Development of Permanent Magnet Hall Thrusters for Applications on Future Brazilian Space Missions

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Abstract: The Plasma Physics Laboratory of UnB has been developing a Permanent Magnet Hall Thruster (PHALL) for the UNIESPAÇO program, part of the Brazilian Space Activities Program (PNAE) since 2004. The PHALL project consists on plasma source design, construction and characterization of the Hall type propulsion engine using several plasma diagnostics sensors. PHALL is based on a plasma source in which a Hall current is generated inside a cylindrical channel with an axial electric field produced by a ring anode and a radial magnetic field produced by permanent magnets. In this work it is shown a brief description of the plasma propulsion engine, its diagnostics instrumentation with the Integrated Plasma Diagnostics Bench, computer simulation studies and possible applications of PHALL on orbit transfer maneuvering for future Brazilian geostationary satellite space missions.

I. Introduction

The Plasma Physics Laboratory of the University of Brasília (UnB) has been developing a Permanent Magnet Hall Thruster (PHALL) for the Brazilian Space Program since 2004 [2-5, 10]. Electric propulsion is now a very successful method for primary and secondary propulsion systems. It is essential for deep space long duration solar system missions and for station keeping of geosynchronous satellites, where the thrusting system can be designed to be used on orbit maneuvering or on satellite attitude control in long term space missions [7, 8].

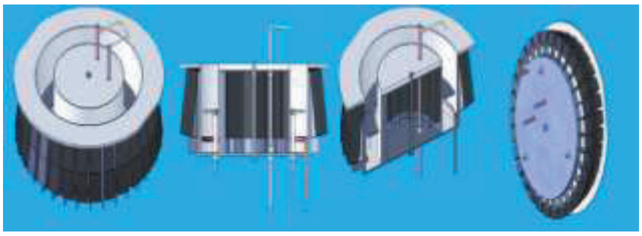
Applications of Hall Thrusters on future Brazilian space missions are foreseen for the next decade beginning with the use of small divergent cusp field Hall Thrusters on CUBESATS. The SBG system, a future Brazilian geostationary satellite system is already been developed by an international consortium of space industries. A joint Brazilian space mission on the solar system has also been consider for the future. ASTER project is a mission to a near earth asteroid that is planned to be carried on using Hall thrusters [12].

The PHALL project consists on plasma source design, construction and characterization of plasma propulsion engines based on Hall current generated inside a cylindrical channel with an axial electric field produced by a ring anode and a radial magnetic field produced by permanent magnets [1, 11]. One of the main advantages of PHALL thruster is the production of a steady state magnetic field by permanent magnets providing electron trapping and Hall current generation within a significant decrease on the electric energy supply [4, 5]. This advantage turns PHALL thruster into a specially good option when it comes to space usage for longer and deep space missions, where solar panels and electric energy storage on batteries is a limiting factor.

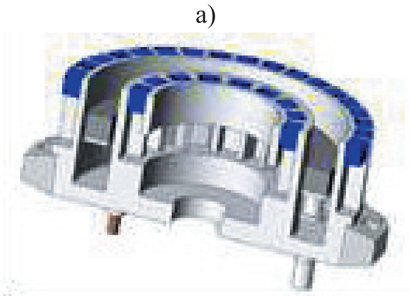
Our project consists in designing a plasma source and construction/characterization of plasma propulsion engines based on a Hall current ionizing mechanism generated by the perpendicular electric and magnetic fields produced by the vertical electric fields of a bottom ring anode and the perpendicular radial magnetic fields produced by permanent magnets on the exit of a cylindrical annular channel. This thruster has to be studied in vacuum mimicking conditions and therefore we have to perform the tests inside a long and cylindrical vacuum chamber were we have attached a whole paraphernalia of plasma diagnostics and electric power systems for thruster excitation and characterization (Figure 1).

Figure 1. General experimental setup with vacuum chamber and diagnostics for Hall thruster tests.

One of the main advantages of our PHALL thruster is the production of a steady state magnetic field by permanent magnets providing electron trapping and electron Hall current generation with a significant decrease on the power consumed from the electric power supply. This advantage turns the PHALL thruster into a specially good option when it comes to space usage for longer and deep space missions, where solar panels and electric energy storage on batteries is a limiting factor. Two prototype models, PHALL I and II, were already developed and tested with different types of permanent magnets (Figure 2).



a)



b)

Figure 2. Hall thrusters developed by our group, a) PHALL I, b) PHALL II.

This work describes the Hall plasma source construction and characteristics and the plasma diagnostics system used on BID, an Integrated Plasma Diagnostic System.

II. PHYSICAL CHARACTERISTICS OF PHALL

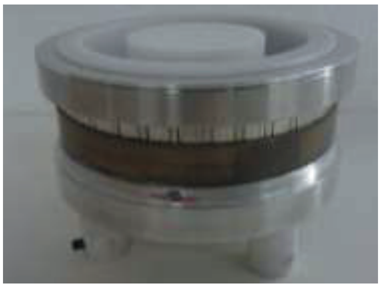
Now we will describe briefly our Hall plasma source general construction and characteristics. Our first prototype, the PHALL I (Figure 2.a)) had long magnets disposed at an angle at the inside and outside of the circular annular cavity and a tungsten wire at the top to initiate the discharge by thermionic electron emission. Later on this thruster was refined in PHALL II by using shorter magnets and a hollow cathode for electron emission (Figure 2. b) and Figure 3).

III. DIAGNOSTICS

The plasma diagnostics system [2, 10] used on our Integrated Plasma Diagnostic System, so called BID, will now be detailed (Figure 4). Our system contains several Langmuir probes that are used for plasma density and temperature measurements. We also use a Faraday Cup, Ion probes and a Spectrograph (Andor SR-750-B2, within 435nm to 700nm - line broadening measurements) to measure ion temperature and transport parameters inside the Hall current channel and the ejected plasma plume.

In order to control the argon fuel purity a mass spectrometer is also planned to be used in the future. We are developing at this time a setup for detailed thrust and specific impulse measurements. We are also researching any relevant plasma physics phenomena that may significantly interfere on PHALL thruster performance due to the occurrence of instabilities inside and outside of the Hall current channel. In order to better understand the

a)



b)

Figure 3. PHALL II, a) showing the magnets without top protection, b) with top hat dielectric protection.

turbulence and plasma oscillations that occur during the thruster operation, we have a wide frequency range instability detection system based on a RF detection probe connected to a Spectrum Analyzer (Agilent CSA 100 khz-6 Ghz). Instabilities on the PHALL discharge current is monitored in a real time data acquisition system, based on a PCI-DAS 1602/12 board containing 16 analogic inputs, 24 digital channels operating within a 330 KHz sampling rate.

In the highest pressure conditions, the electron plasma density and temperature space profiles inside the plasma source channel are respectively in the range of 2.0 - 2.5x10^{10} part/cm^3 and temperature from 30 eV to 65 eV. Plasma potential measurements show that inside the plasma source channel the anode determines the plasma potential. Outside the channel, the potential decreases mainly due to the plasma neutralization made by the thermionically emitted electrons. It was also observed that plume expansion creates density gradient. The plasma acceleration is measured using an ion energy analyzer.

In spite of low frequency oscillations found in the ion probe measurements, we calculated the total thrust of the PHALL. The results from the ion collector current are placed in the interval of 18mN to 39mN indicating that the PHALL is working with 27% of efficiency - as expected for this first experimental model. If the total thrust is calculated from the input power in the Hall discharge, the maximum thrust goes from 44mN to 86mN. Hence, our PHALL has only 43% of the maximum thrust that can be obtained from this discharge. These values can at least be scaled up to the thrust values of the existent SPT.

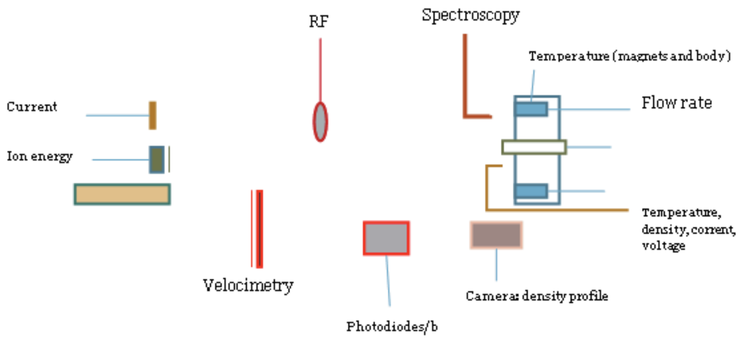


Figure 4. Representation of our Integrated Plasma Diagnostic System.

With PHALL I we obtained the following performance parameters: Maximum thrust available of 126 mN, maximum specific impulse of 1607 seconds and an electric efficiency of 67.2 percent; on the other hand, we had a very low ionized mass rate, of approximately 6 percent. We associate this low ionization to the type of cathode used on this first prototype. We also show performance characteristics for the PHALL II (Table 1).

TABLE 1- Working parameters of PHALL I and PHALL II.

	PHALL I	**PHALL II**
Thrust (mN)	26.5 – 126.0	23 - 150
Thrust power (N/m2)	1.5	2.4 – 8.7
Specific Impulse (s)	803.5-1607	1500 - 2000
Power (W)	1250	500 -1000
Mass flow rate (mg/s)	5.0	2.0
Electrical efficiency (%)	67.2	80
Total efficiency (%)	8.4	45 - 60

PHALL I and II (Figure 5) gave us the opportunity to obtain, for the very first time, characteristics and performance parameters of a Permanent Magnet Hall-Effect Thruster. The main feature of these thrusters is the possibility of extra economy of satellite electric power consumption due to the use of permanent magnets. This is the main advantage of this new design for HETs, as power in space is, in general, severely limited.

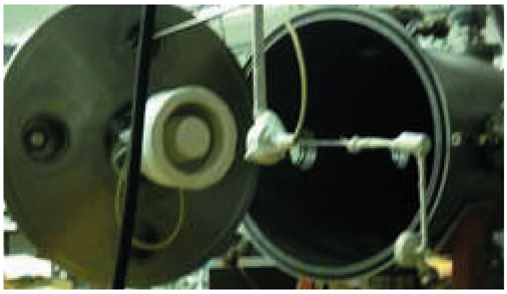


Figure 5. PHALL II assembled for plasma characteristics and thrust measurement.

IV. Numerical and Computer Simulation Results

Hall plasma thrusters can be modelled using particle-in-cell (PIC) simulations. In these simulations the plasma is described by a set of equations which represent a coupled system of charged particles and electromagnetic fields. The fields are computed using a spatial grid (i.e., a discretization in space), whereas the particles can move continuously in space. Briefly, the particle and fields dynamics are computed as follows. First, forces due to electric and magnetic fields are employed to calculate the velocities and positions of particles. Next, the velocities and positions of particles are used to compute the charge and current densities at discrete positions in space. Finally, these densities are used to solve the electromagnetic field equations in the grid, which are interpolated at the position of the particles to obtain the acting forces, and restart this cycle.

Currently, we are testing software for PIC simulations to study turbulence, waves and instabilities that arise in Hall plasma thrusters. We have successfully reproduced a two-dimensional simulation of a SPT-100 Hall thruster (Fig. 6). We aim to adapt this code to represent the Hall plasma thruster currently being developed at the Plasma Laboratory at University of Brasília. Preliminary results show that the average ion velocity at the exit channel can increase depending on the position of the permanent magnets.

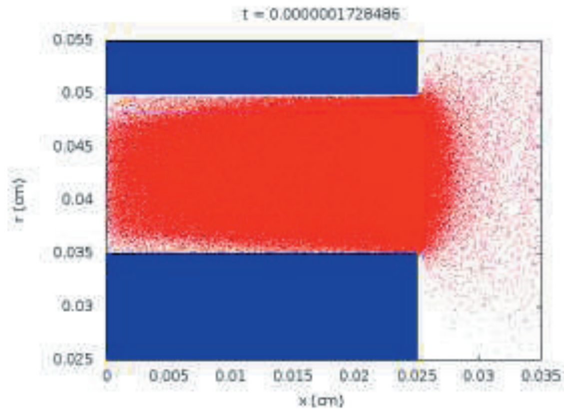


Figure 6: Particle-in-cell simulation of a SPT-100 Hall effect thruster. The simulation is performed in a two-dimensional section of the thruster using cylindrical coordinates. Blue rectangles represent the ceramic channel, and red dots represent the simulated ion particles (ions are accelerated to the right).

V. Applications and Developments for Future Brazilian Space Missions

Near future developments will include experimental PHALL lifetime test system assembly in a vacuum system with a much bigger volume and pumping speed capability. We will compare these results with correspondent preliminary simulation results. We will also develop for the bigger chamber a new direct thrust and specific impulse measurement instrumentation system in order to obtain detailed performance characteristics of our PHALL thruster. Also we are in the process of concluding a completely automated system for plasma diagnostic measurement which will provide all plasma characteristics and parameters in real time on the spot.

Finally, based on the measured parameters of the accelerated plasma, we present an aptitude figure for the PMHT. It contains the specific impulse, total thrust, propellant flow rate, electric power, efficiency and all parameters needed to foresee what type of space mission will be suitable for the thrusters we are developing. We perform numerical simulations [6] of satellite orbit raising from an altitude of 700 km to 36000 km using a PMHT operating in the 100mN – 500mN thrust range for two situations: in the first case, the satellite is in a circular orbit and is subjected to a continuous, constant thrust tangent to the orbit. In the second case, the satellite is on an elliptic orbit with pericenter of 700 km and apocenter tangent to the geosynchronous orbit.

However, in this case we applied continuously pulsed thrust with direction tangent to the orbit at the apocenter.

The second situation resulted in a faster orbit transfer. In order to perform these calculations, integration techniques of spacecraft trajectory were used. The main simulation parameters were: orbit raising time, propellant mass, satellite mass, thrust specific impulse and exhaust velocity. Figure 7 shows the maneuver time to send a spacecraft to geostationary orbit, from 700 km altitude circular orbit, using continuous thrust as a function of propellant mass flux (measured in laboratory for PHALL) and of satellite mass. Figure 8 shows numerical calculation [9] of propellant consumption for orbital transfer maneuvering. The propellant mass is calculated for pulsed thrust in the correspondent apocentral orbit angle opening. Figure 9 shows the time necessary to circularized orbit using pulsed thruster, supposing satellite geostationary orbit crossing apocenter, with pericenter at 700 km altitude, for several values of PHALL total thrust.

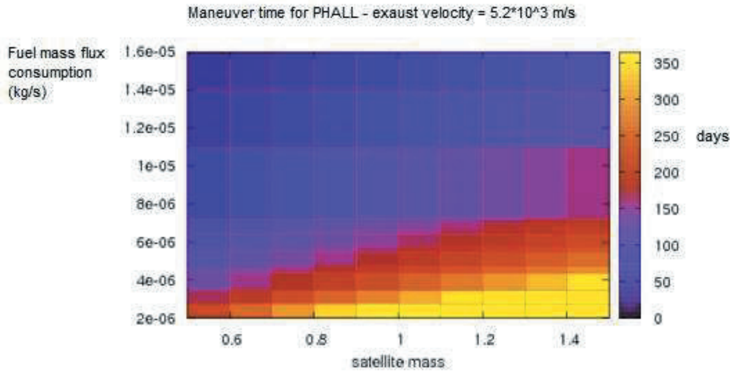


Figure 7 - Maneuver time to send a spacecraft to geostationary orbit, from 700 km altitude circular orbit, using continuous thrust as a function of propellant mass flux (measured in laboratory for PHALL) and of satellite mass.

VII. Electric Propulsion use for Space Transfers - Application for Future Brazilian Space Missions for Solar System in situ Research

Triple asteroid systems are known to exist in the main belt and in outer solar system, but were unknown in the Near Earth Asteroid-NEA region. In February, 2008, based on Arecibo radar delay-Doppler images, it was reported the discovery of the first NEA triplet system, 2001 SN263. This interesting system was chosen as the target for the ASTER MISSION – proposed to be the First Joint Brazilian Space Exploration undertaking in the Solar System [12]. The ASTER mission will be deployed as a single 150 kg module spacecraft propelled by Hall type electrical thrusters. The spacecraft transfer from an initial Earth orbit to outside of the Earth's sphere of influence and heliocentric transfer to the asteroid. In order to lower the mission cost it is suggested to use the electric propulsion (low thrust) for both parts of the transfer.

A. Formulation of the problem and initial data

We analyzed three different kinds of space orbit transfers using a PHALL type electric propulsion system [12]:

– transfer between two circular Earth orbits;

– augmentation of the orbital energy

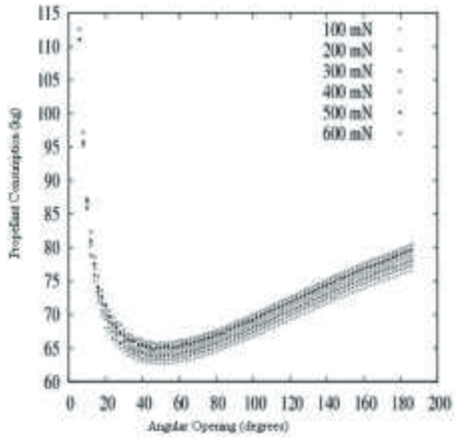


Figure 8- Propellant mass consumption as a function of the apocentral angular opening for various thrusts.

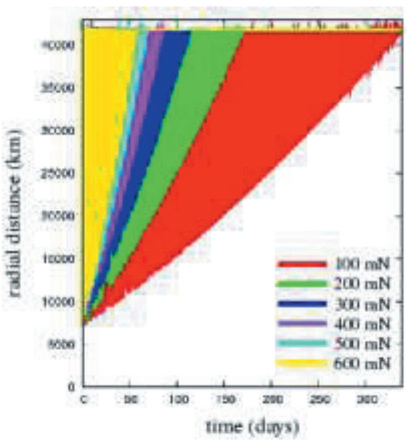


Figure 9- Time necessary to circularized orbit using pulsed thruster, supposing satellite geostationary orbit crossing apocenter, with pericenter at 700 km altitude, for several values of PHALL total thrust.

with purpose of exiting Earth's sphere of influence;

– insertion into trajectory to a near-Earth asteroid or Venus.

The parameters of the electric propulsion system used for this analysis are given in Table 2.

Table 2. Parameters of the electric propulsion.

Power, W	Thrust, N	Specific impulse, s	Efficiency	Comments
1000	0.085	1083	0.45	Measured parameters
1000	0.085	1605	0.67	Expected parameters
1700	0.085	2500	0.61	Parameters ideal for the propulsion geometry

The initial wet mass for the spacecraft was taken as 100 kg.

B. Transfer between circular orbits

Transfer from a circular Earth orbit of 400 km altitude to a higher circular orbit, up to the geostationary one is analyzed here. A transfer without coast arcs is considered, i.e. thrust during whole transfer without interruptions is assumed; this case corresponds to the minimum time transfer. The thrust is assumed tangential. Under these assumptions the low-thrust trajectory is spiral with instantaneous orbits close to circular ones at any time of the transfer.

The mass flow rate can be found for the parameters given in Table 1 as follows:

$$\dot{m} = \frac{dm}{dt} = \frac{F}{I_{\mathrm{sp}} g} \tag{1}$$

where F and I_{sp} are thrust and specific impulse, $\mathrm{g} = 9.80665\ \mathrm{m/s^2}$ is acceleration of free fall. Then the spacecraft mass m, transfer time t, and number of orbits N versus radius of the final orbit can be calculated using the following equations [2]:

$$m = m_0 \exp\left(-\frac{v_0 - v}{I_{\mathrm{sp}} g}\right), \quad t = \frac{m_0 - m}{\dot{m}}, \quad N = \frac{\left(I_{\mathrm{sp}} g\right)^3}{2\pi\mu\dot{m}}\left|L_3\right| \tag{2}$$

where m_0 is initial spacecraft mass, v_0 and v are velocities in the initial and final circular orbits, $\mu = 398600.45\ \mathrm{km^3/s^2}$ is the Earth gravitational parameter, integral $L_3 = \int_0^t \left(v_0 / I_{\mathrm{sp}} g + \ln t\right) dt$ is calculated in [2]. Figures 10 to 12 show the m, t, and N values respectively versus radius of the final orbit for the three electric propulsion cases given in Table 1.

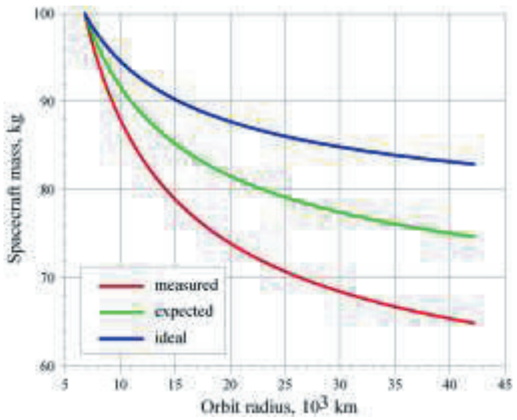


Figure 10. Spacecraft mass in the transfer between two circular orbits.

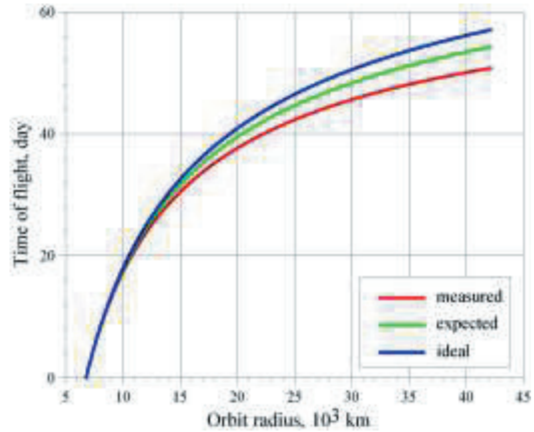


Figure 11. Time of flight between two circular orbits.

Note that transfers between coplanar orbits are considered here; e.g. in the case of transfer to the geostationary orbit it is assumed that the initial orbit is equatorial. If the initial and final orbits are mutually inclined then the final mass will be smaller and the transfer time will be longer.

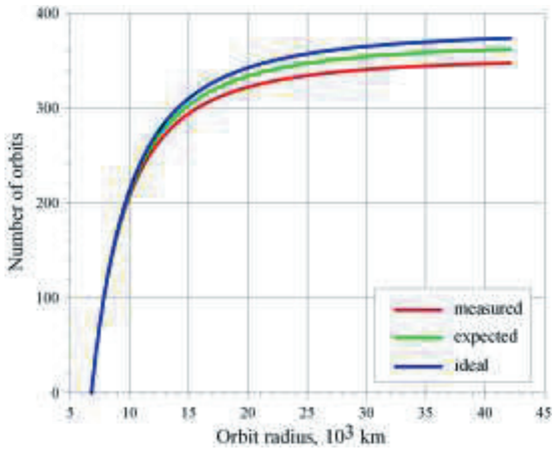


Figure 12. Number of orbits in the transfer between two circular orbits.

C. Transfer outside Earth's sphere of influence

Transfer from a low Earth orbit (LEO) to a heliocentric trajectory by means of the electric propulsion with parameters given in Table 2 is analyzed here. The transfer trajectory is an elliptic spiral with thrust arcs around each perigee passage. Scheme of the transfer is given in Figure 13 where launch into LEO (1), thrust arcs (2), coast arcs (3), and insertion into the heliocentric orbit (4) are shown.

The transfer time may be varied by means of variation of the thrust arc lengths. The analysis was made for the transfer time between its minimal value (corresponding to the transfer without coast arcs) to one year. Initial Earth orbit was assumed circular of 400-km altitude. Final orbit was given only by its energy equal to $C_3 = 0.64$ $(km/s)^2$ (i.e. final velocity at infinity is equal to 0.8 km/s). This value makes possible transfer only to some of the near-Earth asteroids and is not sufficient for transfer to other celestial bodies; however, a higher final energy would need a long thrust arc in the final elliptic orbit of the spiral transfer what would lead to a high propellant consumption. This is why if a higher orbital energy for further flight is needed, it is better to add necessary rest of the energy after leaving the Earth sphere of influence, i.e. at the beginning of the heliocentric trajectory. The final spacecraft mass (i.e. mass at the beginning of the heliocentric trajectory) in the transfer with thrust and coast arcs is given by:

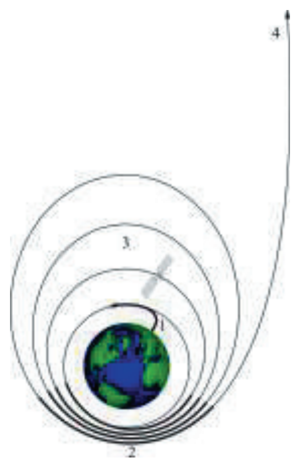


Figure 13. Scheme of the transfer to the heliocentric orbit.

$$m = m_0 - \dot{m} \quad (3)$$

where mass flow rate $\dot{m}$ is given by Equation (1), $t = \sum_{i=1}^{N} t_i$ is total thrust run time, t_i is time of the thrust run in the *i*th thrust arc, *N* is number of orbits. Figure 14 shows the spacecraft final mass versus transfer time for the considered propulsion system. Note that the thrust arc lengths were selected in an optimal way for each transfer trajectory (i.e. for each given transfer time). This is why the final spacecraft mass shown in Figure 14 is maximum possible for the parameters given in Table 2.

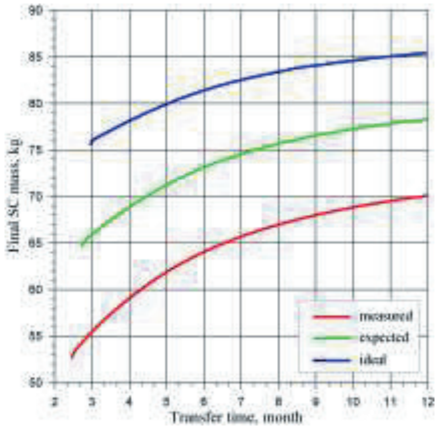


Figure 14. Final spacecraft mass for the transfer to a heliocentric trajectory.

As is seen in Figure 14, minimal time of the transfer to the heliocentric trajectory of the given orbital energy with the considered propulsion system is 2.5 to 3 months. The spacecraft mass sent to the heliocentric trajectory may be 52.5 to 70 kg for the existing propulsion system (i.e. with the measured parameters), 65 to 78 kg for the desired parameter values, and 75.5 to 85.5 kg for the ideal system parameters (see Table 2). Number of orbits in the spiral transfer varies approximately from 400 to 1300.

D. Transfer to a celestial body

Here the spacecraft insertion into trajectories to a couple of near-Earth asteroids and Venus using the considered propulsion system is analyzed. Venus is considered among the small bodies because gravity assist of this planet or Venus and Earth gravity assists (so-called VEGA maneuver) considerably extends reachable small bodies, up to the main-belt asteroids. These transfers are based on ones considered in the previous section. Namely, it is assumed that a six-month transfer to a heliocentric trajectory is performed (Figure 14) and then the spacecraft velocity is augmented to a needed value using the electric propulsion (i.e. a deep space maneuver at the beginning of the heliocentric trajectory is performed). Some parameters of the insertion into the transfer trajectories are given in Table 3. The years of launch when the parameters are achievable are shown in brackets after the body names.

Table 3. Insertion into trajectory to celestial bodies.

Celestial body	Propulsion parameters	Deep space maneuver value, km/s	Deep space maneuver duration, day	Final spacecraft mass
Asteroid (35107) 1991 VH (2024)	measured expected ideal	0 0 0	0 0 0	64.0 73.1 82.3
Asteroid (65803) Didymos (2024)	measured expected ideal	0.1 0.1 0.1	0.87 1.00 1.12	63.4 72.6 81.9
Venus (2015)	measured expected ideal	1.7 1.7 1.7	14.8 16.9 19.0	54.5 65.6 76.7

Zero value of the deep space maneuver for asteroid (35107) 1991 VH means that for launch in 2024 this asteroid may be reached without the deep space maneuver, i.e. only by means of the thrust run near Earth with escape velocity 0.8 km (see previous subsection).

VIII. Conclusion

We have come a long way in our study of plasma propulsion of the Hall current type and have progressed from PHALL I to II and are preparing even a third further improvement which will be disclosed soon. PHALL II has shown a much improved performance with respect to our first approach and we are developing contacts in order to try and send one of these to the outer space for real life testing. Possible applications of PHALL on future Brazilian space missions dedicated to geostationary satellite orbit maneuvering from low earth to geosynchronous orbit is foreseen. PHALL experimental results and computer calculations have shown that electric propulsion with Hall thrusters can improve and give important contributions to future Brazilian space program missions.

The results obtained on the plasma density and temperature, the thrust measured by ion collector probe and ion energy analyzer are motivating results to forthcoming tests. Ion temperature measurements are showing a strong influence of the electric field on ions inside the acceleration zone. A computational study of satellite maneuvering using the PHALL was successfully conducted. These studies indicate that Permanent Magnet Hall Thrusters are a good candidate for spacecrafts performance control in long duration space missions. The possibility of an extra economy on satellite energy consumption due to the use of permanent magnets is one of the main advantages of this new design for Hall Thrusters.

Results of the analysis given in sections III and IV show that the considered electric propulsion system can be used for quite complicated maneuvers in space, up to transfers to other celestial bodies. However, transfers outside the Earth's sphere of influence with the existing propulsion system (i.e. with measured parameters in Table 1) need rather high propellant consumption. The following ways may lower the propellant consumption:

– transfer with shorter thrust arcs and, respectively, longer transfer time;
– launch from a higher initial orbit what would lower the total ΔV and, respectively, the propellant consumption;
– improvement of the propulsion system parameters to the desired or ideal values (see Table 2).

Note that the Earth's shadow was not taken into account in the analysis. If solar power is used for the electric propulsion then the thrusters cannot work (depending on battery size) when the spacecraft is in the shadow, which leads to a longer transfer time and slightly higher propellant consumption. Although the goal of the analysis was just to estimate the considered propellant system capacity for the space transfers; more detailed analysis including also the influence of the shadow may be necessary in the future for specific space missions.

Acknowledgements

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