ELECTROSTATIC INSTABILITIES OF A MAGNETOPlasmaDYNAMIC THRUSTER IN THE INHOMOGENEOUS MEDIUM

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Abstract

The results of plasma instability investigation using the magnetoplasmadynamic (MPD) engine are presented. The interrelation between ion-sound waves and high-frequency electrostatic oscillations in a plasma moving through the inhomogeneous electric and magnetic fields has been discovered. The plasma oscillation spectrum could be controlled by varying the relative gradient distributions of magnetic field strength and concentrations of neutral and charged particles. Contrary to the investigations of low-frequency oscillations performed previously, the particular emphasis has been placed on the plasma instability of MPD engine in the frequency range of 500 MHz to 10 GHz corresponded to the electron Langmuir oscillations in the plasma plume. The special features of electromagnetic emission from the MPD engine have been discovered experimentally in relation to plasma plume potentials depending on pressure and discharge performance characteristics of the engine.

Introduction

The experimental and analytical investigation of electrostatic instabilities and plasma plume oscillations is an important phase of MPD thrusters design and their operating modes optimization. The results of ground-based experiments can be used for characterization of the electromagnetic environment produced by MPD thrusters and spacecraft systems compatibility evaluation. The electrostatic instabilities investigations of MPD thrusters are correlated with the analysis of physically realizable mechanisms of plasma acceleration and permit the development of the remote sensing procedures for identification of thruster operating modes based on electromagnetic radiated emission measurements.

The principal results of the plasma instabilities investigations of MPD thrusters is defined as electrostatic waves generation at the specific operating modes of engines [1]. The generation modes are characterized by the electromagnetic mechanism of plasma acceleration with an unstable electron velocity distribution function. The physical models of MPD thrusters as electrostatic waves contributors have been developed from electron stream initiation in the regions of crossed electric and magnetic fields and non-equilibrium plasma flows.

The electron stream acceleration along magnetic field lines in cathode regions is considered to be the first instability model of MPD discharge. The energy of electron oscillations is determined from the cathode potential difference according to the quasi-linear plasma instability theory [2]. The electron stream scattering on oscillations is the main mechanism of plasma waves saturation. The increased electrostatic waves are exhibited, especially with formation of anode layers when thruster operating modes are characterized by limitation on discharge current and concentration of electric field inside of an anode region of the MPD discharge. The abnormal operating modes were emphasized depending on anode geometry, location of electrodes in the accelerating magnetic field and propellant flow rate [3]. The increased anode heating was found to be at the limited operating modes of the MPD thruster experimental models.

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Plasma exhaust velocities at abnormal operating modes as calculated from measured thrust and propellant mass flow rate is considerably in excess of the magnitudes determined by Hall plasma accelerating and electrothermal propulsion mechanisms [1, 3]. The occurrence of accelerating ions in the plasma plume is attributable to turbulent electron - ion friction as a result of plasma instability wave generation. The quantitative evaluation of turbulent plasma acceleration based on interaction between drift electron streams and propellant ions is consistent with experimental results [1].

The report is devoted to the experimental investigation of the fundamental instabilities and plasma oscillations in the MPD thruster under laboratory conditions in relation to the discharge operating modes and ambient gas pressure. The interrelation between ion-sound waves and high-frequency electromagnetic oscillations in the plasma flow moving through the inhomogeneous electric and magnetic fields has been discovered. The experimental data were attributable to the beam-plasma instability of the MPD thruster caused by electrons accelerated in an electric field of the external plasma region.

**Experimental Setup and Procedures of Measurements**

The investigations were carried out for the several experimental structures of the steady state applied-field MPD thruster (Fig. 1), which differed in dimensions and form of electrodes, quantity of magnetic field intensity, angular opening of magnetic forces lines, mass propellant flow rates and power characteristics of the discharge. These structures permitted to perform the main regimes of jet efflux into the space of dropped pressure. The thruster operating modes were determined by discharge voltage in the range of 70 to 120 V with discharge current from 50 to 130 A and magnetic field of 0.05 - 0.1 T. The experiments were conducted with nitrogen (air mixture of nitrogen and oxygen) as a propellant with ambient pressure in the vacuum test facility of $5 \times 10^{-5}$ to $2 \times 10^{-2}$ torr by restriction on pumping speed of the vacuum system. The evaluation of thruster operating modes and plasma plume parameters such as concentration and temperature of electrons, distributions of pressure, electric and magnetic fields was produced. The plasma diagnostic measurements were essential to an understanding of plasma accelerating process at the different ambient gas conditions.

The registration of low-frequency oscillations of plasma potential in the frequency range of 1 to 500 kHz was produced by the electric probes moved along the discharge and plasma plume. The test setup for electromagnetic field measurements in the frequency ranges of 1 - 40, 30 - 100 MHz and 1 - 10 GHz had magnetic loop antennae placed outside the dielectric window of the vacuum test facility as given in Fig. 2. The antennae sensors were oriented to register the electromagnetic fields radiated from the plasma emission contributors. The report is concentrated on the frequency range where electromagnetic emissions might impact to operation of the space radio communication systems.

By using the sensitive measurement radio sets, the electromagnetic emissions were registered from the thermal level associated to electron temperature of 1 - 10 eV as experimentally defined. The thresholds of high-frequency waves generation were determined from discharge voltage and pressure dependencies.

The impact of the metal vacuum test facility on electromagnetic measurements results was in pronounced changes of electromagnetic radiated fields in the vicinity of the MPD thruster. This prevented the determination of a plasma instability contributor directly. In accordance with the proposed measurements procedures, the standard radiation sources placed inside of the vacuum test facility were used for estimation of electromagnetic energy flows from the thruster. The electromagnetic signals at radio sets entrances were calibrated with the radio emission signals of the standard radiation sources with known energy parameters in the designated frequency band of 1 - 10 GHz having similar radiation geometry and disposition inside of the vacuum facility as the thruster contributors of electromagnetic radiation. The calibrating signals for the thruster radiated emission measurements were produced by the discharge plasma noise generator with the thermal emission level determined by electron temperature. The disposition dependencies of calibrating signals
intensity at the different frequencies (Fig.3) were used for evaluation of electromagnetic field energy parameters.

**Experimental Results and Discussion**

The laboratory and space experiments [4-6] have demonstrated that the main physical processes in MPD thrusters depend on the distributions of relative gradients of magnetic field intensity $\nabla H/H$, ambient gas pressure before switching on discharge $\nabla p/p$ and concentration of charged particles $\nabla n_e/n_e$ along the plasma plume produced by the MPD thruster. The different acceleration mechanisms can be realized by varying the relationships of the mentioned magnitudes (Fig.4).

The relative gradients of the plasma parameters being equal, accelerating forces acting on charged and neutral particles are aligned with a plasma flow centreline. As a consequence, the charge electro-compensating exists and the plasma motion is analogous the neutral gas one [3]. In that situation the plasma flow and discharge parameters get extremal values, the anisotropy of charged particles pressure is absent and high-frequency oscillations and plasma azimuthal irregularities are either suppressed or stabilized. The above-mentioned features are most usually evident in a plasma flow at the gas pressure $P \approx 10^{-3}$ torr. In this case the plasma potential as related to the cathode amounts to zero and the azimuthal Hall current is a minimum. Because of gas sealing clots and spacing waves as in a resonator, the regular ion-sound oscillations formed standing waves along a plasma flow in the frequency range of 50 to 150 kHz are generated (Fig.5).

With breach in the optimum conditions on plasma acceleration the plasma flow potential ranges up to important magnitudes: negative for $P < 10^{-3}$ torr and positive for $P > 10^{-3}$ torr. The plasma motion becomes turbulent with the wide spectrum of random noise oscillations and azimuthal spoke waves. The electromagnetic radiation in the investigated frequency ranges of 0.1 to 100 MHz and 1 to 10 GHz are generated by the MPD plasma flow due to excitation of electron plasma oscillations (Fig.6). Under the experimental conditions the beam-plasma instability realized because of charge incompensating and electron acceleration into a plasma flow by electrostatic field take place [1]. As is obvious from the experimental distributions of the electric and magnetic fields, the magnetic field lines aren't equipotential, resulting in run away electrons and high-frequency turbulent phenomena.

The measured intensity of non-equilibrium electromagnetic fields excited by the plasma flow decreases to the thermal radiation level in the frequency range of 1 to 5 GHz (Fig.7.8). The thermal radiation is induced by plasma layers with electron concentration $n_e \sim 10^{11}$ cm$^{-3}$ and temperature $T_e \sim 5$-10 eV. The non-equilibrium electromagnetic radiation from outer layers of the plasma flow is 2 - 3 orders of magnitude more than the thermal level. The gas pressure dependencies of the electromagnetic radiation intensity as given in Fig.6, are attributable to the critical magnitude of electric field density for run away electrons with plasma collisions. The influence of gas pressure on plasma wave increment are found to be in the MPD thruster operating modes.

Brief mention should be made on the electromagnetic radiation at the frequency range of 0.1 to 100 MHz (Fig.9) associated with excition of surface electrostatic waves in the MPD plasma plume. It takes additional research to understand the mechanism of electrostatic instability and plasma waves generation in the above-mentioned frequency range.
Conclusions

The present experimental investigations showed that the different modes of plasma acceleration and electrostatic instabilities of the MPD thruster were related with the determined distributions of plasma flow parameters, magnetic field intensity and ambient pressure.

The control of the electrostatic instabilities at the frequency ranges of ion-sound waves and electron plasma oscillations has been realized for optimization of plasma acceleration process in the MPD thruster.

The instabilities operating modes of the MPD thruster are related with electrostatic potential of plasma flow - cathode because of charge incompensating of the plasma flow. The generation of electron plasma waves is produced by run away electrons accelerated by electrostatic fields.

The electromagnetic radiation measurements can be treated as an efficient diagnostic procedure of the plasma acceleration in the inhomogeneous ambient medium.

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Fig. 5

Distance from WPD engine
- 5 m
- 10 m
- 17 m

Fig. 6