Features of using plasma flows to compensate the aerodynamic drag of mini-satellites moving in the ionosphere

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Abstract. The possibilities of using plasma flows formed in electric jet engines (EJE) are considered. One of the variants of the EJE construction are ion sources with multi-cell ion-optical systems used to compensate the aerodynamic drag of mini-satellites in the Earth's ionosphere with the aim of ensuring long-term operation of the latter at low flight altitudes ($\sim 180–220$ km). The analysis of methods of simulation of the operation of such engines together with air intakes under ground conditions is given. The possibility of using plasma–ion sources producing molecular beams of nitrogen or air ions with low (orbital) flight speeds as a source of the free flow in the simulations is considered. A source with volumetric ionization of the working gas and electron oscillation in the magnetic field in a chamber between the walls held at the cathode potential and a large multi-cell aperture of the ion–optical system is used to create the flow. The results of the studies of the operation of a plasma–ion engine (PIE) together with air intake obtained by the gas-dynamic simulation method are presented. The possibility of a high performance of the engine under non-standard conditions is shown. It is found that a stable operation of the PIE can be realized at pressures of $6 \cdot 10^{-5}–10^{-4}$ Torr in its chamber, which is important for matching the engine with the air intake.

1. Introduction

At present, stationary plasma engines (SPE) developed by A.I. Morozov (National Research Center Kurchatov Institute) are actively used to correct the trajectories of satellites in geostationary orbits and their orientation in space. In such engines, xenon is used as fuel (working gas). At the same time, a number of the aerospace organizations (JAXA, the Aerospace Corporation, SITAEL S.p.A.) are conducting research on the use of plasma electric jet engines (EJE) to reduce the aerodynamic drag of long-life satellites intended for monitoring the Earth’s surface from low and ultra-low ($\sim 200$ km) orbits. In this case, the working medium brought aboard is replaced with the gases of the upper atmosphere. A feature of such engines, in addition to a large resource, is the requirement for an allowable reduction in their energy efficiency and the coefficient of utilization of the mass of the working medium, which are necessary for the transition from xenon to nitrogen and oxygen, which have higher ionization potentials and lower effective ionization cross-sections and atomic numbers.

Such engines should operate using air intakes. This technological feature requires significant changes in the design of engines. Their rear wall and channel should contribute minimal aerodynamic resistance to the airflow coming from the air intake. In addition, to enable the use of the satellite in a relatively wide range of heights, the working pressure in the EJE channel should be low (at the level
of $1 \cdot 10^{-4}$ Torr). The engines in which the central body is a necessary element of construction, including the SPE and others operating at pressures of ~$10^{-3}$ Torr, do not meet these requirements.

To a greater extent, the problem of interest can be solved by using engines whose ionization chamber volume is slightly filled with structural elements, such as, after appropriate modification, the plasma–ion engine (PIE) according to the Kaufman scheme, in which the electrons oscillate in the chamber in a longitudinal magnetic field applied the walls that are held at the cathode potential. In the studies carried out at the Central Aerohydrodynamic Institute (TsAGI) with the participation of a number of organizations under the “Yantar” program [1–3], it was found that the effective neutralization of a 100-mm-diameter PIE ion jet by electrons can be realized under full-scale conditions. In this case, the engine runs on air, argon, and nitrogen, a stock of which is available on board the flying laboratory. Creating engines that work in conjunction with air intakes is impossible without research under ground conditions and development of appropriate simulation methods.

2. Simulating methods and research results

At TsAGI, two approaches to this goal were developed. For this research, an installation was designed with a 9-m-long 1.4-m-diameter vacuum chamber. It is evacuated to $1 \text{--} 2 \cdot 10^{-5}$ Torr and filled with the working gas (nitrogen, air) at flow rates necessary to obtain the required flow parameters, which simulate the full-scale conditions. During the work performed within the framework of the first approach, we used the method developed by Yu.E. Kuznetsov for simulating the joint operation of the PIE and the air intake, in which the airflow was supplied not into the input cross section of the air intake, but into the cross section between the air intake and the engine (Figure 1).

![Figure 1. Method for simulating the joint operation of the PIE and air intake: 1 – air intake, 2 – PIE, 3 – anode, 4 – screen grid, 5 – accelerating grid, 6 – synthesized plasma flow, 7 – neutralizer electron emitter, 8 – ionization chamber, 9 – cathode, 10 – solenoid, 11 – working gas supply.](image)

In this case, the flow was divided in two parts. One part is directed to the EJE and ensures its normal operation and the other flows through the air intake channel to the vacuum chamber and ensures the required level of pressure at the PIE input. It replaces the actual flow under full-scale conditions that arises due to the reflection of molecules from the internal structural elements of the air intake. At a free molecular flow, the temperature of molecules was the same as the temperature of the elements from which they were reflected. By controlling the consumption of the supplied air, it is possible to change the flow of the neutral component in the ionization chamber under conditions when its back wall is replaced, for example, with a grid of a certain transparency or a system of diaphragms.

Figure 2 shows three key parameters of the engine when operating on air as functions of the magnitude of the output ion current: engine thrust $P$, energy efficiency $\eta_N$, and utilization factor of the working gas $\eta_M$. 


Figure 2. (a) Engine thrust and (b) energy efficiency and working gas utilization factor as functions of the ion current at the engine output.

It follows from the above data that even when the PIE works together with an air intake, these parameters can have high values if the technological, gasdynamic and electrophysical elements are appropriately coordinated in the system. For a specific engine, at the power consumption levels of 1.4–1.5 kW, the values of the main parameters (thrust, efficiency, working medium utilization factor) were close to those typical for engines of this class operating on gases supplied into the ionization chamber directly from tanks. If the permissible value of the power under the operating conditions should not exceed 500 W, the energy efficiency of the engine when working together with the air intake can continue to be high. However, the utilization factor of the working medium decreases.

Figure 3. (a) Scheme of the plasma flow source in which the full-scale flight velocity is realized and (b) its photo: 1 – case of the ionization chamber, 2 – cathode, 3 – anode, 4 – screen grid, 5 – accelerating grid, 6 – plasma flow, 7 – neutralizer.

Another approach to simulating the joint operation of the EJE and air intake consists in carrying out tests under the conditions where the air intake and the EJE associated with it are placed in a gas flow of sufficiently large transverse dimensions in which full-scale conditions (flow velocity ~8 km/s and molecular concentration) are reproduced. However, these techniques are not currently implemented. Traditional gasdynamic methods with gas acceleration in a nozzle generate flows at speeds of up to 7 km/s, while electrostatic and electrodynamic methods are effective at speeds above ~15–20 km/s.
At TsAGI, we have experience in creating flows with the required parameters. Flows of ions, and after charge exchange, flows of a mostly neutral gas with a velocity of 8 km/s and a diameter of 10–20 cm can be obtained by applying the modified PIE scheme shown in figure 3a. The ionization rate in the ionization chamber is provided by the sum of voltages $U_{A1} + U_{A2}$. The ions are extracted from the ionization camera by a system of two grids with a coaxial arrangement of cells (the photo in figure 3b). As a result of the self-consistent process of establishment of quasi-neutrality, the ions leaving the source have an energy $e(U_{A1} - U_{pl})$.

When the value $U_{pl} \sim 3–3.5$ V, the flow of $N_2^+$ ions with a velocity of 8 km/s outside the source is created at a potential difference $U_{A1} = 13–14$ V. Estimates show that to obtain the full-scale values of the molecular concentration in simulation of heights of 180–220 km at moderate values of solar and geomagnetic activities and a flow diameter of 10–20 cm, ionic currents of 150–320 mA calculated by $N_2^+$ ions are required at the source output.

![Figure 4. Dependence of the anode current on the solenoid current in the PIE chambers: 1 – $U_A = 100$ V, $I_c = 13$ A; 2 – $U_A = 90$ V, $I_c = 12.2$ A; 3 – $U_A = 80$ V, $I_c = 11.5$ A.](image)

Figure 4 shows the results of the studies of the dependence of the anode current value $I_a$ in the ionization chambers on the solenoid current $I_s$ at extremely low pressures in the chambers ($I_c$ is the cathode heater current). In case of the PIE, the pressure may be lower than $1\cdot10^{-4}$ Torr, which is important for the coordination of the operation of the PIE and air intakes.

### 3. Conclusions

The conducted research suggests that the use of the ion–plasma systems is promising both to provide aerodynamic drag compensation of mini-satellites when they move in the ionosphere, and to create flows running on objects and models of flows, during the simulations of the operation of the EJE together with air intakes under ground conditions.

### References

[1] Artsimovich L A, Grodzovsky G L et al 1970 *TsAGI Science Journal* **3** 65

[2] Filatyev A S, Skvortsov V V 2017 *TsAGI Science Journal* **1** 111

[3] Skvortsov V V 2013 *Aerodynamic Researches with the Participation of Streams of the Synthesized and Low-Temperature Plasma* (Moscow: Fizmatlit)