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RADIO FREQUENCY PLASMA REACTIVE ENGINE

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At the present time, designers of plasma reactive space engines pay especial attention to radio frequency plasma reactive engines (rf PRE). In such engines, the working body – quasi-neutral plasma – is formed with rf discharge [1]. Development of such types of engines seems to be promising due to the absence of electrodes prone to electrocorrosion, heated cathodes, keep-alive electrodes etc., which are used for plasma engines of all types. That would add to the plasma engine life.

The main problem for the rf PRE development is a transfer the rf power from the generator to the working body – low temperature plasma.

For example, it is well known [2] that the average rf power transferred to the unity volume of gas is:

$$\overline{P} = \frac{ne^2E_0^2}{2m}\cdot\frac{\nu_e}{\nu_e^2+\varpi^2}$$

where:

E_0 –electric field
m - electron mass,
n – electron concentration,
ν – frequency of elastic collisions,
ω – frequency of the applied field

From above one can see that the effective power exchange is only possible if the frequency of the applied field does not exceed the frequency of collisions.

$$\nu_e = \overline{V}NQ$$

V- average electron velocity,
N – ion concentration,
Q – collision cross-section

Here N is directly proportional to P and inversely proportional to the gas temperature

Thus ν_e usually lies in the range between 10^9 and 10^{10} s^{-1}. This value defines the upper limit of rf application.

The lower limit can be defined from the plasma frequency.

$$f_{pl} = \frac{\varpi_{pl}}{2\pi} = \left(\frac{ne^2}{4\pi m\varepsilon_0}\right)^{1/2}$$

where:

n – is the electron or ion concentration,
ε_0 – dielectric susceptibility of vacuum,
m – electron mass.

The estimation made with the formula shows that

$$f_{pl} = 8980(n)^{1/2}$$

For example, for electron concentration in the range from 10^8 to 10^{14} cm^{-3} the corresponding plasma frequencies fall in the range between 100 MHz and 100 GHz. Let us assume that ω_{pl} is one-half period of plasma oscillations. If $\omega < \omega_{pl}$ electrons will move in such a way to create the field of opposite polarity neutralizing the external field. That screening electron motion tends to reduce the resulting field in plasma to zero. With $\omega > \omega_{pl}$ electrons do not compensate the external field, and it penetrates plasma. Hence, with $\omega_{pl}/\omega < 1$ the field penetrates plasma, and the energy exchange is possible between electromagnetic wave and plasma. From the given arguments one can see that the effective low temperature plasma heating is possible in relatively narrow frequency range.

The other important factor that influences rf application in reactive space engines is technical parameters of their construction. It is known that traditionally for plasma keeping and heating with a high frequency field cavities of different kinds were used due to rf energy accumulation in them. However, in an “empty” (without plasma) cavity tuned to a certain frequency, with initiation of the discharge an additive conductivity arises that consists of normalized active and reactive conductivities [3,4]. The active component of the conductivity causes the change in the internal resistance of the cavity that leads to a drop in Q. The reactive component of conductivity changes the eigenfrequency of the cavity, and necessity arises to adjust the frequency of the generator-engine system. The absorbed power depends both on the value of mismatch of resistors and on the frequency mismatching. Hence for the application of the cavity as a construction for rf reactive engines it is necessary to match rf generator with every initiation of the engine, or to adjust the engine parameters with adjusting elements, though it is extremely undesirable.

Taking into consideration the above, we set ourselves a task of development and examination the engine without the indicated drawbacks. A short length of the coaxial line with the wave resistance ρ =75 Ohm, 500 mm in total length, and external diameter of 100 mm was chosen as a basis for the construction. The specified overall sizes are not critical, as they were the sizes of the waveguide elements available. In principle, the specified sizes can be varied in reasonably wide limits. The matter of fact that with the initiation of the discharge inside a coaxial, its parameters, frequency, and resistance were changed as it was mentioned above, the antinode of current moved along the coaxial. And as

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one end of the coaxial was disconnected and presented a shortening capacity built as a cone adapter to the coaxial smaller in diameter, the section of the coaxial from the antinode of current to the antinode of voltage presented a quarter-wave cavity for the given generator frequency. Therefore, in the described construction a kind of automatic matching to resonant mode takes place. It is only necessary to select the value of the shortening capacity in such a way that the antinode of the current would remained always inside the construction. The cone adapter, which we used as a shortening capacity played one more important part. With it the necessary value of the electric field intensity was provided for the rf breakdown and initiation of the discharge that was about 140-170 V/cm in our experiments, the value of the gap between the central and outer conductors was 8-10 mm and could be regulated in the course of the experiment. At the other end the coaxial also had a cone adapter, which ended with 75mm terminal; it was used to supply rf power form the generator. In our experiments the coupling between the generator and the construction under investigation was ruled out (henceforth, module for short) with a loop or a rod as in that case it is difficult to provide the matching between the module and the generator. In the body of the module there were holes for pumping out and intake of the gas. Air was used as a working body. The first experiments were carried out in the pulse mode. The power supplied to the module was 1400 W at the active load was 75 Ohm. The rf pulse duration τ was 400μs with pulse frequency 2Hz. When the pressure about 1 torr is achieved the discharge was initiated inside the module, which could be observed in the inspection window. In the process of the discharge glowing the control of incident and reflected waves was being carried out. The comparative calculations have shown that the absorbed rf power is 500 W that is 30% of the supplied power.

As the construction of the installation did not permit to carry out direct measurements of the thrust of the module we had carried out an experiment to prove qualitatively the positive effect of the rf discharge. In the course of the experiment the right (operating) section of the module was placed in the vacuum volume, and a hole in the cone – a nozzle – were reasonably large, the diameter was 15 mm. With the pump and the vacuum volume that closed the module, the pressures inside and outside the module at the nozzle section were leveled.

Diaphragm made of the metal foil 30x40 mm in size was placed at the distance of 20 mm from the nozzle section. It was noted that at the moment of the rf power pulse delivery to the module the discharge was initiated in it, and at that time a sharp deflection of the diaphragm took place. That indicates that at the moment the pressure inside a module increases sharply, and the exhaust of the gas from the nozzle to the vacuum volume occurs. It is rather difficult to carry out quantitative measurements of the module parameters in the pulse mode. Because of this, having improved the construction of the module we came to experiments with the generator operating in the continuous mode.

We assembled a generator that provided continuous rf power about 260-270 W with the active load of 75 Ohm. An eigenfrequency of the generator was 120MHz. The operating pressure was 0.5-1 torr. With rf power supply to the module the discharge initiates in it. With that the absorbed power is 60 W. In the process of discharge glowing considerable heating of the module surface occurs in the place of the maximal electric field. With the pressure increase to 1.5-2 torr the discharge glowing weakens, and with the further increase it fades. That indicates that the power of the generator is not enough to keep the discharge glowing. It is necessary to increase the generator power to 1-2 KW. In the process of the discharge glowing a slight frequency departure of about 1-5 MHz is observed. At the present time a module is under construction that could be placed to the special measuring test-bench and to carry out direct thrust measurements.

The previous show that rf energy application in gas dynamic engines can result in various positive effects as the increase in thrust, specific pulse, saving in the working body, and in increase in the service life. Further experimental investigation and development of these engines can made them competitive to plasma engines and in some cases their application will be preferential.

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