The Use of Interplanetary Medium as Fuel for Plasma Thrusters

A R Karimov1,2, O V Yakovlev1, P A Murad3
1Department of Electrophysical Facilities, National Research Nuclear University MEPhI, Kashirskoye shosse 31, Moscow, 115409, Russia
2Institute for High Temperatures, Russian Academy of Sciences, Izhorskaya 13/19, Moscow, 127412, Russia
3Morningstar Applied Physics, LLC, Vienna, USA

Abstract. Consuming long-range interplanetary medium as a fuel for driving plasma thrust is crucial. The methods of capturing the space environment depending on its density and the ship velocity are critical issues. The possible ways of creating ionization for neutral fluxes as a function of the solar radiation flux are also analyzed as a potential propellant. These processes define the permissible type of the plasma source. These options look extremely promising where a low thrust device continuously operating, could possibly deliver a celestial target close to the speed of light. Under such conditions at a considerable distance, the density of such material diminishes and it may be impossible to maintain a continuous operation mode of the plasma thruster but instead operate as a pulsed engine which might potentially be workable.

1. Introduction

The exploration of the Solar system requires a creation of a space engine with a large specific impulse. Unfortunately, such characteristics can’t be provided by traditional chemical reactive engines. This follows directly from the Tsiolkovski’s formula (see, for example, [1]):

\[ v_f = v_{ex} \ln \left( \frac{M_r + M_p}{M_S} \right), \]  

(1)

here \( v_{ex} \) is the effective exhaust velocity, \( M_r \) is the rocket mass, \( M_p \) is the propellant mass, \( v_f \) is the final velocity of the rocket. As an alternative to chemical engines, one can use plasma-driven engines. For example, the end-Hall thrusters are capable to create the exhaust velocity of the order \( 5 \cdot 10^5 \) m/s while the maximum velocity of chemical engines is only \( 10^3 \) [1-3].

Nowadays there are several schemes of plasma thrusters: coaxial plasma thruster, stationary plasma thruster, Hall plasma thruster, plasma thruster energy/momentum exchange in crossed magnetic fields [2-9]. These devices differ from each other in the way of creating acceleration to provide thrust and performance. Nevertheless, there is a generic feature for all devices: in order, they have worked, one should obtain plasma from neutral atoms treated as propellants, and then one should accelerate this plasma flow to generate thrust. It is clear that this takes some energy and material which is continuously expended. In comparison with chemical thrusters, which can use only the reserve propellant, in plasma thrusters, one can use solar energy and interplanetary medium as a fuel. In the present piece, these issues will be addressed.

2. Interplanetary medium characteristics

As the interplanetary medium is a composition of substance and fields which fill space inside the Solar System, it appears justified to study its components. Ignoring the zero-point field and matter, the main components of the interplanetary system are the Solar wind, the high energy charged particles, the interplanetary dust, and neutral gas [10-12]. The Solar wind includes the ionized flux of the hydrogen
ions of density $n_H = 5 - 6 \text{ cm}^{-3}$ with velocity 250—750 m/s moving from the Solar Corona [11]. Evidently, there are particles of the flow, where it is impossible to register. Taking into consideration such unknown part of the flow, in the present estimations, we will slightly increase the density of the Solar wind $n_w$ by setting it equal to 10 particles per cm$^3$.

A source of small particles forming a dust component is the collapsing nucleus of comets and the collisions of different bodies in the asteroid belt [11,12]. It was found that the dust concentration decreases in ecliptic as a function of $R^{-1/3}$, and at the distance $R_* \geq 3$ Astronomical Units (AU), dust is almost absent [10]. The total mass of dust in the Solar system estimates as $M_d = 10^{19} - 10^{20}$ g, and the major part of the mass (about 2/3 of the total mass), is concentrated in the dust particles of mass $m_d$ in the mass range $10^{-3} < m_d < 10^{-5}$ g [10-12]. Using these data, we obtain an estimate of the average density for the dust component in terms of the hydrogen atoms in a sphere of a radius $R_*:

$$n_d = 3M_d/(4\pi R_5^3 \mu_H) = 10^3 \text{ cm}^{-3},$$

here $\mu_H = 1.66 \times 10^{-24}$ g is the mass of the hydrogen atom.

Neutral gas in the Solar system was discovered by observing resonantly scattered solar radiation. At distances of $r = 5$ AU from the Sun, the neutral gas is distributed practically uniformly or homogeneous, the concentration of hydrogen atoms on the average being 0.06 cm$^{-3}$, helium 0.012 cm$^{-3}$ [11,12]. As is seen, the density of this component of the interplanetary medium is much smaller than the contribution of the solar wind and dust and it can be neglected.

Proceeding from these data, we come to the conclusion that only the matter of solar wind and interplanetary dust are really suitable as a fuel for plasma thrusters. For further estimates, we shall set that the density of interplanetary medium varies in the range $n_w \leq n \leq n_d$, i.e. from 10 to $10^3$ cm$^{-3}$.

In order to understand the possibility of using solar radiation for ionizing neutral atoms and their subsequent acceleration, we estimate the radiation power distribution as a function of the distance from the Sun. (It should be noted that here we limited our consideration to the distances on the boundary of the asteroid belt.). Taking into account that the surface temperature of the Sun at a distance of $R_S = 10^8$ m, is $T_S=6000$ K [11,12], from the Stephan-Boltzmann’s law. We get

$$W_s = \frac{\sigma T_S^4}{(r/R_S)^2},$$

where $\sigma$ is the Stefan-Boltzmann constant. This dependence is sketched in Fig. 1, where for the convenience of perception, the distances from the Sun to the planets falling into a sphere of radius $R_*$ are labeled.

**Figure 1.** The radiation power with respect to the distance from the Sun. Here $R_{Mer}$ corresponds to the Mercury orbit, $R_V$ - the Venus orbit, $R_E$ - the Earth orbit, $R_{Mar}$ - the Mars orbit and $R_C$ - the Ceres orbit.

3. The plasma production from interplanetary medium
Proceeding from information about the distribution of interplanetary medium and the Solar radiation, now we can estimate the parameters of plasma where we can produce as an interplanetary medium to use it in a plasma thruster as a fuel. Also, we have discussed the possible ways to increase the plasma density up to generate thrust at minimally required values.

As a plasma source, we shall consider the cylindrical charged chamber of volume $V = 10^3 \text{ cm}^3$ where a low-pressure discharge is induced. As a rule, such types of discharges can be performed with the help of an HF microwave field at a pressure of $p \sim 10^{-3}$ Torr that corresponds to the particle density $n_0 \sim 10^{10} - 10^{11} \text{ cm}^{-3}$ under normal conditions (see, for example, [2, 13]). This indicates that it is impossible directly to use the interplanetary medium to organize a low-pressure discharge. We need to apply an additional technical parameter to obtain the required number of particles $N = n_0 \cdot V = 10^{14} - 10^{15}$ into the chamber under consideration.

![Figure 2. The scheme of trap for interplanetary substance (here, we set D=100 cm and d=10 cm).](image)

We presume to do this with the help to trap interplanetary substances by using a special geometry (see Fig. 2) and the accumulation of particles with increasing the spacecraft’s flow velocity with respect toward incoming particles. Such a conical structure should be placed on a moving spacecraft in the direction of its travel. Furthermore, the surface of such conical construction is suitable for the solar panel location.

Let us explain the simple mechanism of particle capture by assuming that the particle medium is stationary. In this case, the flux of particles that reach the surface, due to the relative velocity of the particles relative to the ship, is determined only by the ship velocity. The falling particles, repeatedly are reflected from the conical surface and fall into the region of the discharge chamber. Proceeding from the continuity of the particle flux: $n D^2 = n_c d^2$, where $D$ is the diameter of inlet, $d$ is the input diameter of the discharge chamber, we see that the density of particles in the narrow part of the conical funnel $n_c$ can be increased with respect to the input density $n$ in $k = (D/d)^2$ times. For example, for the sizes $D$ and $d$ of the trap shown in Fig. 2, we obtain $k = 10^4$. It should be borne in mind that this variant of density enhancement is workable as long as the medium remains collisionless, i.e. pressure effect does not work. In our case, the collisionless regime may be violated in the narrowest part of the trap. So in estimations of the mean free path $\lambda$, we put the density in the discharge chamber being equal to the desired value $n_0 = 10^{11} \text{ cm}^{-3}$. Then for the characteristic gas-kinetic cross-section $\sigma_g = 10^{-16} \text{ cm}^2$, we get $\lambda = 1/(\sigma_g n_0) = 10^5 \text{ cm}$, that is much larger than the characteristic size of the discharge chamber, so there is no need to take into account the initial pressure of the medium.

Now we shall pass over to estimate the accumulation of particles due to a change in the relative velocity of the interplanetary medium. It is easy to see that the flux of the interplanetary particle incident on the trap has filled the selected volume to a given number of particles $N$ for the time $\tau_{\Pi}$:

$$\tau_{\Pi} = \frac{N}{\pi R^2 v n_c},$$

(3)

where $v$ is the relative velocity of incoming flow, $n_c = k \cdot n$ is incoming particles after passing the trap with $k = 10^4$ the input radius of the discharge chamber. Here we restrict our consideration by two characteristic cases: the flux is created by the solar wind with density $n = 10 \text{ cm}^{-3}$ and the flux...
consists from dust particles with a density of \( n = 10^3 \text{ cm}^{-3} \). In Fig. 3 the characteristic times of particles accumulation for these both cases are plotted as a function of the relative velocity, for which we take the ship velocity.

To assess the necessary energy expended on the ionization of neutral atoms and their acceleration, we shall use the data on the radiation power for the Sun presented in Fig. 1. In these estimates, we assume that the ionized medium consists only of hydrogen atoms having a minimum ionization potential of \( \varepsilon_i = 13.6 \text{ eV} \). For simplicity, we shall neglect to brake the ship by the oncoming flux of interplanetary medium and restrict our consideration by only elastic head-on collisions of the oncoming particles with the spacecraft surface. Despite the obvious physical fallacy of such an assumption, the result implies this is the simplest possible way to account for the contribution of particle deceleration in the energy balance:

\[
W_S \tau \varepsilon = \varepsilon_i N + \mu H N \frac{v^2}{2} + \frac{v_e^2}{2},
\]

\[\vdots
\]

where \( \tau \) is the accumulating time for ionization and accelerating particles by the sun radiation, \( S \) is the square of a solar panel. As previously mentioned, the elements for a solar battery may be located on the surface of the trap so in the present estimates one can use \( S = \pi D^2 / 4 \). The value of velocity \( v_e \geq 0 \) is determined by the acceleration method and an additional discussion of this moment is required, but in order to obtain a minimum energy estimation in order of magnitude one can assume \( v_e = 0 \). Then from (4), we get

\[
\tau \varepsilon = \frac{\varepsilon_i N + \mu H N v^2 / 2}{W_S \pi R^2}.
\]

Depending on the velocity of the device, the power of solar radiation and the geometric sizes of a solar panel, this relation determines the characteristic time for the required energy accumulation. However, it should be borne in mind that these estimates of the times \( \tau \varepsilon \) should be considered as upper-bound marginal valuations.

Fig. 4 presents the dependence \( \tau \varepsilon \) for the space region between Venus and the asteroid belt between Mars and Jupiter. In these estimations, we take \( S = 80 \text{ m}^2 \). As is shown from this curve, the value \( \tau \varepsilon \) changes from 0.1 s at a distance \( \sim 1 \text{ AU} \) to several seconds for distances \( r \geq 6 \text{ AU} \). Under such conditions, it is impossible to maintain a continuous operation mode of the plasma thruster but a pulsed engine might be workable. Comparison of the dependencies presented in Figs. 3 and 4 show that the magnitude of pulse primarily depends on the capturing interplanetary matter that is brought about by the ship’s velocity with respect to the interplanetary substance. One can try to reduce the pulse time by increasing the area of the trap, however, this will affect the dimensions of the spacecraft.
Increasing the craft’s velocity makes it possible to decrease the accumulation time. In this case, a continuous mode of operation is not ruled out for high velocities.

![Figure 4](image)

**Figure 4.** The value of the energy accumulation time as a function of $W(r/R_S)$ under $S_* = 80 \text{ m}^2$.

Finally, we may speculate about the plasma source which may be used provide the pulsed mode of a plasma source. It is clear that at low pressures, it is difficult to use a high-frequency discharge since it is caused by the particle collisions which occur rarely. In this case, there appears a problem how one should handle a required pulsed system of the discharge system. To enhance performance, one may use microwave discharges in a waveguide for the plasma production or the initiation of a discharge in a low-pressure gas. The gas may be propelled by microwave radiation with a stochastically jumping phase (see, for example, [13-15]). Although the first option is more technically simple as a breakdown power minimum value for microwaves with a stochastically jumping phase depends weakly on a working gas pressure that is caused by the anomalous nature of collisionless electron heating [14]. Such a feature allows extending the discharge existence region in a direction of overpressures. Therefore, it would be useful to combine both methods in examining this effect on the source.

4. Conclusion

In the present model, we have studied the use of the interplanetary substance as a fuel for plasma engines. For this, we used astrophysical data on the density of the cosmic medium, which we recounted relative to hydrogen atoms. It appears that the minimum and maximum density in terms of hydrogen atoms varies in the range from $n_{\text{min}} = 10$ to $n_{\text{max}} = 10^3 \text{ cm}^{-3}$. The minimum estimation corresponds to taking into account only the solar wind and the maximum value that is obtained from interplanetary dust concentrated within a sphere of radius 3 AU from the Sun. Moreover, a low-pressure plasma source requires a density of the order $n_c \geq 10^7 \text{ cm}^{-3}$. This means that for the low velocities of spacecraft, it is impossible to use the interplanetary medium as a fuel for plasma thrusters. However, with increasing rocket's velocity, as expected, the use of additional capturing space particles makes it possible to increase the density of the discharge volume. So in the example considered, the trap increases the particle density in $k = 10^4$ times irrespective of the rocket velocity only due to the ratio of geometric sizes. The dependencies presented in Fig. 3 indicate that the accumulation time of particles for the accepted value $n_c$ depends on the device velocity. It should be noted that for simplicity, in the present estimations we have neglected by the relative velocity of particles with respect to the rocket. In the general case, this is not justified. As seen from the above dependencies, the incoming particle flux can only provide a pulsed mode of operation for the plasma source. In this case, the pulse frequency of such a device must vary with the rocket velocity and it depends on the density of the external medium.

Interestingly, the solar radiation is considered as an energy source for the ionization of accumulated particles and their further acceleration. Using the power distribution of the solar radiation, we have
estimated the time needed to accumulate energy for ionization and acceleration to the required rocket velocity (see Fig. 4). As seen from the comparison of these dependencies with the accumulation time of particles, the main time will be spent on the particles accumulation regardless of the rocket velocity. In this case, the values for the accumulation time of particles and energy show that the space medium can be used as a fuel for a plasma source operating in the pulsed mode for flights in a radius of 3 AU from the Sun, even with existing technical capabilities. This may also occur for low particle values at the Ceres, where the time particles are hit for collection, the system may automatically operate like a pulsed system. The implication that a pulsed system with this requirement may be more profitable than a continuously operating system which would end up with propellant starvation.

References

[1] Sutton G P and Biblarz O 2010 *Rocket Propulsion Elements* (New York: Wiley)
[2] Goebel D M and Katz I 2008 *Fundamentals of Electric Propulsion: Ion and Hall Thrusters* (New Jersey: John Wiley & Sons)
[3] Grishin S D, Leskov L V and Kozlov H P 1975 *Electric Rocket Engines* (Moscow, Russia: Mechanical Engineering)
[4] Jahn R G and Choueiri E Y 2002 Electric Propulsion *Encyclopedia of Physical Science and Technology Third Edition* vol 5 (New York: Academic Press) pp 125-141
[5] Kim V P 2015 *Tech. Phys. 60* 362
[6] Kozlov A N 2008 *J. Plasma Phys.* 74 261
[7] Raitses Y, Merino E and Fisch N J 2010 *J. Appl. Phys.* 108 093307
[8] Karimov A R and Murad P A 2017 *IEEE Trans. Plasma Sci.* 45 1710
[9] Karimov A R and Murad P A 2018 *IEEE Trans. Plasma Sci.* 46 882
[10] Leinert C, Richter E, Pitz B and Planck V 1981 *Astron. Astrophys.* 103 177
[11] Podgorniy I M and Sagdeev R Z 1969 *Adv. Phys. Sci.* 98 410
[12] Beirman L 1966 *Adv. Phys. Sci.* 90, 163
[13] Raizer Yu P 1991 *Gas Discharge Physics* (New York: Springer)
[14] Chen F F 1991 *Plasma Phys. Cont. Fusion* 33 339
[15] Lieberman M and Lichtenberg A 2005 *Principles of Plasma Discharges and Materials Processing* (New Jersey: Wiley-Blackwell)