Expansion of Secondary Plasma Generated in an EP Plume. Theory and Experiment

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Abstract

In the paper the results of a study of backward and radial secondary plasma flows, arising in the exhaust plume of a thruster with anode layer (TAL) are represented. The scheme of experiment was intentionally built to validate a theoretical calculation technique for the characteristics of secondary plasma. The measurements were taken at several positions of probes both along and across a flow. The values of following parameters were measured: radial and axial elements of ion flow densities and their speeds, electron temperature and concentration. In the paper the operational parameters of a TAL tested model and the experiment technique are described. In the paper a summary of physical processes responsible for generation of secondary plasma is also adduced, and there is a comparative analysis of experimental data to theoretical calculations.

Introduction

During a thruster operation, secondary plasma is generated inside an engine's exhaust plume. In space conditions, as a rule, the secondary ion flow, compared to the directed exhaust plume, is insignificant. However, for long-life space vehicles the total effect of the secondary ion flows can appear significant. The fact is that unlike an exhaust plume (where ions have a narrow directional pattern of velocity), the secondary ions scatter in all directions from the zone of generation located near the thruster exit. The arising radial and backward flows of secondary ions fall on all near structural elements of a spacecraft (SC) inaccessible for the exhaust plume. Therefore it is important alongside with a computational model for a main flow to have a reliable math model for distribution of secondary ion flows' parameters.

It follows from the model developed in TsNIIMASH[1] that distribution of parameters of secondary plasma - both in a radial direction and backward – has some special features. The features are demonstrated by the fact that the radial flows density function of longitudinal coordinate has a maximum. Its position and size depends on parameters of a main flow and neutral background. So, an experiment was executed to directly validate the developed model and to detect a maximum in the distribution of secondary plasma.

Scheme of Experiment

To determine parameters of radial and back flows of secondary plasma there were used flat, one-sided, oriented sensors (probes), connected in pairs in the circuit of a double electrical probe. Their layout in a vacuum chamber is shown in Figure 1.

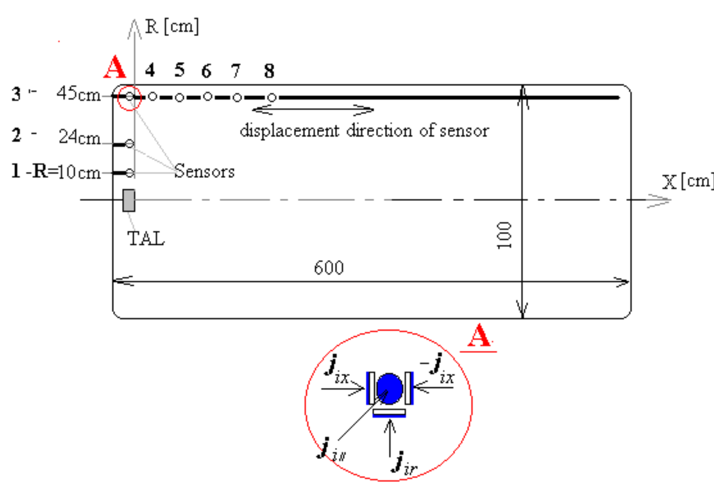

Figure 1. Sensors layout in a vacuum chamber.

To determine parameters of a back plasma flow in a local area, there were used detectors of two types, having three or four flat, one-sided sensors. One sensor was oriented in the $-X$ backward axial direction, the other one was oriented in a $+R$ radial direction and the third one's sensitive surface was oriented in *XOR* plane, i.e. always being tangent to the direction of plasma spread. Thus, in each pair of sensors, connected in the circuit of a double probe, the sensitive plane of the first was perpendicular to the specified direction (R or $\pm X$), and of another one was tangent to the velocity of plume. Inside a detector made of four sensors, there was built in one more sensor, having its sensing surface oriented in «+X» direction. Altogether 16 sensors were used. All sensors were placed in the horizontal plane of the stand. Three detectors, each having three sensors, were spaced at the fixed distances $R = 10, 25, 45cm$ along a radial direction behind the TAL's exhaust exit, in section $X = -0.5cm$, and the fourth detector, having four sensors, was mounted on a movable device at the fixed radial distance $R = 45cm$. That detector enabled measurement of plasma parameters at several points along axial direction $X=0.5\div250cm$ and axial distributions not only for radial flows, but also for forward ($+X$) and backward ($-X$) ion flows.

To take measurements there were used: in the near zone of plume, at points 1÷3 - the sensors of about 1-cm diameter; in the distant zone, at points 3÷8 - the sensors of $\varnothing \cong$ 8,5cm. The circuit for measurements enabled connection of required combinations of sensors and recording of current-voltage curve (CVC) on two-coordinate analog recorder.

The tests were performed with anode layer thruster D80 [2] in parallel with performance mapping of the thruster. The specific feature of D80 is a two-stage scheme where the first stage is used for propellant ionization and the second one - for acceleration on the ions. The design allows to operate in a single stage mode when all voltage applied to second stage electrodes and first stage electrically shorted.

In case of two stage operation mode total applied voltage V_{sum} is distributed between the first stage (V_d) and second (accelerating) stage (V_a), and $V_{sum}=V_d+V_a$.

Technique of measurements with probes

When a flat probe is used for measurement of parameters of moving plasma (see, for example, [3]) the essential contribution of ion current into the total current through probe is taken into account. To define parameters of plasma a technique of measurements with a double, flat, directed probe has been used. It enables in a specified area measurement of the density of current for an incident ion flow $j_{i\perp}$. Furthermore, combining oriented sensors in the circuit of a double electrical probe one can also measure other parameters of a plasma flow, in particular: ions velocity V_i, concentration n and electron temperature T_e .

The accuracy of technique increases with the velocity of a flow. The desirable range of the technique application is specified in [4]:

$$(kT_e/M_i)^{1/2} \quad << \quad V_{in} << (kT_e/m_e)^{1/2}$$

In our experiment the said conditions were met. The used technique had been verified in experiments by independent methods [3,4], including the authors of paper during measurements of a flow velocity in the Hall-effect sources of plasma where $T_e >> T_i$ [5].

In order to reduce the influence of edge effects, the value of current was defined on the CVC of a probe at the point where the curve turns linear.

Measurement Results

In fig. 2-5 the results of measurements are shown for two operation modes of TAL in a one-step mode. In Figure 2 and Figure 3, correspondingly, the axial and radial distributions are shown for axial (j_{ix}) and radial (j_{ir}) elements of ion flow density. In Figure 4 and Figure 5, the radial distributions behind the thruster exit ($X=-5cm$) are shown for electron temperatures, plasma potential, and also radial (v_{ir}) and axial (v_{ix}) elements of the velocity of a secondary ions flow.

As one can see from the $j_{ir}(x)$ graph, the area of maximum radial component of the ion flow density is at the distance of about 30-40 cm from the thruster exit that is due to the generation of secondary, slow ions.

As far as it is possible to evaluate from the radial distributions of plasma parameters n_i , T_e, the flow velocity V_{ir} and floating potential ϕ_f , the measured increase of ions flow velocity satisfactorily coincides with the values calculated after the formula: $(2\Delta e\phi_f /M_i)^{1/2}$. E.g., for the mode of $U_d = 300V$, $I_d = 3{,}5A$: measurements demonstrate 2,6-kmps increase of radial speed in the plane of TAL's exit, and calculation of acceleration by a radial electrical field - 3,1 kmps.

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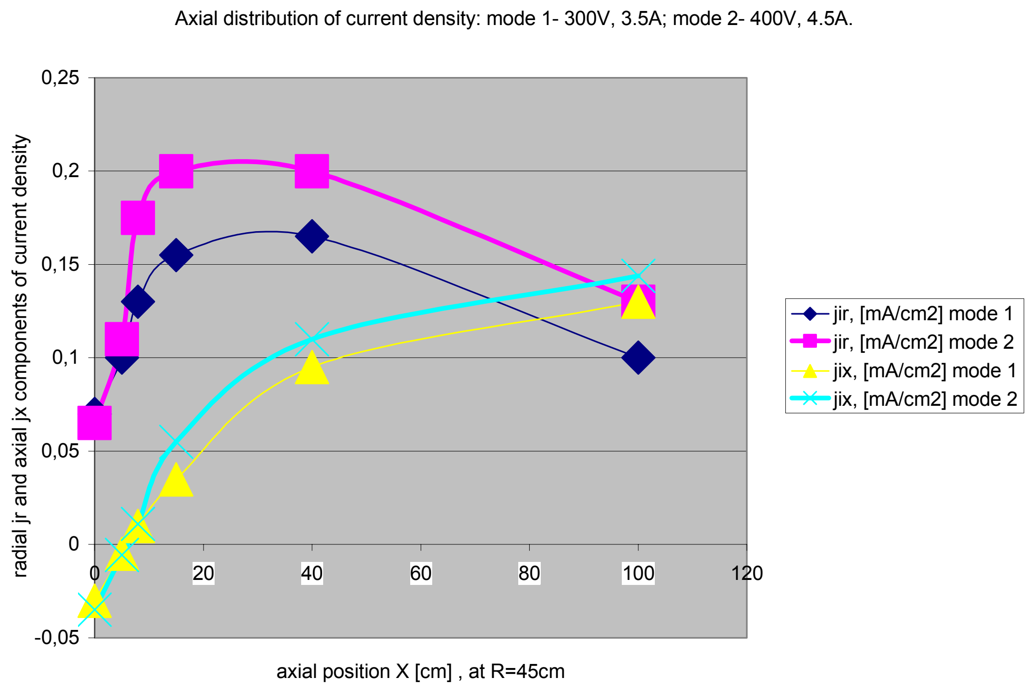

Figure 2

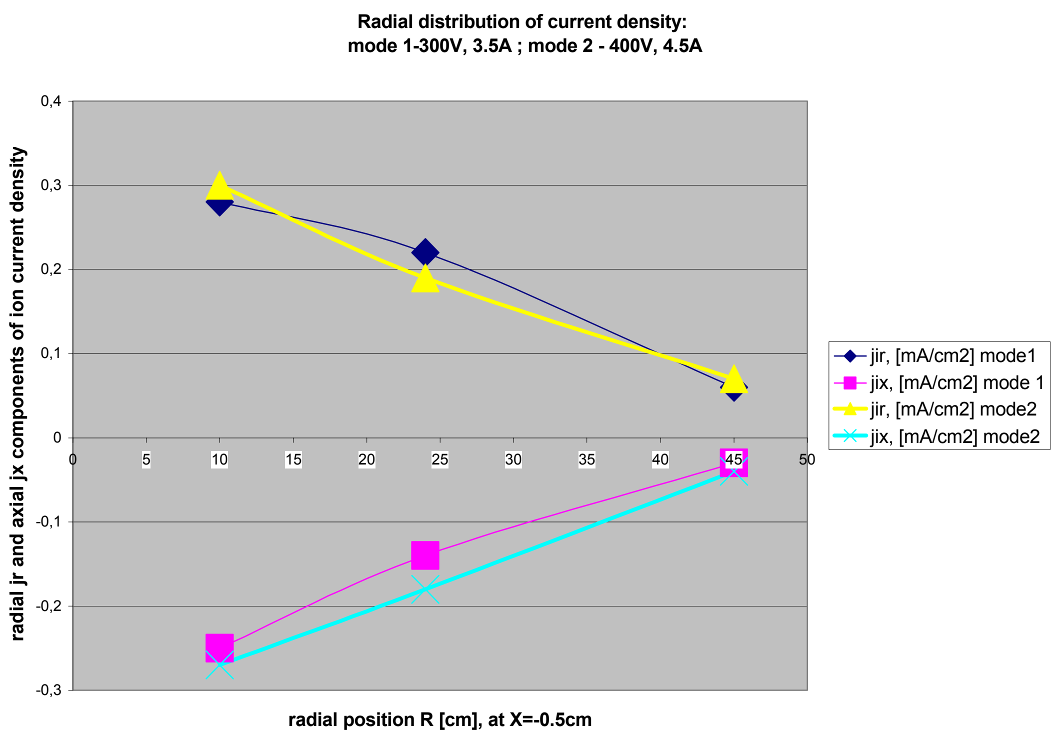

Figure 3

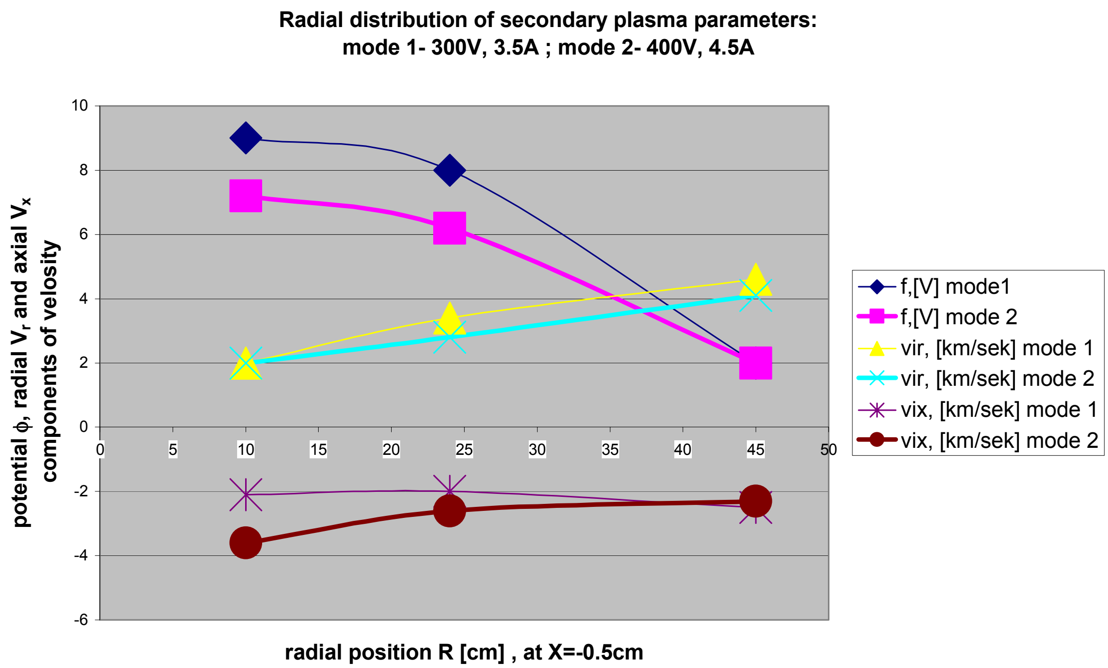

Figure 4

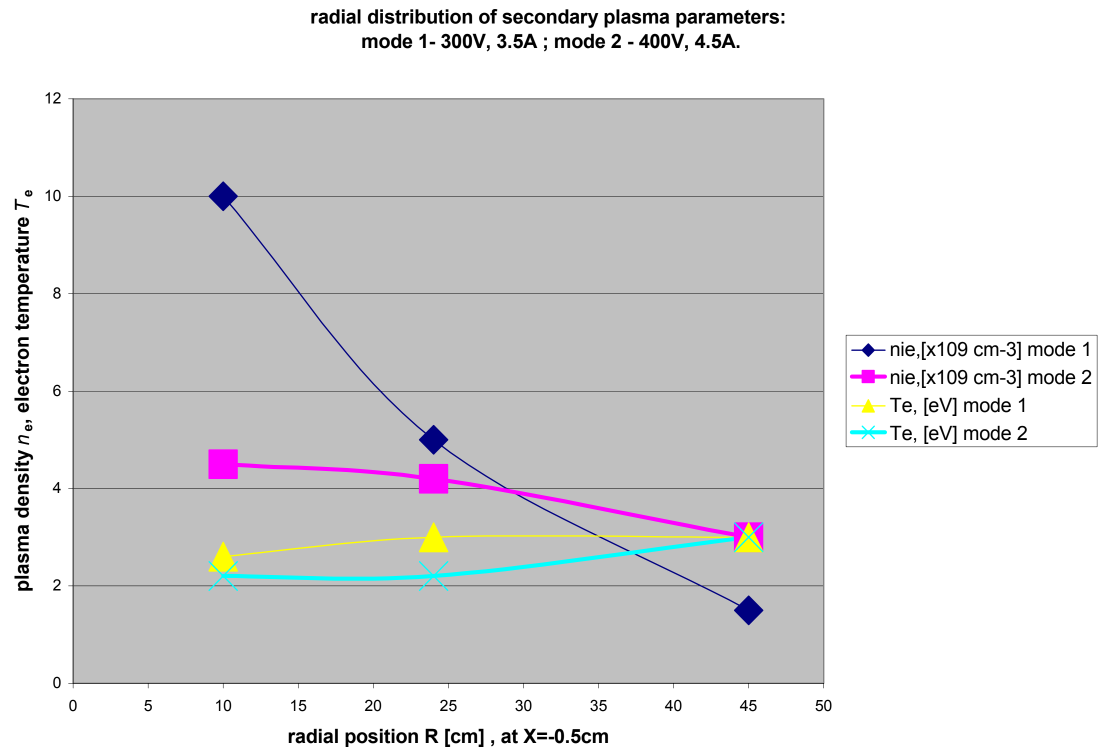

Figure 5

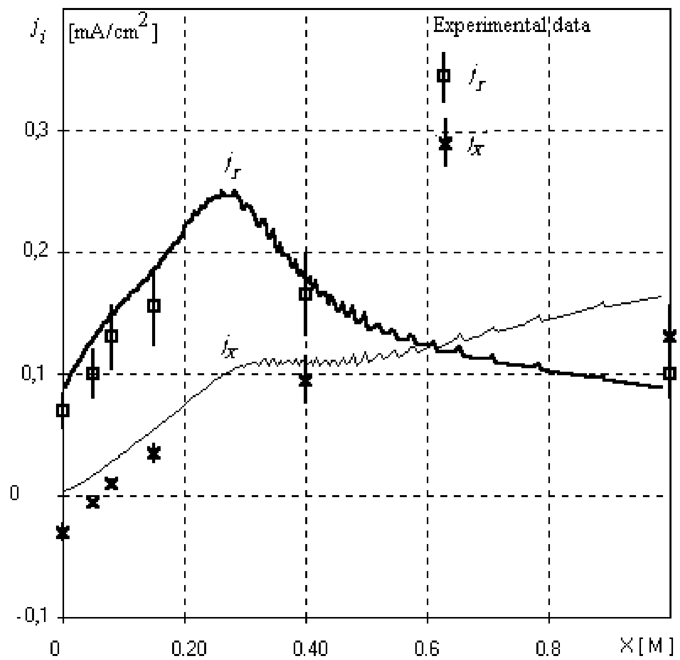

Figure 6 Longitudinal distribution of components of density of ions radial flows of in the D-80 plume at R = 45cm. The calculation is carried out for n_n=2·10^{12}cm^{-3} , T_{e0}=12eV , T_{ef}=2eV

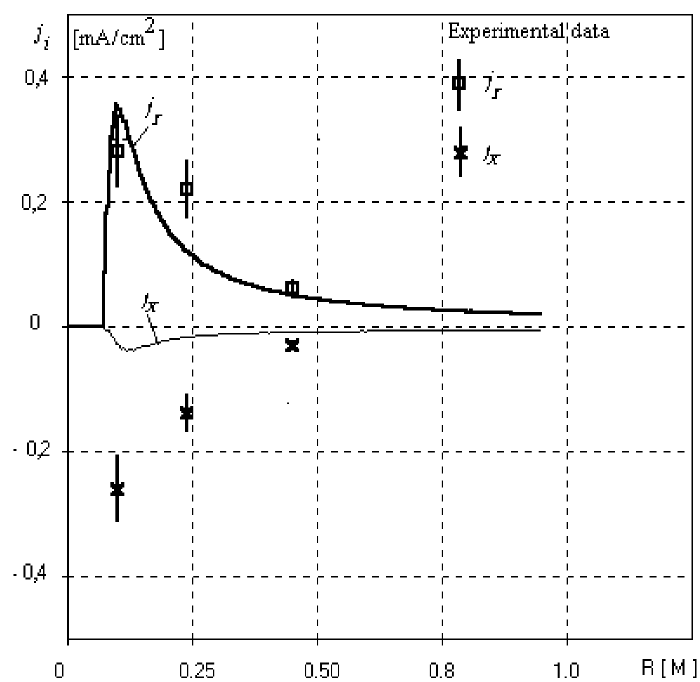

Figure 7 Radial distribution of components of density of ions radial flows of in the D-80 plume at X=-0.5cm. The calculation is carried out for n_n=2·10^{12}cm^{-3} , T_{e0}=12eV , T_{ef}=2eV

Analysis of Findings

The preliminary analysis of measurements has shown that there are following experimental facts verifying mathematical model:

1) The density of "background" plasma ions backflows after the thruster exit into aft hemisphere - $j_{i\perp}$ = $0{,}1 mA/sq.sm$ - coincides with the values calculated for the level of concentration of noise neutrals - $nn=2\cdot 10^{12} cm^{-3}$. The value of total ion backflow into a hemisphere of 1-m diameter (the chamber diameter) is evaluated at 1-A level that makes approximately 1/3-1/4 part of the total gaseous xenon flow rate, and also coincides with the numerical model.

2) The value of "background" plasma ion backflows into the aft hemisphere after the thruster exit $j_{i\perp}$ does not practically depend on the discharge parameters of the thruster - U_d, I_d, but essentially depends on the density of background gas (xenon) in the chamber which at a constant speed of evacuation (scavenge) is determined by the gas flow rate through a thruster.

3) The energy of backflow ions has averaged out $\varepsilon=17 eV$. In the investigated range of capacity (3…5 kW) the energy value does not practically depend on the level of accelerating voltage U_d if the flow rate of working gas is constant, and according to the theory it matches with the potential difference in a plasma exhaust in which the birth of secondary ions occurs.

4) If the flow rate of working gas is constant, the n_i and T_e values remain practically constant when the value of accelerating voltage U_d changes.

5) For different operation modes, measurements of electron temperature T_e near the thruster (behind its exit) and T_e at the distance of ~ 2,5m (in the plume) have shown that the T_e value remains practically constant along and across the plume.

The results represented above agree with the measured energy spectra for an ion beam taken in [6].

A comparison of experimental results to numerical calculations for ion current density distributions is shown in Figure 6 (radial and axial). The calculations were made on the basis of the technique explained in [1] by means of *SPlaF* code for the conditions when the concentration of residual gas in a chamber was $n=2\cdot 10^{12} cm^{-3}$. In the figure there are two types of curve: the thick one corresponds to the radial distribution, and the thin one to the axial density of an ion current. The calculations have been made for two possible values of initial temperature of electrons: 12 eV and 6eV. The comparison shows a quite satisfactory coincidence of the calculated data with the measured values.

Conclusions

On the basis of the executed experiments and comparison of theoretical calculations to experimental data it is possible to make the main conclusions as follows:

- at the pressure of residual gas (xenon) of ~ 10^{-4} Torr in a vacuum chamber, the primary ion beam recharges rather fast, generating a rather dense background of secondary ions;
- the secondary, slow ions are mainly accelerated across a plume by the electrical fields generated due to a potential difference in the plume and get the energy of ~20eV level in the electrostatic field of the beam;
- the density of a radial, secondary ions flow in a 1-kW Hall-effect thruster reaches its maximum at the distance of 30...40 cm from the thruster exit;
- secondary ions backflows into the aft hemisphere are formed in the said initial sone of plume;
- the calculation results by means of *SPlaF* computational code, in which a theoretical technique for evaluation of secondary plasma parameters is realized, coincide satisfactorily with the experimental data.

References:

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