FLAT ORIENTED PROBE IN THE RAREFIED PLASMA FLOW

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Abstract.

The mathematical model and method of probe ion current calculation has been developed allowing to determine the mean ion velocity in the accelerated flow of rarefied plasma using the measurements of ion current under at least two probe orientations in the flow.

Introduction.

Electric propulsion thrusters (EPT) will be widely used in a space technology. They are generating the accelerated flows of rarefied plasma. Therefore it's necessary to develop the diagnostic means to determine reliably the plasma parameters in the mentioned flows, such as plasma density, particle temperatures, their energies and velocities etc. There are known the Langmuir probes allowing to determine ion currents, plasma density, electron temperature and plasma potential. The ion distribution in energies could be determined by retarding potential analyzers (RPA). It's possible also to determine the ion distribution in velocities using the ion flight time distribution for the definite path. The last method is complex enough and not so often is used in the experimental practice. Therefore there was studied the possibility to determine the mean ion velocity in the accelerated flow using simple flat probe. It's clear that probe characteristics consists of an information on the ion velocities. The problem is only how the measurement is to be realized and how to process probe characteristics to determine the value of ion velocity. Some results of this problem study are represented in the paper.

1. Problem statement.
1.1. Introduction notes.

Plasma consisting of the ions and electrons with densities n_i, n_e respectively and temperatures T_i,

T_e is considered. Plasma flow is moved with the mean velocity v_∞. It's supposed that

$$V_e >> V\infty \geq V_i,$$

where V_i, V_e are the thermal velocities of ions and electrons.

There is flat insulated probe positioned in the flow having the characteristic size r_p and potential φ_p relatively to the space. Normal line to the active probe surface is positioned under angle γ relatively to the vector $\vec{V}_\infty$. If $\gamma = \gamma_1 = \pi$ the mentioned active surface is oriented to the coming flow. If $\gamma = \gamma_2 = \pi/2$ this surface is parallel to $\vec{V}_\infty$.

The probe could be a thin circular plate or stripe type one. It's active surface is metallic one, back side of probe is covered by insulator. If one size of stripe type probe is significantly larger than another one such probe could be called as a tape probe. The tape probe is very convenient for the numerical simulation because it permits to   reduce the dimension of the problem.

It's supposed that in all cases

$$r_p << \lambda,$$

where λ - the mean free path of plasma particles between collisions.

The probe current depends on probe sizes and its potential as well as on plasma parameters, namely on n_e, n_i, T_i, T_e, V_∞. This dependence is nonlinear due to the "end" and "edge" effects. If somebody will not takethese effects into account it's possible to obtain wrong results [1]. The edge effect is causing an increase of probe current due to the higher electric field intensity near the edges and respectively due to the increased current density (Fig. 1). Impact of this effect is increased with the decrease of probe sizes.

"End" effect is caused by the existence of the directed ion velocities [2], because for example some particles appearing in the zone of the collecting probe electric field can't be collected by probe surface due to tthe limited time of their appearance in the mentioned zone.

1.2. Mathematical model of processes near the active probe surface.

Mathematical model of processes near the active probe surface includes the Vlasov's kinetic equations for the plasma particle dynamics description, Poisson equation for the selfconsistent electric field and system of the initial and boundary conditions. It's convenient to write these equations when y axes is directed normally to the active probe surface. For the stripe type probe x axes id directed parallel to the short side of stripe (if the active probe surface is parallel to the $\vec{V}_\infty$, x axes is directed along the $\vec{V}_\infty$ vector). For the mentioned conditions:

$$\frac{\partial f_i}{\partial t} + V_x \frac{\partial f_i}{\partial x} + V_y \frac{\partial f_i}{\partial y} + V_z \frac{\partial f_i}{\partial z} + \frac{q_i}{m_i}(E_x \frac{\partial f_i}{\partial V_x} +$$

$$+ E_y \frac{\partial f_i}{\partial V_y} + E_z \frac{\partial f_i}{\partial V_z}) = 0$$

$$\frac{\partial f_e}{\partial t} + V_x \frac{\partial f_e}{\partial x} + V_y \frac{\partial f_e}{\partial y} + V_z \frac{\partial f_e}{\partial z} + \frac{q_e}{m_i}(E_x \frac{\partial f_e}{\partial V_x} +$$

$$+ E_y \frac{\partial f_e}{\partial V_y} + E_z \frac{\partial f_e}{\partial V_z}) = 0$$

$$\frac{\partial^2 \varphi}{\partial x^2} + \frac{\partial^2 \varphi}{\partial y^2} + \frac{\partial^2 \varphi}{\partial z^2} = \frac{1}{\varepsilon_0}(n_2 - n_i)e$$

$$E = -\nabla \varphi$$

$$n_{i,e} = \int f_{i,e}(x, y, z, V_x, V_y, V_z) dV_x dV_y dV_z$$

$$f_{i,e} = q_{i,e} \int V_{y,i,e} f_{i,e}(x, y, z, V_x, V_y, V_z) dV_x dV_y dV_z$$

$$f_{i,e}\Big|_\infty \cong f_{i,e}\Big|_{t=0} = (\frac{m_{i,e}}{2\pi k T_{i,e}})^{3/2} n_\infty \times \exp$$

$$\left\{ -\frac{m_{i,e}}{2k T_{i,e}}\left[(V_y + V_\infty Cos\gamma)^2 + ((V_x - V_\infty Sin\gamma)^2 \right] \right\}$$

$$f_{i,e}(x_e, y_e, z_e, V_x, V_y, V_z, t)\Big|_{V_y < 0} = 0$$

$$\varphi(x_p, y_p, z_p, t) = f_1(t)$$

$$\varphi(x_\infty, y_\infty, z_\infty, t) = 0$$

In the represented system:

$f_{i,e}$ - the distribution functions for ions and electrons respectively,

φ, E - electric potential and electric field intensity.

Index "p" related to the active probe surface.

$f_1(t)$ - probe potential in time.

Typically during the simulation jump of electric potential was used.

2. Method of the problem solution and obtained results.

The represented system of equations has been solved by method of iterations in time. It allows to study the evolution of the distribution functions, their moments and selfconsistent electric potential. At each time frame the kinetic equations has been solved by method of PIC or by method of characteristics [3,4]. The solution depends on the following nondimensional parameters:

$$r_0 = \frac{r_p}{r_D}, \varphi = \frac{e\varphi_p}{kT_i}, \varepsilon = \frac{T_{i\infty}}{T_{e\infty}}, u = \frac{V_\infty}{(\frac{2kT_i}{m_i})^{1/2}},$$

where r_D - Debay radius.

There were calculated the ion currents under different conditions taking into account the "end" and "edge" effects.

Obtained results of simulation show that the ion current $j_\perp$ under $\gamma=\pi$ is increased with an increase of V_∞ due to increase of the ion flow to the probe surface (Fig. 2). Initially under low V_∞ values probe current is higher than $n_i V_\infty$ and is determined as classical (Bohm's) current. Ultimate current value under high V_∞ is to be close to the $n_i V_\infty$.

Increase of u_0 is causing decrease of the $j_\parallel$ value (when $\lambda=\pi/2$) due to the mentioned above "end" effect (see Fig. 2). It is important that the value of $j_\perp/j_\parallel$ depends mainly on the u_0 value.

So, using it it's possible to determine the V_∞ value if some one has data on kT_i values. The last one could be estimated from ion energy distribution measurements by RPA or from the other measurements [4].

There was studied the impact of the probe position nonaccuracy on the values of measured currents.

This nonaccuracy depends on the V_∞ also and under γ deviation $\Delta\gamma=20°$ the error could reach 30% and more under high u_0 values (Fig. 3). But real values of $\Delta\lambda$ could be significantly lower.
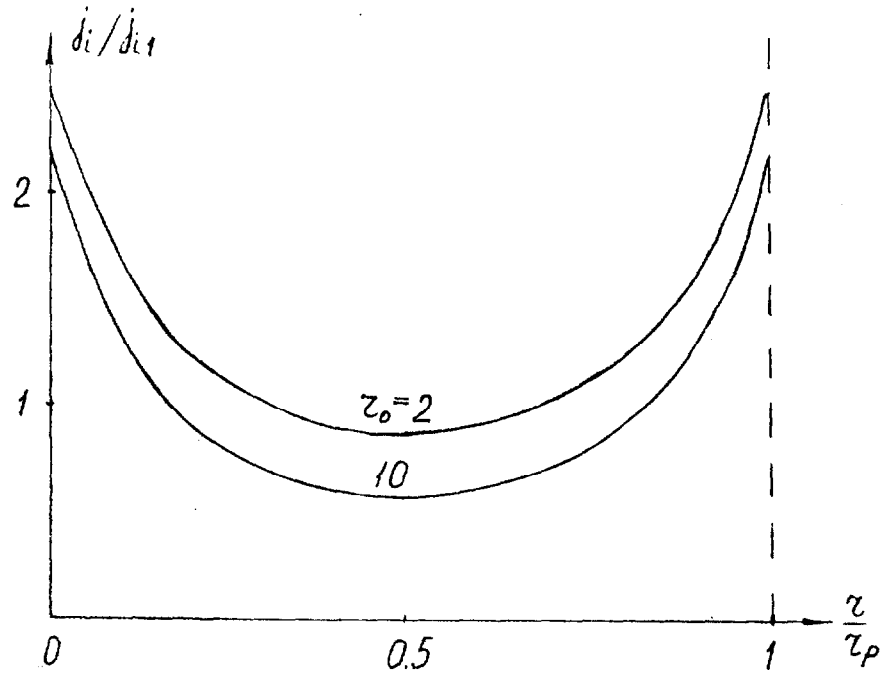
Fig. 1. "Edge" effect on ion current distribution.

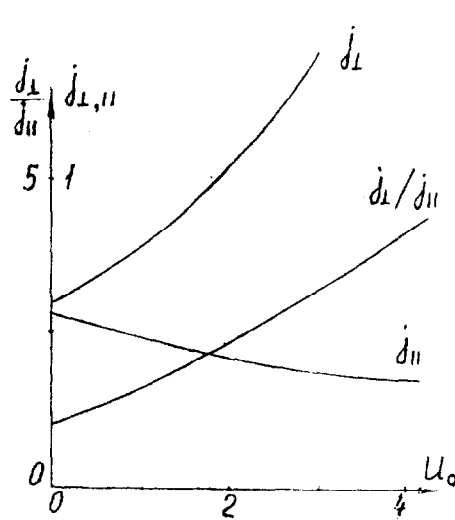($\varphi_0 = -20$, $\varepsilon = 1$, $u_0 = 0$)

Fig. 2. Probe ion currents versus u_0
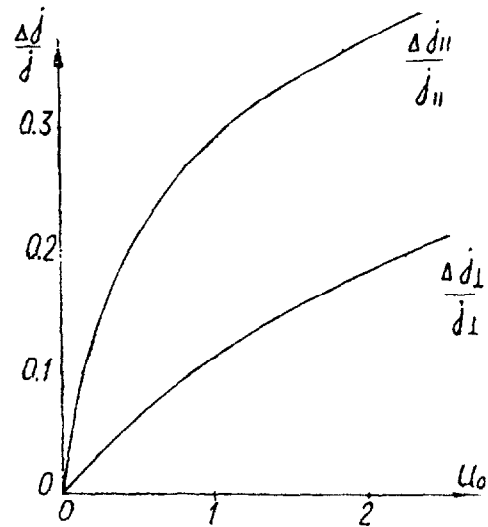
($\varphi_0 = -6$, $\varepsilon = 1$, $r_0 = 3$).

Fig. 3. Probe ion current

deviation versus u_0

($\varphi_0 = -6$, $\varepsilon = 1$, $r_0 = 3$, $\Delta\gamma = 20°$).

Thus, using the developed mathematical model and methodology it's possible to get additional information on the mean rarefied plasma flow velocity.

Conclusion.

The mathematical model and method of probe ion current calculation has been developed allowing to determine the mean ion velocity in the accelerated rarefied plasma flow.

References.

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