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Perspectives of electromagnetic railgun application as plasma engine for spacecrafts

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Abstract
A pulsed electromagnetic accelerator with an external magnetic field can be used as a powerful plasma engine. In the installation of such type, the plasma piston, initiated in the breech section of the rail channel, accelerates under the action of the Ampere force and at the time of exit from the channel muzzle part have a speed of the order of 1-30 km/s depending on the discharge current. In the process of motion along the channel of the plasma piston, the plasma mass effectively increases in it due to material erosion from the surface of the electrodes (rails).The calculated and experimental data on the achieved values of the specific impulse and thrust of such an engine will be given in the report.

1. Introduction

At present great attention is paid to the problem of creating new plasma engines for spacecrafts [1-8]. This is due to the fact that the rising electrical powers of spacecrafts in the near future will make it possible to switch from the use of low-power engines to the engines of considerable powers. Great research efforts are now devoted to the avant-projects and projects aimed at the development of spacecrafts with rather high power (10-100 kW) for the engines. Various applications of such spacecrafts are considered, such as space tugs, space exploration systems, etc.

Despite the fact that electric rocket engines appeared at the dawn of the space age, active research is still underway. Since the electrical power of a spacecraft in an orbit is limited, low-power engines of two types have been created and used in practice for more than 40 years. They are stationary plasma engines and ion engines. They can operate with powers (1 ... 10 kW) given by solar batteries of the spacecraft in the Earth orbit and are mainly used on communication satellites to correct orbital motion. Stationary plasma engines and ion engines, possessing a large resource, high specific impulse values and low energy consumption, are not suitable for long-distance space flights to extraterrestrial objects due low thrusts (10^{-2} - 10^{-1} N).

One of possible way to create plasma thruster with high pulse characteristic is to use pulsed plasmadynamic thrusters with an electromagnetic railgun configuration. The ampere force acting on the plasma armature in the accelerators of this type accelerates the gas located in the plasma armature. When the plasma is accelerated, the mechanical facilities to which the channel is attached receive an impulse in the direction opposite to that of the gas flow. Depending on the ampere force, which is determined by the discharge current, external magnetic field, and the initial gas pressure in the channel, the velocity of the plasma outflow from the channel can exceed that of chemical thrusters by an order of magnitude or more.

Experimental

In the experiments, an electromagnetic rail accelerator placed in a special vacuum chamber equipped with a system for recording the electrical parameters of the circuit and dynamic parameters of the gas flow was used (Fig.1).

Lateral transparent dielectric walls of the railgun channel made of Plexiglas allowed an optical detection of plasma propagation. A set of railgun channels with cross-sectional areas A from 4 to 36 mm^2 and lengths l from 250 to 500 mm were employed. The inductance per unit channel length L' depended on the channel cross-section. For example, for the cross-section A equal to 36 mm^2, L' was 0.37 μH/m.

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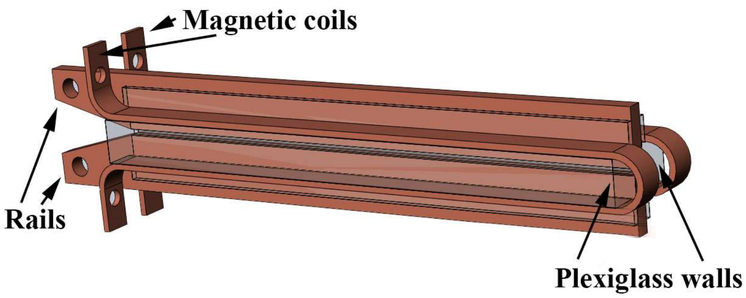

Figure 1. Schematic view of the railgun.

The vacuum chamber with the railgun inside it was filled with a gas (argon, xenon) to operating pressures of 25-500 Torr after pumping to the fore vacuum. The current leads which were hermetically sealed in the chamber flanges provided application of a current pulse of up to 100 kA to the railgun electrodes. The energy storage device in the form of an LC-line was connected to the railgun through an ignitron switch and formed a trapezoidal current pulse with an almost flat top on the load. The discharge current through the railgun was varied by changing the charging voltage on the LC-line capacitors in the range U_0=0.8-4.5 kV, its amplitude reached 60-80 kA in our experiments. The discharge was initiated by a high-voltage spark applied to a thin auxiliary electrode in the breech part of the railgun channel simultaneously with the application of voltage from the energy storage device to the railgun rails.

The shock-wave velocity was determined by the laser radiation cutoff in two channel cross-sections at distances of 80 mm and 5 mm from the muzzle. For example in a Xenon as a working gas with a pressure of 30 Torr and external magnetic field of 1.45 T, the shock wave velocity was 5.27 km⁄s.

Theoretical model of plasma acceleration in the electromagnetic railgun

We use a simple model [9] of plasma acceleration in a channel of rectangular cross-section filled with an inert gas. The plasma armature is considered to be an impermeable flat thin current layer of variable mass occupying the entire cross-sectional area of the channel $A = hw$, where h and w are the channel height and width, respectively. The mass accelerated in the channel $m = m_{pp} + m_{sl}$ is the sum of masses of the plasma armature m_{pp} and the gas in the shock-compressed layer m_{sl}. The plasma armature is filled with the erosion mass $m_{pp}{\sim}m_{er}$ entering the channel from the rails and involved in the motion by the plasma armature. The plasma armature composition (in our case *Cu*, Cu^+, Cu^{++}, *e*) is determined by the electrode surface material. The plasma of the shock-compressed layer consists of atoms and ions of the gas filling the channel after its compression and heating by the shock wave. Both masses increase with time.

In the presence of an external magnetic field the ampere force that accelerates the plasma F_A contains two terms

$$F_A(I, i_1) = F_i + F_e = L'Ii_1/2 + Bwi_1 \qquad (1)$$

The first term F_i is the force of acceleration of the current $i_{pp} = i_1$ flowing through the plasma armature created by the magnetic field of the discharge current I in the rails-electrodes with the inductance per unit length L'. The second term F_e is the force produced by the external magnetic field B acting on the current i_1. A more detailed model explanation is given in [9].

3. Comparison of experimental and theoretical results

Experimental and theoretical data on the plasma armature acceleration in a railgun with a length $l = 25\ cm$, the channel of which is filled with argon and xenon under various initial pressures, are presented in Table 1. The data include the gas type, initial gas pressure p_1, discharge current I, external magnetic field induction B, experimental D_{exp} and theoretical D_{th}, shock wave velocities, plasma armature velocity v, mass of the gas in the shock-

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compressed layer m_{sl} and the total mass flowing in the railgun channel $m = m_{er} + m_{sl}$ at the moment the shock wave reaches the muzzle.

Table 1. Experimental and theoretical data on the plasma armature acceleration in a railgun with a length $l = 25\ cm$.

Gas	p_1, $Torr$	I, kA	B, T	D_{exp}, km/s	D_{th}, km/s	v, km/s	m_{sl}, mg	m, mg
Ar	25	23.4	0	5.9	5.86	5.13	0.50	0.70
Ar	25	21	0.97	8.56	8.8	8	0.50	0.57
Ar	25	39	0	8.5	8.11	7.35	0.50	0.94
Ar	25	37	0.87	10	10.9	9.95	0.50	0.74
Ar	25	32.5	1.49	12.1	12.0	10.9	0.50	0.65
Ar	50	42	0	6.98	6.64	5.88	1.00	1.66
Ar	50	54	0	8.53	7.92	7.13	1.00	1.85
Ar	100	34	0	4.86	4.56	3.75	2.00	2,61
Ar	100	46	0	6.11	5.53	4.74	2.00	3.00
Ar	100	61	0	7.12	6.75	5.96	2.00	3.36
Ar	100	72	0	8.08	7.64	6.84	2.00	3.53
Ar	250	58	0	5.4	4.88	4.05	5.00	6.26
Xe	7.6	24	0	5.88	6.58	5.95	0.50	0.564
Xe	7.6	58	0	10.59	10.35	8.67	0.50	1.23
Xe	15	24	0	4.49	4.8	4.39	1.00	1.10
Xe	15	58	0	8.15	7.93	7.13	1.00	2.09
Xe	30	19.5	0	2.94	2.72	2.35	2.00	2.42
Xe	30	42	0	4.96	4.78	4.35	2.00	3.31
Xe	30	57	0	6.58	6.16	5.58	2.00	3.15
Xe	30	23	0.7	4.36	4.35	3.95	2.00	2.39
Xe	30	22	1.45	5.27	5.31	4.83	2.00	2.24
Xe	30	21	2	5.97	5.83	5.29	2.00	2.15

The comparison of the experimental and calculated shock wave velocities shows that they are in a fairly good agreement. For low currents ($I < I_0$), when the effect of erosion on the plasma dynamics is insignificant, the difference between velocities D_{exp} and D_{th} is a few percent, which confirms the adequacy of the physical model of the plasma armature motion. It can be seen that the application of an external magnetic field leads to a significant increase in the plasma armature and shock wave velocities.

If we compute the power characteristics of a pulsed jet flowing out of channels the dynamic characteristics of a railgun can be obtained. These characteristics and also parameters of the accelerated plasma flowing from the railgun channel are given in Tables 2 and 3. Tables 2 and 3 list data for plasma thruster with Argon and Xenon as a working gas, respectively. Here, I is the maximum electric current flowing in the rails-electrodes, B is the induction of the external magnetic field, t_{fl} is the time of jet outflow from the channel, v is the plasma armature velocity at the channel exit, $m = m_{pp} + m_{sl}$ is the mass of the accelerated plasma and gas that reaches the exit section and outflows as the pulsed jet, $F = mv/t_{fl}$ is the average pulsed thrust during the jet outflow time, $p = mv$ is the jet momentum, and $p_{ud} = v/g$ is the specific impulse per unit mass of the jet.

The time of the accelerated plasma outflow from the channel t_{fl} was estimated from the experiment by using a photosensor that detected the gas luminosity intensity when the shock-compressed layer and the plasma armature passed the channel section located at a distance of 5 mm from the exit from the channel. The time interval between the onset and disappearance of the luminosity of the accelerated plasma in the region adjacent to the exit section of the accelerator channel was approximately equal to the time of escape of the shock-compressed gas and plasma armature from the channel (Fig. 4). A sharp drop in the luminosity intensity corresponds to the initial stage of the hot gas outflow with maximum velocities, when $p_2 \gg p_1$, and the tail of the curve corresponds to the outflow of weakly conducting peripheral layers of the plasma armature. For different initial pressures and gas types in a channel

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of length $l = 25\ cm$ filled with argon or xenon, t_{fl} varied in the range $8 - 12\ \mu s$ and was close by the order of magnitude to $(2-3)\ \Delta/v$. When the average force F was estimated, the value $t_{fl} = 20\ \mu s$ was used.

Table 2. Characteristics of the jet at the exit from the railgun channel filled with Argon (railgun channel length $l = 50\ cm$)

p_1, *Torr*	I, kA	B, T	$V, km/s$	m, mg	F, N	p_s, *mNs single pulse*	p_s, s
100	60	0	5.81	6.79	1970	39	592
100	60	2	8.95	5.61	2500	50	912
100	100	0	8.93	7.77	3450	69	910
100	100	2	11.99	6.27	3750	75	1223
250	100	0	6.9	12.8	4400	88	703
250	100	2	8.92	12.11	5400	108	910

Table 3. Characteristics of the jet at the exit from the railgun channel filled with Xenon (railgun channel length $l = 50\ cm$)

p_1, *Torr*	I, kA	B, T	$V, km/s$	m, mg	F, N	p_s, *mNs single pulse*	p_s, s
15	100	0	11.46	4.02	2300	46	1168
30	100	0	8.99	6.37	2850	57	916
30	100	2	12.1	5.62	3400	68	1232
100	100	0	5.76	17.85	5150	103	587
100	100	2	7.55	7.55	6250	125	770

It can be seen from Tables 2 and 3 that the specific impulse obtained for the thruster based on an electromagnetic railgun reaches $1200\ s$ and the pulsed thrust is up to $5000 - 6000\ N$. The application of an external magnetic field contributes to an increase in both the specific impulse and the thrust of the plasma thruster. It is important to note that there are regimes characterized simultaneously by a high thrust and high specific impulse. For example, the plasma thruster based on the railgun channel filled with Argon at $100\ Torr$, electric current in the rails-electrodes of $100\ kA$, and applied magnetic field of $2\ T$ can produce a specific impulse of $1223\ s$ and a thrust of $3750\ N$.

Conclusion

Experimental investigations of the possibility to use the electromagnetic railgun with an external magnetic field as a pulsed electric thruster have been carried out. An analytical model that describes the gas and plasma flow in the railgun channel has been developed. The theoretical calculations proved to be in a good agreement with the experiment. It has been found that there are operating regimes of the railgun characterized simultaneously by a high thrust $(5000 - 6000\ N)$ and high specific impulse $(\sim 1000\ s)$. Additional possibilities can be provided by optimizing the channel parameters. For example, a decrease in the channel cross section reduces the resistance force, which leads to increases in the plasma velocity and thrust force. The thrust can also be increased by using multichannel railguns and by applying higher external magnetic fields.

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