NON-CHEMICAL PROPULSION ABILITIES FOR NEAR-EARTH MISSIONS

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Abstract

The paper discusses thrust performance of various non-chemical propulsion systems for payload transportation between near-earth orbits. Electric thrusters, such as ion, arc-jet, and stationary (Hall) plasma thruster (SPT) - all being powered by solar arrays, - and a solar thermal engine (STE) are considered, taking into account their efficiency, mass to power ratio and performance characteristics of the solar array. There are examined transportation of payloads from Low Earth Orbit (LEO) to Geostationary Orbit (GEO) and flights of an orbital manoeuvring vehicle (OMV) e.g., for removal of discarded artificial space objects. A simple model, based on Tsiolkovsky formulae and characteristic velocity increment, is used to choose an appropriate type of thruster for specific mission, depending on requirements of short transit time, higher payload or lowest starting mass of a non-chemical transport system. As a rule, the shortest transit time for all maneuvers, considered here, is provided by STE due to its higher thrust and better mass to power ratio. The highest payload is delivered by ion thruster at long transit times exceeding ~250 days. SPT is between these extreme cases in the respect of mass saving (comparing to chemical rockets) and transit duration. Known requirements to power supply for electric propulsion is partially mitigated by using «Sealunch» for LEO - GEO missions.

Introduction

Non-chemical thrusters are believed to be very attractive for application in flights in near-earth space. Whereas they are used for attitude control, station-keeping and so on, their usage as transport systems is yet in future.

There exist some missions, where non-chemical thrusters (with higher specific impulse \(I_p\) than chemical rockets) can be successfully used. They are transportation of payloads from a Low Earth Orbit (LEO) to the Geostationary Orbit (GEO), or to an intermediate orbit, and towing space constructions and discarded objects for cleaning space of debris. Orbital manoeuvring vehicle (OMV) for debris control could be equipped with a non-chemical propulsion system. The main advantage of non-chemical thrusters - their high \(I_p\) resulted in reduction of propellant consumption and increase of payloads, - can be effectively used at reasonably low masses of a thruster and a power supply. In fact, these tasks require a new approach to the propulsion system, since tens and hundreds of kW of power are necessary to solve them. And masses of thrusters and power supplies are correspondingly higher and comparative to the payload mass, unlike the case of electric propulsion for attitude control and station keeping.

Some criteria are used for assessment of non-chemical propulsion performance in space missions. Paper\(^1\) uses the lowest value of starting mass at LEO, when payload mass \(M_p\) is fixed. The present paper uses another criterion - achievement of maximum payload, delivered to GEO, using for illustrative purpose launch capability of the rocket «Zenith».

The other important criterion of acceptability of the propulsion system is transportation time. Transit times from LEO to GEO by ion thrusters with inductive and electrostatic acceleration, MPD and electrothermal thrusters are compared in\(^2\). The analogous analysis was made in\(^3\) for Xe- ion thruster of Kaufman type, stationary plasma thruster (SPT) (both devices now being in operation in space), and solar thermal engine (STE), designed for heating hydrogen and direct conversion of solar energy into thrust in a gas- dynamic nozzle\(^4\). Analysis of flight performance of the latter type of thrusters showed\(^5\), that it may be advantageous over electric propulsion systems due to higher thrust level and lower mass to power ratio.

This paper follows points of analysis of the paper\(^2\) and includes hydrogen arc-jet, Xe-ion and SPT thrusters (all types are supplied by solar array with mass to power ratio \(\alpha_{\text{power}} = 20 \text{ kg/kW}\)) and STE. Performance of SPT, equipped with nuclear power plant of «Topaz»-type is also considered.

Calculation model and input data

Flights with low thrust can be assessed using Tsiolkovsky formulae, equation of mass balance, and characteristic velocity increment \(\Delta V\), defined for spiraling motion of a spacecraft.
\[ M_{PR} = M_0 (1 - e^x), \quad x = \Delta V / g_i \]  

\[ M_{PR} \] mass of propellant.

Starting mass \( M_0 \) of a spacecraft is connected to masses of a power unit \( M_{pow} \) and a thruster \( M_{th} \):

\[ M_0 = (M_{pl} + M_{pow} + M_{th}) / \varphi(x), \]  

\[ \varphi(x) = 1 - (k + 1) (1 - e^{-x}), \]  

\( k \) - tank factor (\( k = 0.1 \) for Xe, \( k = 0.15 \) for H₂ because of thermal insulation, required for liquid hydrogen storage).

The flight is considered to be carried out with constant mass rate \( \dot{m} \), and power \( N \), consumed by a thruster, is related to \( \dot{m} \):

\[ N = \dot{m} (g_{i} l_j)^{2} / 2 \eta, \]  

and from obvious relation \( T = M_{PR} / \dot{m} \) it follows:

\[ T = (g_{i} l_j)^{2} (1 - e^{-x}) (M_{pl} + M_{pow} + M_{th}) / \varphi(x), \]  

\( \eta \) - thruster efficiency. Using specific masses of a power supply \( \alpha_{pow} \) and a thruster \( \alpha_{th} \), transit time is

\[ T = (g_{i} l_j)^{2} (1 - e^{-x}) (M_{pl} / N + \alpha_{pow} + \alpha_{th}) / \varphi(x) \]  

Dimensionless form of equation (2) convenient for analysis is

\[ M_0 / M_{pl} = [1 + (\alpha_{pow} + \alpha_{th}) N / M_{pl}] / \varphi(x) \]  

Estimates of propulsion system performance in LEO-GEO mission

Characteristic velocity increment for spiraling motion of a spacecraft from one orbit to another is:

\[ \Delta V = \sqrt{V_{1}^{2} - 2 V_{1} V_{2} \cos \nu / 2 + V_{2}^{2}}, \]  

\( i \) - inclination angle between initial and final orbits, \( V_1 = 7.866 \text{ km/s} \) at the initial orbit of height \( H = 200 \text{ km} \), \( V_2 = 3.072 \text{ km/s} \) is circular velocity of the spacecraft at GEO. Two illustrative cases are used:

\[ \Delta V = 7.866 \text{ km/s} \] for transfer from the orbit of 51° inclination, and \( \Delta V = 4.716 \text{ km/s} \) for launch in equatorial plane. The latter case is taken into consideration because of new opportunities, opened by «Sealaunch» program, using rocket «Zenith».

Input parameters for the calculation model are taken from various sources. Parameters \( \alpha_{th}, \eta \) and \( I_{sp} \) of a plasma thruster are taken not worse than for model SPT - 100. Paper\(^6\) implies \( \alpha_{th} = 16.7 \text{ kg/kW} \) for SPT, efficiency \( \eta = 58 - 60\% \), \( I_{sp} = 1500 - 2000 \text{ s} \) are typical for SPT - 100. A modernized version of SPT - 100 has \( M_{th} = 18.87 \text{ kg} \) (including power processing hardware) at power \( N = 1.5 \text{ kW} \). It means \( \alpha_{th} = 12.6 \text{ kg/kW} \). A value \( \alpha_{th} = 12 \text{ kg/kW} \) is accepted here.

Following\(^4\), value \( \alpha_{th} = 8 \text{ kg/kW} \), efficiency \( \eta = 65 \% \) and \( I_{sp} = 3000 \text{ s} \) will be used for ion thruster, though this value of \( \alpha_{th} \) seems too optimistic.

Arc-jet has \( \eta = 55 \% \), \( I_{sp} = 1000 \text{ s} \), \( \alpha_{th} = 14 \text{ kg/kW} \) (according to \(^5\)) and \( \alpha_{th} = 5 \text{ kg/kW} \) as Jones has used in\(^1\). For conservative estimate \( \alpha_{th} = 14 \text{ kg/kW} \) is taken.

Solar thermal engines parameters were deduced from published design data\(^4\): \( I_{sp} = 900 \text{ s}, \eta = 75 \% \), \( \alpha_{th} + \alpha_{pow} = 0.4 \text{ kg/kW} \).

Though mass characteristics of nuclear power plant «Topazz» seems to be unfavorable for electric propulsion (\( \alpha_{pow} = 196 \text{ kg/kW} \) according to\(^8\)), an attempt\(^6\) to assess performance of a system SPT + NPP was based on \( \alpha \approx 55 \text{ kg/kW} \). This system is also included in analysis.

Figures 1 - 3 show general results, obtained from Equations (5) and (6). When plotting diagrams of Fig. 3 (except the system STP + NPP, that does not depend on solar energy), calculated values of transit time \( T \) from Eq. (5) were multiplied by a factor \( S \), which takes into account Earth shadowing of solar arrays of the spacecraft. For LEO - GEO mission \( S = 1.1 \).

As it could be expected, solar thermal engines provide comparatively low transit time \( T \) due to very low value of \( \alpha_{th} + \alpha_{pow} \) and moderate specific impulse \( I_{sp} \).

To have more definite insight into performance abilities of transportation systems, starting mass \( M_0 \) is specified as a payload, delivered by a launch system «Zenith» from Earth to LEO - \( M_0 = 13700 \text{ kg} \). The corresponding dependence of payload mass \( M_{pl} \), delivered by a non-chemical transportation system to the Geostationary Orbit, on transit time \( T \) is shown at Fig. 4, and competition of various thruster systems is seen at the Figure. Using two criteria - an acceptable transit time and maximum payload mass at GEO, an appropriate thruster system can be chosen. The transit time \( T \) is often considered as acceptable, if it is less than 100 days, may be, this expectation is mainly due to psychological reasons (see\(^10\) and references there). Fig. 4 shows, that better mass characteristics are offered by STE and SPT, if \( T \leq 100 \text{ days} \) constraint is accepted. If longer missions are permissible \( T \geq 250 \text{ days} \), ion thrusters offer higher payload mass. An advantage of sea launch (\( i = 0^\circ \)) is clearly seen from comparison of solid and dotted curves of Fig. 4.

To be economically viable, the non-chemical thrusters are believed to be capable of transporting payloads more than 20 % higher than existing chemical rocket systems. Three stages of the «Zenith - 3SL» rocket can transport 2900 kg to GEO at sea launch\(^9\) (at \( i = 0^\circ \)). Thus, a non-chemical transportation system, brought to LEO by two stages of «Zenith - 2p» rocket, should be capable of
delivering at least 3500 kg at inclination $i = 0^\circ$, to compete successfully with chemical propulsion. It is seen from dotted lines of Fig. 4, that STE, ion thruster and SPT - all are acceptable in this case and can provide even shorter transit times $T$, than mentioned above. And only solar thermal engine can satisfy the payload mass requirement at launch at another place ($i = 51^\circ$, solid curve 3 at Fig. 4).

Electric power $N$ of a thruster system is very important parameter for comparison of non-chemical transportation systems and for their general assessment. Fig. 4 shows figures at curves, which denote power N, required for operation of non-chemical transportation system. These figures are rather high, and they are especially high at comparatively short transit times. Since this power level is not now available in space, paper recommended the 100-day constraint to be relaxed. It will result in corresponding decrease of necessary power $N$. Another recommendation was to increase the available power at spacecraft well above the 100 kWe regime. However, it should be kept in mind, that increase of a solid array power leads to increase of its overall dimensions, even if mass to power ratio $\sigma_{pow}$ is reduced by e.g. refinement of construction. (Parameter $\sigma_{pow}$ as low as $\approx 10$ kg/kW is often mentioned as really achievable by progress in solar array design). Drastic increase of efficiency of not only separate photo cells, reported from physical laboratories, but of big solar arrays are required to have acceptable overall dimensions of the solar arrays, which are as a rule too large at present time.

Sea launch can partially save the situation, as it is seen from curves at Fig. 4. SPT and STE thruster systems allow to utilize $N < 100$ kWe even at transit times $T < 100$ days.

Relaxed requirement to have trip time as high as $T \approx 250$ days will allow to use advantages of ion thruster and to triple payload mass ($M_{pl} \approx 9000$ kg against chemical rocket engine $M_{pl} = 2900$ kg at sea launch).

An obvious possibility to use available comparatively low power supplies for electric propulsion in LEO-GEO missions is transporting payloads of lower mass, say under 1000 kg class, and allowing transportation times higher then 100-day duration.

Point 4 at Fig. 4 indicates a result of calculation of characteristics of SPT + NPP space transporting system, launched by «Zenith - M» at LEO in the inclination plane $i = 66^\circ$ and then spiraling to the Geostationary Orbit. Low payload mass, obtained in, seems to be a penalty for unfavorable inclination of LEO and nuclear hazard. The latter reason leads to transportation system starting from intermediate orbit of height $H = 10277$ km instead of LEO ($H = 200$ km) and consequently it requires a chemical upper stage «Fregeta» of mass about 1000 kg.

Application of non-chemical propulsion for debris control

An orbital maneuvering vehicle (OMV), equipped with a non-chemical thruster system, can be used for towing discarded space objects between orbits to prevent their damage and formation space debris, or descending payloads from low orbits to dense layers of atmosphere or removal them to upper orbits and to clean near-earth space of debris.

Analysis of a tentative example, using the approach of the present paper, showed, that solar thermal engine, ion and stationary plasma thruster, supplied by solar arrays, are good for towing two objects of mass $\approx 1000$ kg from orbits of height $H = 200$ km, and of different inclinations $i = 51^\circ$ and $i = 28^\circ$, being launched supposedly by different states, to a common gathering orbit at $H = 1000$ km. Characteristic velocity increment $\Delta V$ in this case depends only on inclination angles $i_k$ of the gathering orbit plane relative to the both orbit planes. And thus masses of a transporting system components, required propellant mass and transit time depend on the selection of $i_k$. There exists an optimum orbit plane, compromising for both owners of space objects, for each type of thruster. Transportation to this orbit plane requires the lowest mass of propellant $M_{pr}$. Fortunately, the minimum $M_{pr}$ is shallow for each thruster, and angular positions of minima practically coincide at $i_k \approx 18^\circ$. The appropriate curves are shown at Fig. 5, taken from paper.

This towing of two objects should be carried out in succession of 3 (if the OMV stays at the gathering orbit) or 4 transfers. In the latter case the OMV comes back to the starting orbit. Due to asymmetry of flying situation (the OMV starts towing the first object, having full tanks of propellant, then it makes an idle flight and starts another towing with partially empty tanks). Fig. 5 reveals asymmetry in the position of minimum of $M_{pr}/\mu$ as a function of inclination angle of the gathering orbit plane $i_k$ (\(\mu\) is dry mass of the OMV. $\mu = M_{pow} + M_{pr} + M_{constr}$. $M_{constr}$ denotes mass of construction elements, e.g., fastening facilities of the OMV and others).

Analysis of the paper gave acceptable starting masses of the OMV: $M_0 = 2260$ kg for STE, $M_0 = 1909$ kg for SPT and $M_0 = 1770$ kg for OMV, equipped with ion thrusters. All non-chemical systems have power 10 kW. Arc-jet thruster requires too high starting mass $M_0 = 3277$ kg. Total transportation times are 68 days for STE, 107 days.
for arc-jet, 144 days (SPT) and 270 days (ion thruster). The gathering orbit should be between starting orbits closer to the orbit plane of an object to be towed in second turn.

Non-chemical thrusters are very suitable for removal of discarded objects from GEO to higher orbits and virtually to open space. Characteristic velocity increment \( \Delta V = 1.065 \text{ km/s} \) is required to spiraling a discarded satellite from GEO to the circular orbit around Earth with radius 100000 km. The best choice for this task is an ion thruster, that provides the lowest amount of propellant (~4 % of final mass of a satellite) to carry out this maneuver. Ion thruster is winner in the competition among other thrusters, because transit time \( T \) does not play virtually any role in this case. SPT is also acceptable for this purpose. Some higher propellant mass (~7 % of final mass) is partially balanced by lower mass and other advantages of SPT (lower operational voltage, smaller size, more robust construction and some others).

**Conclusion**

The approach, outlined here, allows to estimate capabilities of non-chemical propulsion systems for solving transport problems in near-earth space and to choose an acceptable type of a thruster and to specify power plant for operation in a joint system.

At present time the two problems hamper wide operation of non-chemical thruster systems in near-earth space: unacceptably long transit time and low available power in space. The present paper showed, that the often used criterion of transit time \( T \) for LEO-GEO mission \( T < 100 \text{ days} \) can be met by performance characteristics of a solar thermal engine and stationary plasma thruster, provided sea launch is used as a first stage for transporting from Earth to LEO. Thus pessimistic assessment of electric propulsion is drastically mitigated by using sea launch for Earth-LEO-GEO mission, since non-chemical transportation takes place in one (equatorial) plane in this case.

At sea launch non-chemical propulsion for LEO-GEO mission is economically viable, as presented paper demonstrated, and ion thruster can transport in excess tree times higher payload to GEO, than chemical rocketry, if transit time \( T \approx 250 \text{ days} \) is tolerable. And even at \( T \leq 100 \text{ days} \) the payload criterion of paper is met by SPT and STE transporting systems, i.e. payload, transported to GEO by SPT or STE, exceeds one, delivered by chemical rocket system, more than in 1.2 times.

To use advantage of the sea launch for LEO-GEO mission more effectively, available electric power \( N \) at a spacecraft should be increased up to 60 - 100 kWe.

Modern capabilities of solar arrays allow to tow discarded objects to a gathering orbit for their storage. Orbital maneuvering vehicle, equipped with non-chemical thruster, promises advantages in transporting discarded spacecrafts and satellites to solve problems of debris control in near-earth space.

The best choice for pushing away a discarded satellite from GEO is ion thruster, since transit time is not a constraint in this case. SPT is also acceptable in this case.

**References**


Fig. 1. $M_0/M_{pl}$ ratio as a function of $M_{pl}/N$ for LEO-GEO mission at LEO inclination $i = 51^\circ$

1 - ion thruster; 2 - SPT; 3 - arc-jet; 4 - SPT + NPP system; 5 - solar thermal engine

Fig. 2. $M_0/M_{pl}$ ratio as a function of $M_{pl}/N$ for LEO-GEO mission at «Sealunch», LEO inclination $i = 0^\circ$

1 - ion thruster; 2 - SPT; 3 - arc-jet; 4 - SPT + NPP system; 5 - solar thermal engine
Fig. 3. Diagram of transit time $T$ vs $M_p/N$ ratio for LEO-GEO mission
1 - ion thruster; 2 - SPT + NPP system; 3 - SPT; 4 - arc-jey; 5 - STE;
Solid lines - at LEO plane inclination $i = 51^0$, dotted lines - at «Sealaunch»
Fig. 4. Payload mass $M_{pl}$ as a function of transit time $T$ from LEO to GEO

1 - ion thruster; 2 - SPT; 3 - STE.

solid lines - LEO inclination $i = 51^\circ$; dotted line - «Sealaunch» at $i = 0^\circ$; figures at the curves indicate required power $N$ in kW
Fig. 5. Propellant mass required for compete route of OMV, normalized to its dry mass, as a function of inclination angle of the gathering orbit: 1 - three-flight route; 2 - 4 - four-flight routes; 1, 2 and 3 - for $M_p/\mu = 3$; curve 4 for $M_p/\mu = 2.5$; 1 and 2 - for $I_{sp} = 900$ s; 3 - $I_{sp} = 1600$ s; 4 - $I_{sp} = 3000$ s; at the insert SO denotes starting orbit, GO - gathering orbit, arrows - directions of towing and idle flights of the OMV.