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APPLICATION OF IODINE PLASMA FOR ELECTRIC PROPULSION

Most state-of-the-art electric space propulsion systems, such as gridded and Hall effect thrusters, use xenon as the propellant gas. However, xenon is very rare and expensive to produce, and it is used in a number of competing industrial applications. Iodine is emerging as an attractive alternative to xenon in several electric propulsion technologies. Its lower cost and larger availability, solid state at standard temperature and pressure, its low vapor pressure and its low ionization potential make it an attractive option. Attempts to implement an alternative to xenon propellants (Iodine, O_2 , N_2 , H_2 , CO_2 etc) in conventional propulsion systems have been met with measured success. However, the use of chemically reactive species, such as O_2, H_2, or iodine, requires the chosen propulsion platform to be chemically compatible with the propellant. Significant reductions in the operational lifetime of the thruster because of chemical incompatibility negates any potential increase in thruster performance or propellant availability. Thus, careful material selection for the electric propulsion system itself and for the components employed on the satellite is required in the light of a typical space mission duration of several years. Due to the more complex reaction processes and energy loss channels in iodine plasma´s however, as well as the historical lack of reliable collision cross-section data, the development of accurate theoretical and numerical models has been hindered. The development of techniques that can be applied to chemically dissimilar propellants, focusing on electromagnetic behaviour, would represent a significant improvement in the state of discharge characterization and thruster analysis. In this work, we conducted a comparative analysis of the existing modeling results for various types of electric propulsion using iodine as a propellant gas, as well as the results of experiments with iodine plasma with an emphasis on the thrust-to-power ratio.

Keywords: *electric propulsion; plasma thrusters; alternative propellants; iodine.*

Introduction

Most state-of-the-art electric space propulsion systems such as gridded and Hall effect thrusters use xenon as the propellant gas. However, xenon is very rare, expensive to produce, and used in a number of competing industrial applications.

As is known [1], the criteria for propellant for electric propulsion (EP) are low ionization potential, and a high energy step between first and second ionization, a high atomic or molecular mass, easy to store and feed. Using a propellant easy to ionize reduces the amount of power needed to turn the neutral propellant into charged particles. A high step between first and second ionization ensures that the amount of doubly-ionized ions, who have twice the charge-to-mass ratio of singly-ionized ions, remains low. A high mass ensures a low charge-to-mass ratio, hence a low beam current for a given thrust, and a high storage density is also an important criteria for the use onboard satellites.

So, a perfect propellant combines high atomic or molecular mass, efficient ionization, and high storage density at standard conditions. Besides it is neither corrosive nor hazardous and can easily be brought into the gas phase. Such criteria have led to the hegemony of xenon as propellant in electric propulsion devices. For example, bismuth meets all the criteria, but bismuth can reach a significant vapor pressure (20 Pa) only at temperatures above 800° C after the melting point (271.4 ° C), which significantly complicates the thruster feed system. Mercury was also once of interest for ion propulsion, however its toxicity ultimately ended its use for electric propulsion application [2]. Unfortunately, no atomic propellant possesses all the properties requested.

Argon is used a lot for testing various devices because of its similarities to xenon and its very low cost, and krypton has been used as a substitute for xenon as propellant for electric propulsion devices, leading to a loss of performance around 20% with a much cheaper propellant [2]. None the less, those gases do not have the high mass and low ionization potential of xenon that are among its core advantage.

The choice of propellant can also be determined by the specifics of the space mission, and then other criteria for its selection are used (low molar mass, high thermal conductivity). This occurs, for example, when atmospheric gases of planets (air, nitrogen, oxygen, carbon dioxide, ammonia) are used as a propellants for atmosphere-breathing electric propulsion systems [3] or using waste products on space stations (ammonia) [4]. In [4], for example, seven criteria for choosing propellants for a magnetoplasmodynamic (MPD) engine were consid-

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ered. It is concluded that molecular gases used as fuel for MPD arcjet engines exhibited high thrust efficiency over a wide range of specific impulses.

The study on alternative propellants to xenon for electric propulsion systems has been carried out since the last century [5], and some references to past research are presented in Table 1. An analysis of the use of alternative fuels for various types of electric propulsion thruster is provided in recent reviews [2,3,6-8].

In this work, we conduct a comparative analysis of existing models and methods for calculating the characteristics of various types of electric propulsion using iodine as propellant gas, as well as the results of experiments with iodine plasma.

Table 1

Propellants for various electric propulsion systems

EP class	Propellant(s)	Ref.
Electrostatic		
Ion thruster		
NPT30-I2	Iodine	[9]
μ10	Kr, Ar, N_2, O_2	[10], [11]
IRIT4	Iodine	[12]
BIT-3	Kr, Ar, Iodine	[13]
Hall effect thruster		
BHT-100-I	Iodine	[14]
BHT-200-I	Iodine	[15]
BHT-600-I	Iodine	[16]
BHT-1000	Mg, Zn, Iodine, Bi	[17], [32]
BHT-8000-I	Iodine	[17]
	Water	[18]
	air	[19]
Electromagnetic		
MPDT	Ar, O_2, H_2, NH_3	[4]
REGULUS T4i	Iodine	[23]
Electrothermal		
Arcjet	Water	[20]
Helicon	N_2, CH_4, NH_3, N_2O	[21]
	Water	[22]
VX-200	Ar, Kr	[33]

Problem definitions

As no atomic species fill all the criteria for a perfect propellant, some studies focus on molecular propellant. The review [6] present a classification between diatomic and multiatomic molecules, and a toolkit they developed to evaluate the suitability of complex molecules for use as propellant. In case of diatomic molecules, the dissociation energy is typically lower than the ionization threshold, e.g. in the cases of iodine, oxygen or nitrogen. Hence, a high fraction of ionized species will be a product of a dissociative collision process to limit losses, aiming at forming a plasma behaving as an atomic plasma.

A very important quantity used for plasma discharges is the collisional energy loss which represents the average energy expended to produce an electron-ion pair when considering all electron collisional processes. In Figure 1, are plotted the effective collisional energy loss per electron-ion pair as a function of electron temperature for the various species: xenon, atomic and molecular iodine. The gray shaded region shows the model variation when considering between 2 (dashed lines) and 25 (solid lines) different atomic iodine excitation states. The best propellant is the easier to ionize which means the one with the smallest energy loss per electron-ion pair created.

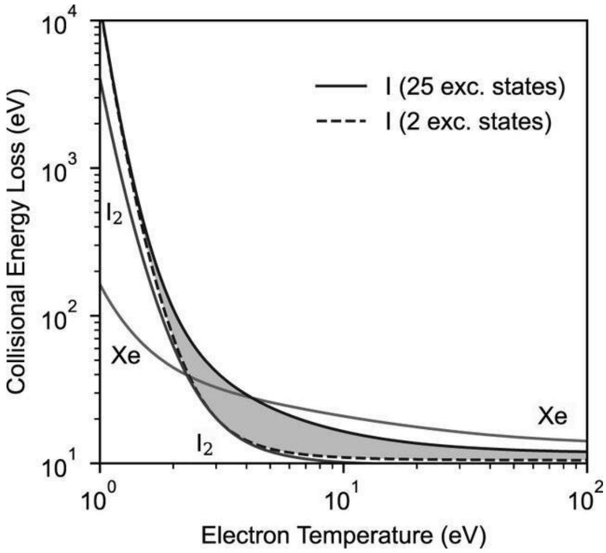

Fig. 1. Effective collisional energy loss per electron–ion pair as a function of electron temperature [24]

Depending on the composition of the plasma (or the rate of molecular dissociation), the cost of creating an electron-ion pair lies somewhere between the molecule curve and the atomic curve.

The electron temperature with in a xenon or an iodine plasma are very similar, so the curve can be compared for a fixed electron temperature. At low electron temperatures (<1.5eV), the energy loss in xenon is below the energy loss of both the iodine molecule and atom. When the electron temperature increases, the trend reverses (because different collision cross sections, reaction process, and inelastic energy thresholds) quickly for the molecule but in the case of a pure atomic iodine plasma (dissociation rate of 100%), the electron temperature must exceed 4 eV for iodine to become advantageous.

Such a high temperature is only reached at low pressure (at low mass flow rate). Energy losses with krypton and argon are higher than for xenon but exhibit the same behavior with Te: there exists an electron temperature (roughly between 1.5 and 4 eV) where iodine can become less advantageous than those two alternative propellants [24].

Even if xenon and iodine thrusters performances are found to be very similar [9, 17], iodine and xenon plasmas should exhibit very different properties, in particular as themass flow rate (and the resulting gas pressure in the plasma chamber) and the electric power used to generate the plasma are varied. Iodine is a molecular and electronegativegas, which is expected to have a higher energy cost per electron-ion pair created, because of the energy cost of dissociation and vibrational excitation. A significant fraction of negative ions is also expected given the very high cross section for dissociative attachement. Furthermore, transport phenomena are also different in molecular gases, and the electron energy relaxation length is expected to be shorter in iodine than in noblegases. All the above effects remain to be quantified and there is a lack of both basic data (cross sections, transport coefficients, etc.) and relevant literature at very low pressure [24].

Methods and Approaches

Iodine has special properties that favor its use as an alternative fuel for electric propulsions. Its atomic mass is slightly lower than that of xenon, it has a lower first ionization energy and a larger ionization cross section, which directly means more efficient plasma generation compared to other options. The low dissociation energy of 1.567 eV [25] results in a predominantly atomic I+ plasma [26]. It costs significantly less than xenon and has virtually unlimited availability. However, the chemical reactivity of iodine may represent a disadvantage of this technology. It is a halogen, and has important effects on numerous materials of interest for space applications.

Figure 2 presents the cross-sectional value for various propellants, including atomic iodine. This shows that iodine should behave better than xenon and krypton. However, iodine is injected as a diatomic molecule, so the assumption of lower ionization costs compared to Xe or Kr may overestimate the associated benefits. Indeed, it is necessary to take into account the cost of dissociation as well as other reactions present in the discharge.

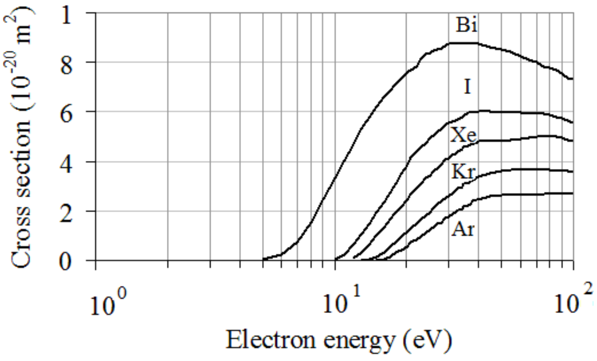

Fig. 2. First ionization cross-section for Bi [27], I [28] and Xe, Kr, Ar [29]

Although ion acceleration methods vary, all designs use the charge to mass ratio of the ions. This relationship means that a relatively small potential difference can produce a high exhaust velocity. This reduces the amount of required fuel mass, but increases the required specific power compared to gas-dynamic devices. Thus, electric propulsion thrusters are capable of achieving high specific impulses. The disadvantage of low thrust is low acceleration, since the mass of the electric power unit directly correlates with the amount of power. At the same time, electric propulsion thrusters are very effective for long-term space missions.

Most electric propulsion thrusters achieve high specific impulse, Isp, by electrostatically accelerating charged particles [5]. The equations for thrust and specific impulse can be written in terms of the mass-to-charge ratio of the accelerated particles. The thrust and I_{sp} associated with an individual, accelerated charged particle, i, is given by:

$$F = \dot{m}_p v_{ex} \simeq \dot{m}_i v_i = I_i \frac{m_i}{q}\sqrt{\frac{2qV_p}{m_i}} = I_i\sqrt{V_p}\sqrt{\frac{2m_i}{q}}, \quad (1)$$

$$I_{sp} = \frac{F}{\dot{m}_p g} \simeq \frac{F}{\dot{m}_i g} = \frac{1}{g}\sqrt{V_p}\sqrt{\frac{2q}{m_i}}, \quad (2)$$

where $\dot{m}_p$, $\dot{m}_i$ are the mass flow rate propellant and ions, respectively, I_i is the output current associated with charged particle emission, v_{ex}, v_i are the effective exhaust and charged particle velocity, m_i is the charged particle mass, q is the particle charge, g is the force of gravity at the surface of the Earth and V_p is the electrostatic acceleration potential.

Taking into account the divergence of the ion beam and the presence of multiply charged ions (q≠e), usually observed in electric thrusters, and the thruster mass utilization efficiency, which accounts for the ionized versus unionized propellant a correction factors γ and η_m are introduced [30]

$$F = \gamma \dot{m}_i v_i = \gamma I_i \sqrt{V_p}\sqrt{\frac{2m_i}{e}}, \quad (1a)$$

$$I_{sp} = \frac{\gamma\eta_m}{g}\sqrt{V_p}\sqrt{\frac{2e}{m_i}}. \quad (2a)$$

Equations (1) and (2) express that the thrust is proportional to the square root of m/q of the accelerated charged particles, and I_{sp} is proportional to the square root of the specific charge q/m. Thus, for a given accelerating voltage, high mass charged particles will result in high thrust with degraded specific impulse, while charged particles of low mass will result in high specific impulse with degraded thrust.

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A critical limitation of electric space propulsion is power and its limited availability on the spacecraft. The power necessary to accelerate charged particles is given by:

$$P = \frac{F^2}{2\dot{m}_p} = \frac{\dot{m}_i I_{sp}^2}{2}. \quad (3)$$

Thus, the power required to accelerate a particle is proportional to I_{sp}^2. Even if sufficient power is available, the electric propulsion system will reach the I_{sp} limit at which the added mass of the high-voltage converters will cancel out the fuel efficiency gains.

Assuming a simplified scenario where the acceleration process entirely exploits the plasma potential V_p inside the source, the speed gained by a single ion results to be

$$v_i \simeq \sqrt{\frac{2qV_p}{m_i}}. \quad (4)$$

Equation (4) implies that there is some optimal value for the outflow velocity (fig. 3). If this condition is violated, the process will be characterized by very low fuel consumption, but very high power input. To satisfy the need for a sufficiently low effective outflow velocity, according to Equation (4), it is convenient to use ions with a large mass-to-charge ratio. In addition, a low ionization potential allows minimizing ionization losses [31].

Of critical importance is the ratio of the thrust achieved to total power used, which depends on the electrical efficiency of the thruster.

$$\eta_e = \frac{P_b}{P_T} = \frac{I_b V_b}{I_b V_b + P_o}, \quad (5)$$

where P_o represents the other power input to the thruster required to create the thrust beam. Other power will include the electrical cost of producing the ions, cathode heater or keeper power, grid currents in ion thrusters, etc.

Thrusters with high exhaust velocities, and thus high Isp's, are desirable to maximize a mission payload mass. It was shown in Eq. (2a) that to achieve high Isp, it is necessary to operate at a high ion acceleration voltage and high mass utilization efficiency. Reductions in ion mass also increase the Isp, but at the cost of thrust at the same power level. This is seen by examining the thrust-to-total input power ratio. The total power is just the beam power divided by the electrical efficiency, so the thrust-to-power ratio using Eq. (5) is

$$\frac{F}{P_T} = \frac{F\eta_e}{P_b} = \frac{2\gamma^2\eta_m\eta_e}{gI_{sp}} = \frac{2\eta_T}{gI_{sp}} \quad (6)$$

An optimized thrust-to-power ratio can, for example, lead to significant mission time savings when using a fixed power system such as solar panels. Figure 3 shows the thrust-to-power ratio and total thruster efficiency as a function of specific impulse, where the overall engine efficiency was obtained by approximating the data [33], and the thrust-to-power ratio was calculated using formula (6).

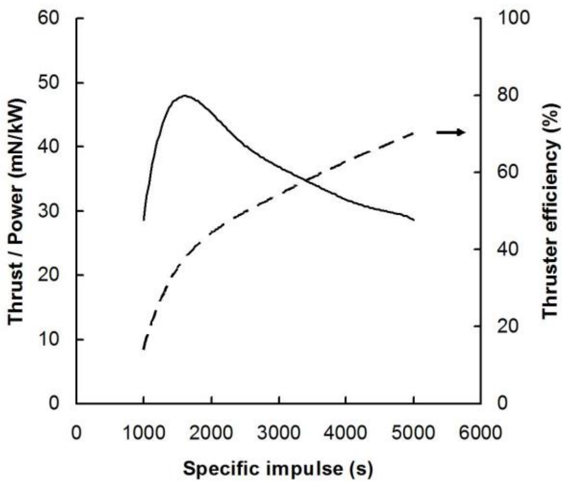

Fig. 3. Thrust-to-power ratio and thruster efficiency of the VX-200 thruster as a function of the specific impulse for argon propellant [33]

From equation (6) it follows that for a given input power and total thruster efficiency, an increase in Isp reduces the thrust of the electric thruster. Thus the only way to increase the thrust-to-power ratio at constant Isp is to increase efficiency. Figure 4 shows the values of the thrust-to-power ratio calculated using Equations 6 and 3 for ideal values of efficiency (equal to 1).

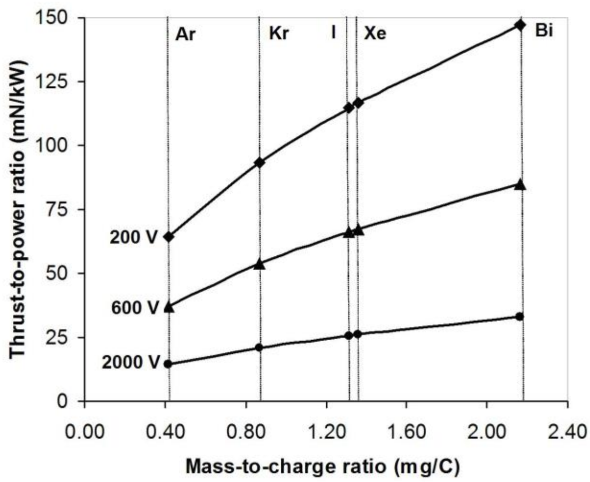

Fig. 4. Ideal values of the thrust-to-power ratio as a function of the ratio of mass to charge of various propellants

In recent years, many studies have been aimed at finding optimal operating modes for various types of eelectric propulsion systems using iodine propellant to increase their efficiency. A comparative analysis of the results and identified problems is presented below.

Results and Discussion

In [34], using a global model for gridded ion thrusters [25], it was found that iodine provides the best thrust-to-power ratio when the input mass flow is below 0.85 mg/s for the PEGASES thruster.

There is an interesting region (0.5 mg/s < $\dot{m}_p$ < 0.85 mg/s) where the thrust-to-power ratio when using iodine is higher than when using any other propellant. With low mass flow and sufficiently high discharge power, iodine provides better traction characteristics than other types of fuel. However, the molecular nature of iodine plays an important role when inlet mass flow increases and iodine loses its advantage. It is assumed that at $\dot{m}_p$ > 1.2 mg/s, too much power is dissipated in the processes of dissociation or excitation of iodine [34].

In [15] experimentally investigated a BHT-200 Hall effect thruster running fueled iodine vapor, which was shown to yield stability and performance similar to xenon. Figure 5 shows the discharge specific thrust (the ratio of thrust to discharge power) as a function of the anode specific impulse for iodine and xenon obtained from tabulated data (Table 4, [15]).

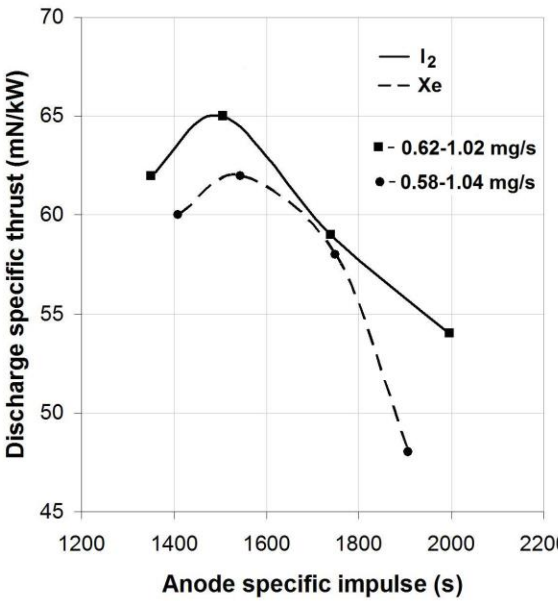

Fig. 5. Discharge specific thrust of the BHT-200 thruster as a function of the specific impulse for iodine and xenon propellants [15]

It should be noted, both in [34] and in [15], the best thrust-to-power ratio for iodine is observed at a mass flow rate of about 0.82 mg/s and an anode specific impulse of 1506 s. The authors of [15] suggest large performance advantages of iodine when operating at high power (at high current). This is partly confirmed in [32] for BHT-1000 at a discharge current of 2 A (see Figure 6, based on tabular data [32]). However, the erosion rate of dielectric insulators with iodine has not yet been assessed and this may limit the lifetime of the thruster when operating at high power.

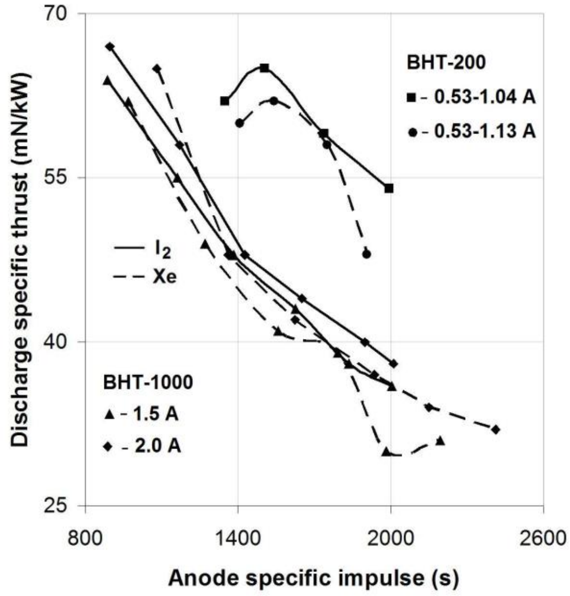

Fig. 6. Discharge specific thrust of the BHT-200 [15] and BHT-1000 [32] thruster as a function of the specific impulse for iodine and xenon propellants

Over the last years the growth of miniaturized satellites has led to the need to miniaturize their propulsion systems with power levels of less than 100 Watts. In 2021, the first iodine-fed plasma-based thruster has been successfully deployed and operated by the ThrustMe [9]. In the same year, the cathodeless thruster produced T4i has been deployed as well and the REGULUS system was tested in Sun-Synchronous orbit [23]. However, the reliable functioning of these systems is strongly limited by their lifetime when operating on iodine. The stated lifetime of NPT30-I2 and REGULUS T4i is less than 1500 hours [9, 23], which is significantly lower than the values for ion and Hall thrusters (7000-10000 h) using xenon [5].

It was also found that a hollow cathode works stably on iodine, but at a higher discharge potential than xenon. The higher discharge potential may have implications on thruster performance and may lead to lower total thruster efficiency [35].

Although atomic iodine proves to be very advantageous in having the lowest energy loss of any propellant (fig. 1), given the very high electron temperatures inside the Hall thruster, wall losses often account for the majority of the energy loss. The wall losses largely dominate the total losses when the electronic temperature rises and it is therefore critical to know precisely the secondary electron emission yield as a function of the temperature for each propellant.

Despite the fact that many studies have been carried out with iodine plasma, for theoretical calculations of engine operation [25], there is no basic data in the literature describing the chemical reactions of various particles. In particular, [25] suggested that the surface recombination coefficient is 0.02, while a larger value is likely to lead to an increase in the I_2 density and, consequently, the concentration of negative ions. However, this value is not derived from measurements in iodine plasma, but rather from an analogy with what was measured in chlorine discharges [37].

Since the wall recombination rate iodine atom is very poorly known, this leads to some uncertainty in the input data of the model and for practical calculations it is necessary to vary this parameter (increase or decrease) in order to agree with experiments, if available [34, 36-38].

Conclusions

The development of electric propulsion systems based on iodine represents a promising alternative to noble gases like xenon, particularly for smaller satellites where high-pressure storage conditions pose limitations. Iodine's properties, including good ionization characteristics, high atomic mass, high storage density, availability, and low cost, make it an attractive option. However, challenges arise due to iodine's condensible nature and chemical reactivity, which differ from noble gases.

In future studies, it is necessary to quantify the energy cost per created electron-ion pair, taking into account the energy costs of dissociation and dissipation during electronic, vibrational excitation of iodine molecules for various types of electric propulsion.

To do this, it is necessary to refine the database for the cross sections of iodine molecules and atoms, in particular in dissociative attachement, in order to determine the fraction of negative ions.

Refining the rate of wall recombination of iodine atoms will minimize the uncertainty of the model input data.

Accurate diagnostic methods, both optical and electrical, are needed to quantify plasma properties and develop reliable models.

A more detailed comparative analysis of locally measured plasma properties and model results will allow targeted optimization of electric propulsion systems using iodine.

Contributions of authors: conceptualization, methodology – **Leonid Bazyma;** formulation of tasks, analysis **– Sai Vigness Ramasamy, Leonid Bazyma;** analysis of results, visualization **– Sai Vigness Ramasamy;** writing – original draft preparation **– Sai Vigness Ramasamy**; writing – review and editing **– Leonid Bazyma.**

All the authors have read and agreed to the published version of the manuscript.

Conflict of Interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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Data availability

The work has associated data in the data repository.

Use of Artificial Intelligence

The authors confirm that they did not use artificial intelligence methods while creating the presented work.

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References

1. Mazouffre, S. Electric propulsion for satellites and spacecraft: established technologies and novel approaches. *Plasma Sources Science and Technology*, 2016, vol. 25, no. 3. Article no. 033002. 37 p. DOI: 10.1088/0963-0252/25/3/033002.

2. Tirila, V. G., Demairé, A., & Ryan, C. N. Review of alternative propellants in Hall thrusters. *Acta Astronautica*, 2023, vol. 212, pp. 284-306. DOI: 10.1016/j.actaastro.2023.07.047.

3. Zheng, P., Wu, J., Zhang, Y., & Wu, B. A Comprehensive Review of Atmosphere ‐ Breathing Electric Propulsion Systems. *International Journal of Aerospace Engineering*, 2020, vol. 1, Article no. 8811847. 21 p. DOI: 10.1155/2020/8811847.

4. Uematsu, K., Morimoto, S., & Kuriki, K. MPD thruster performance with various propellants. *Journal of Spacecraft and Rockets*, 1985, vol. 22, no. 4, pp. 412-416. DOI: 10.2514/3.25766.

5. Martinez-Sanchez, M., & Pollard, J. E. Spacecraft electric propulsion-an overview. *Journal of propulsion and power*, 1998, vol. 14, no. 5, pp. 688-699. DOI: 10.2514/2.5331.

6. Dietz, P., Gärtner, W., Koch, Q., Köhler, P. E., Teng, Y., Schreiner, P. R., & Klar, P. J. Molecular propellants for ion thrusters. *Plasma Sources Science and Technology*, 2019, vol. 28, no. 8, Article no. 084001. 15 p. DOI: 10.1088/1361-6595/ab2c6c.

7. Chadwick, A. R., Dally, B., Herdrich, G., & Kim, M. High-power inductive electric propulsion oper-

ation with alternative propellants. *The Aeronautical Journal*, 2020, vol. 124, no. 1272, pp. 151-169. DOI: 10.1017/aer.2019.141.

8. Borrfors, A. N., & Harding, D. J., Weissenrieder, J., Ciaralli, S., Hallock, A., & Brinck, T. Aromatic hydrocarbons as Molecular Propellants for Electric Propulsion Thrusters. *Journal of Electric Propulsion*, 2023, vol. 2, no. 1. 24 p. DOI: 10.1007/s44205-023-00059-6.

9. Rafalskyi, D., Martínez, J.M., Habl, L. *et al*. In-orbit demonstration of an iodine electric propulsion system. *Nature* 2021, vol. 599, no. 7885 pp. 411–415. DOI: 10.1038/s41586-021-04015-y.

10. Tompkins, J., Dutta, R., & Rovey, J. L. Plasma Hysteresis of Alternative Propellants in ECR Gridded Ion Thruster. In *AIAA SCITECH 2024 Forum*, AIAA paper 2024-1546. 24 p. DOI: 10.2514/6.2024-1546.

11. Barquero, S., Tabata, K., Tsukizaki, R., Merino, M., Navarro-Cavallé, J., & Nishiyama, K. Performance characterization of the μ10 electron-cyclotron-resonance ion thruster using alternative propellants: krypton vs. xenon. *Acta Astronautica*, 2023, vol. 211, pp. 750–754. DOI: 10.1016/j.actaastro.2023.06.036.

12. Jinghua, YANG, Shaoxia, JIA, Zhang, Z., Zhang, X., Ting, JIN., Long, LI., Yong, CAI, & Jian, CAI. Performance of a 4 cm iodine-fueled radio frequency ion thruster. *Plasma Science and Technology*, 2020, vol. 22, Article no. 094006, 7 p. DOI: 10.1088/2058-6272/ab891d.

13. Tsay, M., Frongillo, J., Zwahlen, J., & Paritsky, L. Maturation of iodine fueled BIT-3 RF ion thruster and RF neutralizer. In *52nd AIAA/SAE/ASEE Joint Propulsion Conference*, 2016, AIAA paper 2016-4544. 11 p. DOI: 10.2514/6.2016-4544.

14. Szabo, J. J., Tedrake, R., Metivier, E., Paintal, S., & Taillefer, Z. Characterization of a one hundred Watt, long lifetime Hall effect thruster for small spacecraft. In *53rd AIAA/SAE/ASEE Joint Propulsion Conference*, 2017, AIAA paper 2017-4728. 15 p. DOI: 10.2514/6.2017-4728.

15. Szabo, J., Pote, B., Paintal, S., Robin, M., Hillier, A., Branam, R. D., & Huffmann, R. E. Performance evaluation of an iodine-vapor Hall thruster. *Journal of Propulsion and Power*, 2012, vol. 28, no. 4, pp. 848-857. DOI: 10.2514/1.B34291.

16. Kamhawi, H., Haag, T., Benavides, G., Hickman, T., Smith, T., Williams, G., & Lee, L. P. Overview of iodine propellant Hall thruster development activities at NASA glenn research center. In *52nd AIAA/SAE/ASEE Joint Propulsion Conference* 2016, AIAA 2016-4729. 16 p. DOI: 10.2514/6.2016-4729.

17. Szabo, J., Robin, M., Paintal, S., Pote, B., Hruby, V., & Freeman, C. Iodine plasma propulsion test results at 1–10 kW. *IEEE Transactions on Plasma Science*, 2015, vol. 43, no. 1, pp. 141-148. DOI: 10.1109/TPS.2014.2367417.

18. Shirasu, K., Kuwabara, H., Matsuura, M., Koizumi, H., Nakagawa, Y., Watanabe, H., ... & Komurasaki, K. Demonstration and experimental characteristics of a water-vapor Hall thruster. *Journal of Electric Propulsion*, 2023, vol. *2*, no. 1. 19 p. DOI: 10.1007/s44205-023-00047-w.

19. Pekker, L., & Keidar, M. Analysis of airbreathing Hall-effect thrusters. *Journal of propulsion and power*, 2012, vol. 28, no. 6, pp. 1399–1405. DOI: 10.2514/1.B34441.

20. Hou, L., Shen, Y., Tang, H., & Zhao, W. Improvement on stability of water Arcjet. *IEEE Transactions on Plasma Science*, 2011, vol. 39, no. 1, pp. 608-614. DOI: 10.1109/TPS.2010.2088132.

21. Charles, C., Boswell, R. W., Laine, R., & MacLellan, P. An experimental investigation of alternative propellants for the helicon double layer thruster. *Journal of Physics D: Applied Physics*, 2008, vol. 41, Article no. 175213. 6 p. DOI: 10.1088/0022-3727/41/17/175213.

22. Petro, E. M., & Sedwick, R. J. Effects of water-vapor propellant on electrodeless thruster performance. *Journal of Propulsion and Power*, 2017, vol. *33*, no. 6, pp. 1410-1417. DOI: 10.2514/1.B36389.

23. Bellomo, N., Magarotto, M., Manente, M. *et al*. Design and In-orbit Demonstration of REGULUS, an Iodine electric propulsion system. *CEAS Space Journal*, 2022, vol. 14, pp. 79–90. DOI: 10.1007/s12567-021-00374-4.

24. Lafleur, T., Habl, L., Rossi, E. Z., & Rafalskyi, D. Development and validation of an iodine plasma model for gridded ion thrusters. *Plasma Sources Science and Technology*, 2022, vol. 31, no. 11, Article no. 114001. DOI: 10.1088/1361-6595/ac9ad7.

25. Grondein, P., Lafleur, T., Chabert, P., & Aanesland A. Global model of an iodine gridded plasma thruster. *Physics of Plasmas*, 2016, vol. 23, no. 3, Article no. 033514. DOI: 10.1063/1.4944882.

26. Szabo, J., & Robin, M. Plasma species measurements in the plume of an iodine fueled hall thruster. *Journal of Propulsion and Power*, 2014, vol. 30, no. 5, pp. 1357–1367. DOI: 10.2514/1.B35075.

27. Freund, R. S., Wetzel, R. C., Shul, R. J., & Hayes, T. R. Cross-section measurements for electron-impact ionization of atoms. *Physical Review A*, 1990, vol. 41, no. 7, pp. 3575–3595. DOI: 10.1103/PhysRevA.41.3575.

28. Hayes, T. R., Wetzel, R. C., & Freund, R. S. Absolute electron-impact-ionization cross-section measurements of the halogen atoms. *Physical Review A*, 1987, vol. 35, no. 2, pp. 578-584. DOI: 10.1103/PhysRevA.35.578.

29. Wetzel, R. C., Baiocchi, F. A., Hayes, T. R., & Freund, R. S. Absolute cross sections for electron-impact ionization of the rare-gas atoms by the fast-neutral-beam method. *Physical Review A*, 1987, vol.35, no. 2, pp. 559-557. DOI: 10.1103/PhysRevA.35.559.

30. Goebel, D. M., & Katz, I. *Fundamentals of Electric Propulsion: Ion and Hall Thrusters*. John Wiley & Sons, NJ, USA, 2008. 482 p.

31. Jahn, R. G. *Physics of Electric Propulsion*. McGraw-Hill. New York City, 1968. 339 p.

32. Szabo, J., Robin, M., Paintal, S., Pote, B., & Hruby, V. High density Hall thruster propellant investigations. In Proc. *48th AIAA/ASME/SAE/ASEE Joint Propuls. Conf.*, Jul. 2012, AIAA paper 2012-3853, 15 p. DOI: 10.2514/6. 2012-3853.

33. Longmier, B. W., Squire, J. P., Olsen, C. S., Cassady, L. D., Ballenger, M. G., Carter, M. D., & Ber-

ing III, E. A. Improved efficiency and throttling range of the VX-200 magnetoplasma thruster. *Journal of Propulsion and Power*, 2014, vol. 30 (1), pp. 123-132. DOI: 10.2514/1.B34801.

34. Esteves, B., Drag, C., Bourdon, A., & Alvarez-Laguna, A. Experimental and numerical investigation of a gridded ion thruster running with different propellants (I2, Xe, Kr, Ar). In *International Electric Propulsion Conference, Massachusetts Institute of Technology, Cambridge, MA, USA*, June 2022, p. 416. Avaliable et: https://www.researchgate.net/publication/362155539_Experimental_and_numerical_investigation_of_a_gridded_ion_thruster_running_with_different_propellants_I2_Xe_Kr_Ar. (accessed 24 April 2024).

35. Taillefer, Z. R., Blandino, J. J., & Szabo, J. Characterization of a Barium Oxide Cathode Operating on Xenon and Iodine Propellants. *Journal of Propulsion and Power*, 2020, vol. 36, no. 4, pp. 575–585. DOI: 10.2514/1.b37315

36. Esteves, B., Vicol, R., Laurent, B., Duchemin, O., Tsankov, T. V., Petronio, F., & Chabert, P. Iodine (I2) and noble gases (Xe, Kr, Ar) plasma physics for HETs with preliminary characterisation of the PPS® X00 running on these alternative propellants. In *International Electric Propulsion Conference*, Toulouse, France, June 2024, p. 559. Avaliable et: https://www.researchgate.net/publication/381924720_Iodine_I2_and_noble_gases_Xe_Kr_Ar_plasma_physics_for_HETs_with_preliminary_characterisation_of_the_PPSR X00_running_on_these_alternative_propellants (accessed 10 July 2024).

37. Esteves, B., Marmuse, F., Drag, C., Bourdon, A., Laguna, A. A., & Chabert, P. Charged-particles measurements in low-pressure iodine plasmas used for electric propulsion. *Plasma Sources Science and Technology*, 2022, vol. 31, no. 8, Article no. 085007, 34 p. DOI: 10.1088/1361-6595/ac8288.

38. Vinci, A. E., Bianchi, F. M., & Rafalskyi, D. Modeling and experimental results of low-power iodine-fed Hall thruster propulsion system. In *International Electric Propulsion Conference*, Toulouse, France, June 2024, p. 121. Avaliable et: https://www.researchgate.net/publication/382067633_Modeling_and_experimental_results_of_low-power_iodine-fed_Hall_thruster_propulsion_system (accessed 10 July 2024).

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ЗАСТОСУВАННЯ ЙОДНОЇ ПЛАЗМИ ДЛЯ ЕЛЕКТРОРЕАКТИВНИХ РУШІЇВ

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Більшість найсучасніших електричних космічних силових установок, таких як сітчасті двигуни та двигуни на ефекті Холла, використовують ксенон як паливний газ. Однак ксенон дуже рідкісний, дорогий у виробництві та використовується в ряді конкуруючих промислових застосувань. Йод стає привабливою альтернативою ксенону для кількох технологій електричного двигуна. Його нижча вартість і більша доступність, його твердий стан при стандартній температурі та тиску, його низький тиск пари та низький потенціал іонізації роблять його привабливим варіантом. Спроби реалізувати альтернативу ксеноновим паливам (йод, O_2, N_2, H_2, CO_2 тощо) у звичайних силові установки були зустрінуті з вимірюваним успіхом. Однак використання хімічно активних речовин, таких як O_2, H_2 або йод, вимагає, щоб обрана платформа двигуна була хімічно сумісна з паливом. Значне скорочення терміну експлуатації двигуна в результаті хімічної несумісності зводить нанівець будь-яке потенційне збільшення продуктивності двигуна або доступності палива. Таким чином, потрібен ретельний вибір матеріалів для самої електричної силової установки, а також для компонентів, які використовуються на супутнику, з огляду на типову тривалість космічної місії в кілька років. Однак через складніші реакційні процеси та канали втрати енергії в йодній плазмі, а також через історичну відсутність надійних даних про поперечні перерізи зіткнення розробка точних теоретичних і чисельних моделей була перешкоджана. Розробка методів, які можуть бути застосовані до хімічно різнорідних палив, зосереджуючись на електромагнітній поведінці, означатиме значне покращення стану характеристики розряду та аналізу двигуна. У даній роботі ми проводимо порівняльний аналіз існуючих результатів моделювання різних типів електричних рушійних установок з використанням йоду в якості паливного газу, а також результатів експериментів з йодною плазмою з акцентом на відношенні тяги до потужності.

Ключові слова: електроракетні двигуни; плазмові двигуни; альтернативні палива; йод.

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