INVESTIGATION OF PARAMETERS OF THE WORKING SUBSTANCE - LOW TEMPERATURE PLASMA IN THE IONIZATION RESONATOR CHAMBER OF THE RF REACTIVE ENGINE

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This paper is the extension of investigations of the RF engine designed for orientation and stabilization of the spacecrafts orbit, and it is undertaken for measuring of plasma parameters of RF discharge in the ionization resonator chamber. The experiments were performed at the frequency of 80 MHz on the model engine, in which a length of coaxial line with shortening capacities at the ends was used as the ionization resonator chamber. As the result of the experiments, conditions of the RF discharge ignition in the resonator chamber are studied; dependencies of plasma density and temperature versus applied power and working body pressure are obtained for various gases. The measurements of the thrust were performed at the special-purpose test bench. The data obtained allow making a conclusion that further investigations in this direction hold much promise.

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SETTING UP THE PROBLEM

Presently, in connection with intensive development of telecommunication systems and global Internet system the question about creation of reliable communication satellites with long-term operating life arose. One of the main factors defining operating life of these satellites is the operating resource of low thrust engines, which are used for correction and stabilization of satellites' orbits. As a rule, electro reactive engines of different types with plasma exhaust velocity of the order of $10^3 – 10^5$ m/s are used as low thrust engines.

Engines for orbit correction and stabilization, as well as any other space engines, must possess high flight efficiency over the all range of specific pulses of interest for the given application; must have, if possible, a simple reliable construction and minimum sizes and weight. The operating resource of electro reactive engines is determined mainly with the processes occurring near the surfaces and inside solid bodies interacting with active plasma. Erosion electrodes, insulators, and other constructional elements, which are bombarded with accelerated particles, decrease the operating life of the engine [1]. To increase operating life resource it is necessary to take measures for thermo insulation of plasma that forced us to provide several power supply sources for engines, and high voltage sources among them.

These drawbacks are less specific for RF reactive engines for which specific pulse increases due to heating of the working substance through RF energy transfer from an external source. Energy from the external source is transformed into thermal ion energy, and the latter –"gas dynamically" is transformed into energy of accelerated motion of the working substance. That is, energy from the external source first is transmitted to electrons. Therefore, in the gas discharge chamber it is necessary to form the conditions for transfer of energy from electrons to ions by means of electron-ion interactions.

With estimation of these conditions it is necessary to take into consideration, that most efficient transfer of RF energy from an external source to plasma electrons occurs on frequencies ω much less than frequencies of elastic interactions υ_m, but higher than electron plasma frequency ω_p, and the most probable way of energy transfer to ions is elastic interaction between electrons and ions. At a single elastic interaction electron transfer a small part of its energy ε, of the order of electron mass m to ion mass M ratio, gained in the electric field. Consequently, to transfer all amount of energy a large number of interactions, of the order of M/m, is necessary. Thus, ratio of characteristic sizes of the gas discharge chamber L to the electron free path λei should be no less than M/m. Taking into account, that $\lambda ei=1/n\cdot\sigma_{ei}$, where n is ion density, and σ_{ei} is electron elastic cross section on ions, we would obtain the estimation of the lower limit for density

$$n \geq M/mL\cdot\sigma_{ei}$$

With the characteristic sizes L – 10cm, and electron temperature T_e – (1-10)eV the plasma density should be no less than $(10^{14} – 10^{16})cm^{-3}$. From the other hand, the plasma density should be so that during the time between collisions electron would compensate the energy loss, i. e., the product $\lambda ei\cdot eE_{eff}$, where e is electron charge, E_{ef} – effective value of electric field, should be of the order of $m/M\cdot\varepsilon$, the value of energy transferred by electron. From that we would obtain the upper limit of density.

$$n \leq eE_{eff}/\sigma_{ei}\cdot M/m\cdot\varepsilon$$

When the electric field strength E_{eff} is of the order of 100V/cm and electron energy ε is about (1-10)eV, plasma density should not exceed $(10^{15} - 10^{17})cm^{-3}$. Thus, "thermal" acceleration of ions is possible in a rather narrow range of densities.

$$(10^{14} – 10^{16})\ cm^{-3} \leq n \leq (10^{15} – 10^{17})\ cm^{-3}.$$

With these densities, for heating plasma electromagnetic waves are most effective with frequencies $\omega>10^9$ Hz. In this frequency range cavities of different types are used, in which accumulation of RF energy occurs. However, application of cavities as a base for construction of the engine ionization chamber is under question. In the cavity adjusted to a certain frequency, after ignition of the discharge additional conductivity arises that leads to alteration of self-resonance frequency and its Q-factor. Power absorbed with plasma depends both on the value of mismatching, and on adjusting in frequency. Thus, for optimization of engine efficiency it is necessary to tune the RF-generator additionally or to regulate the parameters of the engine itself with each start-up. That would complicate the construction and, as a result, would increase the cost of thrust. Another problem is associated with creation of compact and light generators of sufficient thrust in this frequency range.

The goal of the present work is continuation of studies connected with development of a compact RF frequency engine for stabilization and correction of the orbit, which could operate in the frequency range of (10^7 - 10^8) Hz with operating life no less than 15 years.

THE EXPERIMENTAL INSTALLATION AND MEASURING PROCEDURES

A number of trial experiments [2] allowed us to optimize the engine model construction add to choose measuring procedures. To carry out studies two model engines were manufactured. One of the module, 50cm in length and 10cm in diameter operated on the frequency of 80 MHz and was meant for investigation of parameters of discharge in the chamber. The second one, somewhat smaller in sizes, operated on the frequency of 120 MHz and was adapted for arrangement of a thrust meter in the operating volume of the test bench. The choice of frequency range was due to availability of a large base of semiconductor elements operating in this range that makes it possible to create compact generators of the required power. As a base for ionization cavity chamber construction was chosen a section of coaxial line with the wave resistance of 75 Ω (Fig.1).

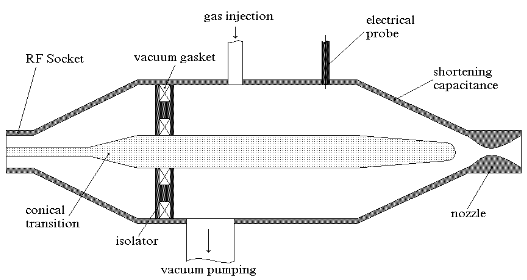

Fig.1. Scheme of ionization cavity chamber

One of the ends of the coaxial line was open and was a shortening capacitance with a nozzle. The other end of the chamber was provided with a conical transition to a coaxial line of a smaller diameter ended RF socket with wave resistance of 75 Ω, through which power from RF generator was supplied to resonator chamber. In such construction the maximum electric field strength always lies at the open end of the cavity. After ignition when resistance and frequency of the cavity change, maximum of the current moves along the coaxial line. However, if the value of the shortening capacity and dimensions of the cavity chamber are chosen to be so that maximum current in the "empty" cavity and after ignition of the discharge lies inside the construction, then into the ionization chamber there always be an area, that is a quarter wave cavity for the given generator frequency. Thus, after ignition of the discharge, the "automatic" adjusting of the ionization chamber into resonance mode occurs.

The models were supplied with systems of vacuum pumping, of gas injection, electric probes, vacuum electrostatic sockets, and they were placed in the vacuum chamber with the residual pressure of 10^{-5}mm Hg. The models of the engines and the vacuum chamber were pumped off to the residual pressure, and then with a gas injection valve the pressure required for the experiments is established, the RF generator were switched on, and after that the necessary measurements were performed. The consumption of the working substance was not controlled when measuring the plasma parameters.

The power applied to the discharge was controlled at the RF socket of the module upon the difference in energies of incident and reflected waves. The energies of the incident and reflected waves were determined with power gauge. The voltage of the discharge ignition was measured with a special voltmeter. It was assumed that on frequencies of 10^8 Hz connections a probe of the voltmeter having the wave resistance of 75 Ω, large input resistance and low input capacitance does not affect the distribution of the electric field along the coaxial line of the module.

The plasma density and temperature were measured upon volt-current characteristics of the electric probe. The measurements of the thrust were performed at the special-purpose test bench at the Kharkov Aero-Space University "KhAU". The test bench was intended for integrated investigations of electro rocket engines and engine installations on their base.

The basis of the test bench is a device for measuring the thrust placed in the vacuum chamber with the operating volume of 10 m^3 and with the limit residual pressure of $4.5 \cdot 10^{-6}$ mm Hg and the pumping rate of 40 m^3/s. The test bench is provided with automated system for control processing and displaying of the data. The mechanical part of the device for measuring the thrust is a beam fixed on three thread stems. The electric part of the device is fabricated on the technical base of "MicroDAT". Connect with the complex for the data processing and displaying is performed with a RS–232 interface. The test bench provides the thrust measuring in the range from 0 to 6500 mg with the scaled error of 0.5%.

THE RESULTS OF THE MEASUREMENTS

As the working bodies hydrogen, helium and nitrogen were used. The measurements were performed in the pressure range (10 – 10^{-2})mm Hg. The power supplied to the modules was altered from 30 to 500 W. In the Fig.2 the typical dependencies of the ignition voltage on the pressure in the ionization chamber are given.

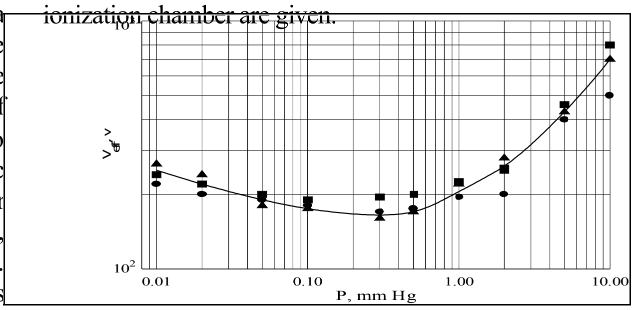

Fig. 2. The typical dependencies of the ignition voltage on the pressure. (▲-hydrogen, ■-helium, •-nitrogen)

The ignition voltage in the pressure range of $5 \cdot 10^{-1}$mm Hg has a minimum near 170V and, practically, does not depend on the sort of the gas.

The electron temperature within the experimental error is the same over the all range of pressure, up to 5mm Hg, does not depend on the sort of the gas, slightly rises with the supplied power and comprises 3 – 4 eV. The typical dependencies density versus pressure for different supplied energies is shown in the Fig.3. The electron density is almost proportional to the pressure op the operating gas and practically does not depend on the value of the supplied power. The value of the thrust after the discharge ignition rose by 25 – 33% with change of the supplied power from 100W to 250W and was equal to 70 – 80 mg.

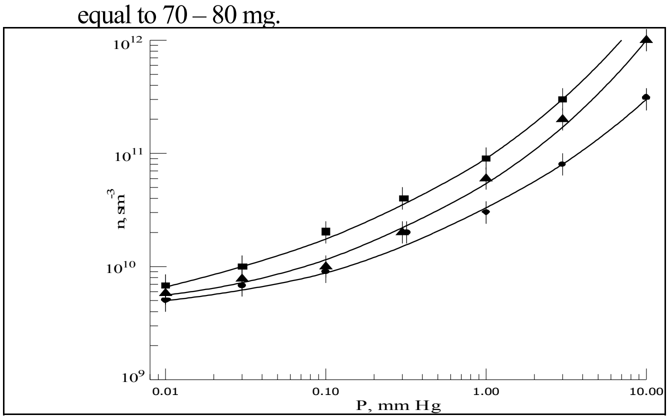

Fig. 3.The typical dependencies density versus pressure: (• - 100W, ▲- 150W, ■ – 200W)

DISCUSSION OF THE RESULTS

Within the typical range of value of external parameters, plasma in the ionization chamber is under affects of standing electromagnetic wave with the frequency υ_E less than frequency of elastic collisions υ_m. So, it is a case of low frequency ($\upsilon_m > \omega$), though discharge occurs on high frequencies ω. The electron free path and their amplitude of oscillations in the RF field are less than the chamber dimensions. The electron motion is completely diffuse in nature, and the main process of energy transfer to ions is elastic interaction between electrons and ions. Estimations show that practically over the all range of the external parameters, the time of electron energy leveling off is one or two order less then the time of energy transfer to ions. That is, electron distribution in energies is Maxwellian. The shape of volt-current characteristics of the probe testifies that indirectly. The theory of the electric probe accounting collisions still has not completely obvious simplifying assumptions. Nevertheless, obtained values of density and temperature can be interpreted as typical for RF discharges with drifting electron motion and discharge currents of several tens of milliampers.

The main differences of the investigated discharge from the typical are: slight dependence of electron density and pressure on the value of supplied power, and independence of ignition voltage on the sort of gas.

Apparently, the first difference can be explained by blowing through the discharge of a neutral gas. On the stream of the gas the discharge is stabilized at the less values of density and temperature, and a part of energy supplied to plasma is expended on raise of the thrust. The raise in the thrust with increasing supplied power confirms this assumption.

The second difference is associated with peculiarities of the cavity chamber construction. In the area of the cone shortening capacitance the chamber has alternating cross section, thus the distance between electrodes changes, and the discharge can be ignited at the optimum values of pressure $\boldsymbol{p}$ and value of the discharge gap $\boldsymbol{d}$.

CONCLUSIONS

The experiments carried out on the model engine, where a section of the coaxial line of the proper sizes with shortening capacitances of proper values was used as an ionization cavity chamber, show that in such construction discharge is possible on frequencies about 10^8 Hz. Direct measurements of thrust confirmed efficiency of transformation of energy from external source in internal energy of the working substance. The simplicity of the construction and possibility to create compact generators of sufficient power in the used frequency range give us assurance in good prospects of future investigations in the given direction.

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ДОСЛІДЖЕННЯ ПАРАМЕТРІВ РОБОЧОГО ТІЛА – НИЗЬКОТЕМПЕРАТУРНОЇ ПЛАЗМИ В ІОНІЗАЦІЙНІЙ КАМЕРІ-РЕЗОНАТОРІ ВИСОКОЧАСТОТНОГО РЕАКТИВНОГО ДВИГУНА

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Представлена робота продовжує дослідження НВЧ – двигуна, призначеного для орієнтації та стабілізації орбіти космічних апаратів, й виконана з метою виміряти параметри плазми НВЧ – розряду в іонізаційній камері – резонаторі двигуна. Експерименти проводились з частотою 80 МГц на макеті двигуна, в якому в якості іонізаційної камери використовувався відрізок коаксиальної лінії зі скорочуваючими ємностями на кінцях. В експериментах вивчені умови запалювання НВЧ – розряду в камері–резонаторі, отримані залежності густини та температури плазми від прикладеної потужності та тиску робочого тіла для різних газів. На спеціалізованому випробному стенді були проведені вимірювання тяги. Отримані результати дозволяють зробити висновок про перспективність подальших досліджень у цьому напрямку.

ИССЛЕДОВАНИЕ ПАРАМЕТРОВ РАБОЧЕГО ТЕЛА - НИЗКОТЕМПЕРАТУРНОЙ ПЛАЗМЫ В ИОНИЗАЦИОННОЙ КАМЕРЕ – РЕЗОНАТОРЕ ВЫСОКОЧАСТОТНОГО РЕАКТИВНОГО ДВИГАТЕЛЯ

С.А. Вдовин, Б.В. Зайцев, В.А. Бомко, А.Ф. Кобец, Б.И. Рудяк, М.С. Лесных, В.Г. Журавлев, В.М. Рашкован, Л.А. Базыма, А.В. Бастеев, В.И. Белоконь

Настоящая работа является продолжением исследований СВЧ – двигателя предназначенного для ориентации и стабилизации орбиты космических аппаратов и предпринята с целью измерения параметров плазмы СВЧ – разряда в ионизационной камере – резонаторе двигателя. Эксперименты проводились на частоте 80 МГц на макете двигателя, в котором в качестве ионизационной камеры – резонатора использовался отрезок коаксиальной линии с укорачивающими емкостями на концах. В экспериментах изучены условия зажигания СВЧ разряда в камере - резонаторе, получены зависимости плотности и температуры плазмы от приложенной мощности и давления рабочего

тела для различных газов. На специализированном испытательном стенде были проведены измерения тяги. Полученные данные позволяют сделать вывод о перспективности дальнейших исследований в этом направлении.