the present methods. To overcome this delay and difficulty concerned, the base is needed on the ion-ion par techniques of ion propulsion rocket[7].

The new ion propulsion system is now intensively studied with negative ion-negative ion pair using chlorine gas[1]. In addition, chlorine atoms can gain electrons through heated ferroelectric cathode to form negatively charged ions[8]. Electron gun[8] is based on a ferroelectric cathode made up of a 5 × 5 × 5 mm^3 lead:lanthanum:zirconium titanate in 12:65:35 ratio ceramic plate and its energy spread is 6-100 eV, trigger voltage is 0.8-1.5 kV, anode voltage is 0.5 kV.

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The knowledge of the mean free path is useful to evaluate the distance from which negative ions can be extracted and to understand the relative importance of collision with positive ions[9]. Calculated distance (R) between same type negative ions is maintained on the value that is lower than the value calculated from mean free path relative to collision with positive ions[9]. Its main determined factor (R) divided by time taken is calculated with the help of negative ion particle mass in terms of proton mass. The required thrust is produced with low electric power[6]. The proposed method (Cl^--Cl^- pair concept) may help the rocket to reach the Mars orbit in time less than 90days and also used to space propulsion[1].

2 Materials and Method

Governing Newton's II law is simplified for thrust as per Case 1 Equations of Table 1. Thrust is a force supplied by rocket engine to the Mars mission, since the Mars mission equipment mass changes with time due to propellant consumed[3]. The thrust is calculated by the time rate of changes of momentum.

Mass flow rate and amount of propellant needed are assesses as per Case 2 Equations of Table 1. For a cumulative period of days of operation, need for amount of chlorine gas propellant (m) is obtained by multiplying mass flow rate by time period requiring propellant. Calculation of propellant flow rate is the ratio of amount of propellant to time period requiring propellant. Similarly, other method of calculation of propellant flow rate is due to negative ions via ion beam current[10-12] (I_b).

Case 3 Equations of Table 1 helps in many calculations. Firstly, Cross-section is around 10-14 m^2 when attachments of electron with chlorine gas to form negative ions. Calculation of distances (R) between the same negative ions is related by the following equation of state. Electron affinity is also calculated[13] as per Case 3. The collision-less process starts when $\Delta E < 3.6$ eV. R is less than the one that was calculated using mean free path (λ) relative to the collision with positive ion. The time (τ_o) taken for the distance (R) between same negative ion related to the accelerating voltage (accelerating parameter is magnetic field) is also as per Case 3. Exhaust velocity (v_{ex}) is given by R/ τ_o. Finally, thrust is calculated as per Case 3.

Figure 1 shows the ion propulsion rocket system containing the following components : tank with chlorine gas (contained as cryogen), electron gun (cathode and annular anode), high power voltage supply (500V), ionisation chamber ($Cl_2+2e \rightarrow 2Cl^-$

Table 1 — Equations Used in Modeling Ion Propulsion Rocket.

Case	Equation	Description
1	Newton's II Law of Motion $T = \frac{d(m_p v_e)}{dt}$ $T = \dot{m}_p v_e$	$\dot{m}_p$ - propellant mass flow rate in kg/s v_e - exhaust ion velocity of the propellant m_p – mass of propellant
2	Propellant Mass Flow Rate $m = \dot{m}_p t_p$ $\dot{m}_p = m/t_p$ $\dot{m}_p = I_b Mi/q$	m – amount of chlorine required t_p - number of days X 24 × 3600 Ib – ion beam current Mi – mass of ion in terms of mass number q – charge on electron
3	Exhaust Velocity and Thrust $R = \sqrt[3]{1/n}$ $\Delta E = E_i - E_f$ $\tau_o = R\sqrt{\frac{M_i}{2eV}}$ $v_e = \frac{R}{\tau_o}, T = \frac{m}{t_p}\frac{R}{\tau_o}$	R – Distance between same type of ions n – negative ion density ΔE - electron affinity for ion τ_o – time taken for accelerating ions v_e - escape velocity

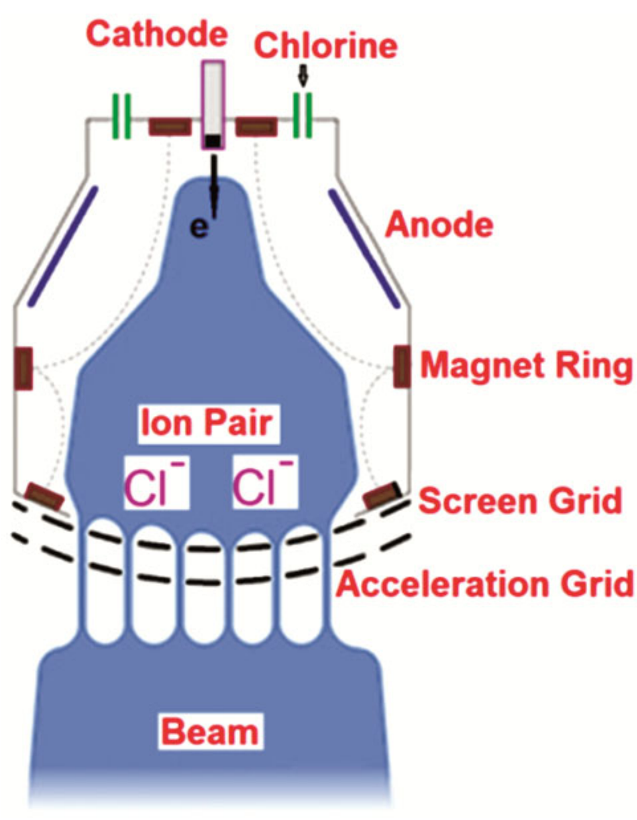

Fig. 1 — Schematic of ion propulsion rocket system.

plasma), and strong magnetic field[5,14,15] (500G). MATLAB was used in getting solutions and plots of all rocket equations enumerated in Table 1. (As these are simple calculations, and reside on basic rocketry ideas; Microsoft EXCEL software can also be used to solve.)

3 Results and Discussion

Rate coefficients (reaction: attachment of electron to chlorine) were calculated due to the velocity of electron that has been taken with slight variation in the energy level of electron beam. The simulation results are shown in Fig. 2, that indicates a linear dependence of the operating rate coefficient on the energy level of electron beam, the linear dependence typical to velocity of electron with a mass of electron (9.1×10^{-31} kg) is opposite to the supply voltage (300-500 V) dependence in spreading energy of electron beam (eV), a electron beam is in interaction with a chlorine atom in the rate coefficient is extremely large and inversely proportional to the distance between same atom negative ions. In this case, most electrons created are converted to negative ions, hence forming negative ion-negative ion beams.

Figure 3 shows the radial negative ion fraction (α) due to magnetic fields and confines that for high magnetic fields (500G). The plasma presents the usual stratified structure with an electronegative (α is large) at magnetic field case radius (r) of 0.05 m. The plasma appears electronegative along the whole radius. In addition, for r < 0.12 m, the negative ion density becomes several orders of magnitude lower than that of the electron. Table 2 gives distance between neighbouring negative ions. In the case of only maintaining electron affinity value for chlorine gas, the reducing of ion fraction value at high radius because of negative of negative ion density is larger than electron, hence forming a positive ion –negative ion plasma.

Figure 4 shows negative ion densities and electron densities as a function of radius for the magnetic field

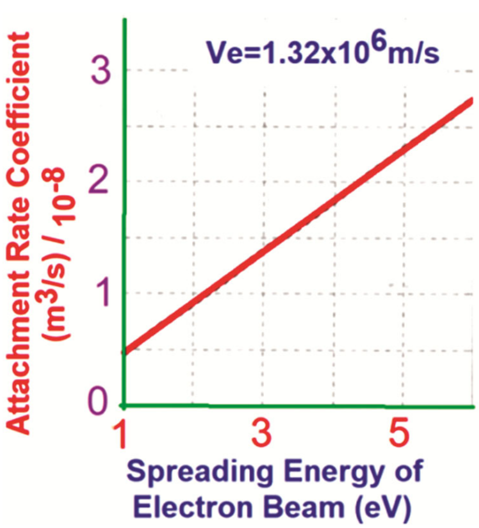

Fig. 2 — Attachment rate coefficient as a function of energy of electron beam.

Table 2 — Calculated distance between same ions.

Radius(m)	Number Density(/ m^3)	Distance(m)
0.015	10^{19}	4.6×10^{-7}
0.2	10^{18}	1×10^{-6}
0.3	10^{17}	2.5×10^{-6}

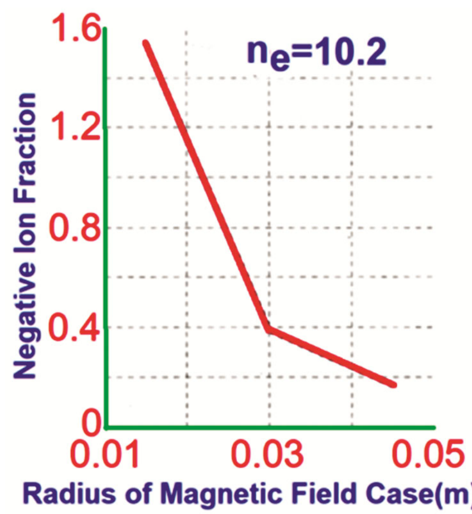

Fig. 3 — Negative ion fraction as a function of radius.

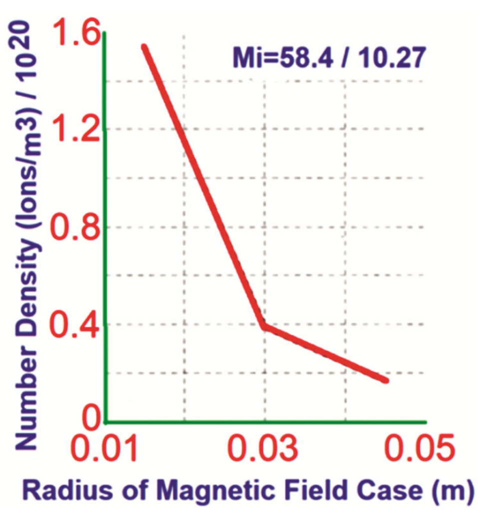

Fig. 4 — Negative ion density as a function of radius.

case. The ion fraction increases and negative ion density becomes of lower order of electron density (10^{20}). At a r ≤ 0.015 m, the negative ion-negative ion density of the order of 10^{19} /m^3.

The same charge amount of ions is created at underneath range of electron affinity (ΔE = 3.6 eV). Its range should be around 3 eV which is proposed for this technique. The thrust force depends only on the negative ion charged particles and must be of the same sign if the two ions are of the same charge, they will move in the same direction. Table 3 shows the distance calculated for same ions. The final energy (3 eV) of negative ion depends on temperature, distance between same ions dependence on the attachment of cross-section.

Figure 5 shows cross-section along with the attachment of electron beam to atom under the initial energy (6 eV) of spreading electron. The cross-sectional area is around 0.9 × 10^{-14} m^2 at the temperature 34815 K and distance between same ions is 4.6 × 10^{-7} m. The linear dependence typical to distance between same ions which is related to number density per unit volume, is opposite to the cross-section which is directly proportional to the negative ion temperature.

Table 3 — Comparison of previous method with present method.

Parameter	Ion-electron pair	Negative ion pair
Engine	Ion engine (Hall effect thruster, magnetic plasma dynamics)	Ion propulsion with negative ion pair
Thrust	67.2mN	1.5N
Power	2.05kW	2kW
Propellant	Xenon (Xe)	Chlorine(Cl_2)

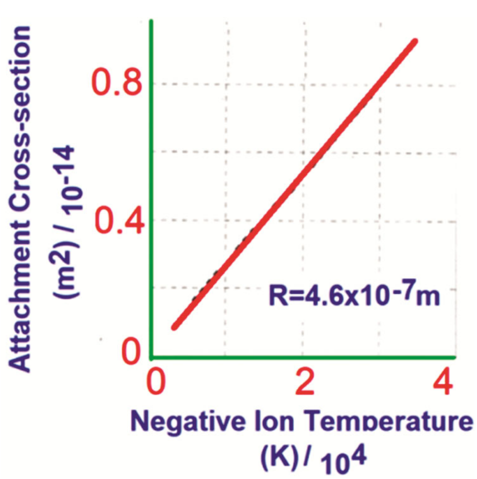

Fig. 5 — Attachment cross-section as a function of final energy of negative ion temperature.

Figure 6 shows the time taken calculated by taking accelerating voltage with slight variation in the distance between ions. The same negative ion is formed on a longer time scale in the order of 1ns. For data presented in Fig. 7, the ion propulsion system used a total ion beam current (assuming) 20 - 150 A, propellant flow rate 10^{-5} kg/s, electron gun coupled electron beam energy level 1- 6 eV (operating voltage <1000 V), accelerating voltage is 100 V, time scale is in the order 10^{-9}- 10^{-10}, the value of distance between same ions 10^{-6}- 10^{-7}, which yields simulated results that show a total thrust 1.5 N at velocity of 23000 m/s.

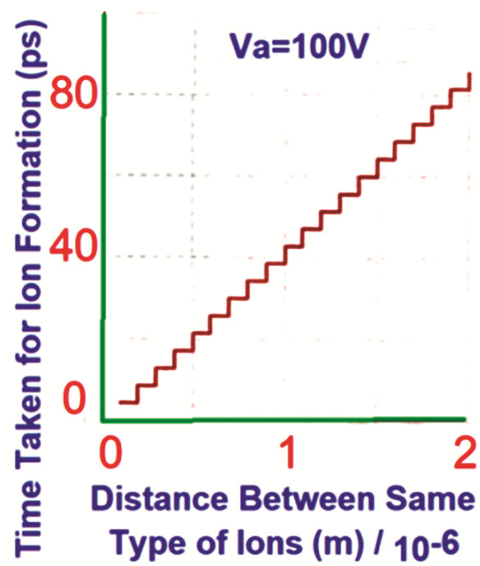

Fig. 6 — Time taken as function if distance between same ions.

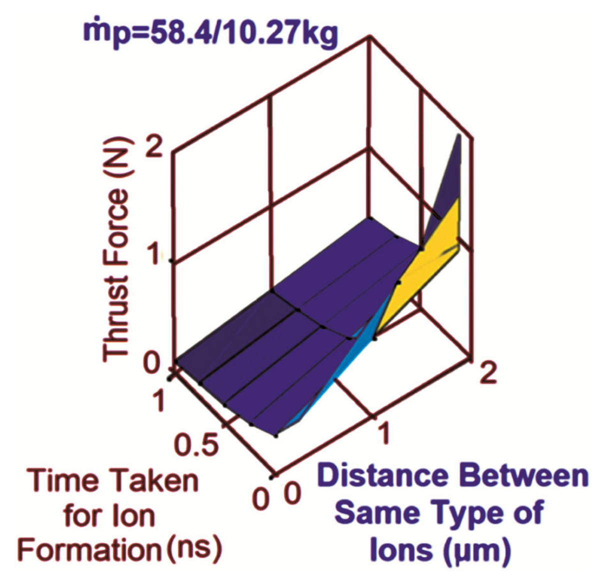

Fig. 7 — Variation of Thrust Force of Ion Propulsion Rocket as a function of Mean Free Path to Time Taken for Ion Formation.

Earlier techniques are ion propulsion rocket system (generally is called electric propulsion) with using mostly ion-electron pair method[16] (Kr^+-e^- / Xe^+-e^- / Ar^+-e^-/ etc) . The large amount of electric power is needed for the developing of the thrust because of the range of ionization energy 1170 kJ/mol or 12 eV is involved for removing electron from atom to form positive ion with electron. The reduction is collision process is possible at high electric power, then in the production of good thrust in electric propulsion. Operating this scheme is done only at high temperature. The electrical mobility value records approximately 1.4 cm^2/Vs for positive small ions. The current method (Cl^--Cl^- pair) uses low electric power which is needed to develop the thrust because of the range of electron affinity 349 kJ/mol (or 3.6 eV) is involving for attachment of electron from atom to form negative ions. Its collision process does not occur at the range of $\Delta E \leq 3.6$ eV and operation only at low temperature. The electrical mobility value is appropriately 1.9 cm^2/Vs for small negative ions.

4 Conclusions

The electronegative gas thruster is a new concept of plasma propulsion where negative ion pairs are used for thrust. Initially plasma production is achieved with negative ion pair using adding electrons to chlorine atom through heated ferroelectric cathode to form negatively charged ions. The negative ion density is less than electron density. Forming negative ions pair at magnetic field case radius (r) $\leq$ 0.12m with a negative ion density of order of 10^{19} /m^3. It raises reaction rate coefficient as cross-section increases as a function of energy level. The repulsive force will be forceful when two ions are same and provides for an accelerating thrust, at low electric power and same charges negative ion is formed on a longer time scale in the order of 1ns. Finally, achieved thrust value reaches as high as 1.5 N.

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