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Abstract

Progress in combined device/plume modeling is presented for a Teflon-fed, pulsed plasma thruster from plasma generation to the plume far field. In this work we apply a one-dimensional unsteady model for the plasma generation and acceleration process. A new kinetic ablation algorithm is employed to calculate the Teflon ablation rate as a function of plasma parameters. A near cathode sheath model is included to calculate the plasma potential at the thruster exit plane. Results are compared with data for the electrothermal device, PPT-4. Performance characteristics of the PPT such as mass ablation and thrust impulse are calculated. Predicted plasma properties, thruster performance and plasma parameter distribution in the plume are found to be in agreement with available experimental data.

Introduction

Pulsed plasma thrusters (PPT's) have combined advantages of system simplicity, high reliability, low average electric power requirement and high specific impulse[1]. The PPT is considered as an attractive propulsion option for orbit insertion, drag makeup and attitude control of small satellites. PPT's, however, have very poor performance characteristics and an overall efficiency at the level of about 10%[2]. To improve the PPT performance several directions are being considered[3]. Accurate simulation of these devices and plumes is required for the design of PPT's with improved performances and for assessment of spacecraft integration effects.

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In the present study we concentrate on the pulsed plasma thruster called PPT-4 that was developed recently at the University of Illinois[4]. This is an electrothermal device that derives most of its acceleration from the electrothermal or gasdynamic mechanism. This thruster is axially symmetric and a discharge occurs between the annular cathode at the thruster exit plane and the circular anode located at the far end of a cylindrical cavity made of Teflon. The plasma generated inside this cavity is accelerated in a diverging nozzle that is attached to the downstream end of the cavity. The device has a pulse length of about 10 μs, and the overall specific impulse was measured to be 850 s.

In a series of previous papers, we describe our efforts to model various aspects of this electrothermal PPT. In Ref. 5, a model of the Teflon ablation and plasma discharge processes is described. The model was calibrated against mass ablation data from the PPT-4. In Ref.6, the charging, heat and flow effects associated with large Teflon particulates in the plasma jet of the electrothermal PPT were considered. Here it was predicted that the small macro-particles are expected to decompose within the plasma jet. Finally, in Ref. 7, the results obtained in Ref. 5, at the thruster nozzle exit were used as boundary conditions to perform a particle-based PIC-DSMC computation of the electrothermal PPT plume. A significant conclusion from Ref. 7 was that almost all of the back-flow to the spacecraft from this device arises from carbon ions due to their high mobility.

The main physical processes in this type of PPT occur in the Teflon cavity. Rapid heating of a thin dielectric surface layer leads to decomposition of the material of the wall. As a result of heating, decomposition and partial ionization of the decomposition products, the total number of particles increases in the cavity. The problem of the ablated controlled discharge has a general interest since it can be used for various applications[8,9,10]. In these devices, the discharge energy is principally dissipated by ablation of wall material, which then forms the main component of the discharge plasma. The ablated vapor increases the pressure within the capillary and the plasma is expelled through the exit. Previously, discharge evolution in the PPT-4 Teflon cavity was studied by Keidar *et al*[11] assuming uniform plasma parameters. However, further understanding of the physical processes involved requires more detailed analyses including spatial variation of the plasma parameter distribution along the cavity and a more sophisticated ablation model. The present model of the capillary discharge employs a recently developed ablation model[12]. These changes allow us to provide more accurate boundary conditions for the plume simulation.

The capillary discharge model

The model presented here describes the physics of the plasma generation and acceleration in a Teflon cavity for a pulsed electrical discharge as shown in Fig. 1. The main features of the model of the electrical discharge in the dielectric cavity include Joule heating of the plasma, heat transfer to the dielectric, Teflon ablation and electrothermal acceleration of the plasma up to the sound speed at the cavity exit. Mechanisms of energy transfer from the plasma column to the wall of the Teflon cavity includes heat transfer by particle convection and by radiation. The Teflon ablation is based on a recently developed kinetic ablation model[12]. It is assumed that all parameters vary in the axial direction x (see Fig. 1). Since the axial pressure and velocity gradients are much greater than the radial gradients we assume that radial variation of plasma temperature, pressure and velocity are neglegible[13,14]. The axial component of the mass and momentum conservation equations read:

$$\partial\rho/\partial t + \partial(\rho V) = 2\Gamma(t,x)/R_a \quad (1)$$

$$\partial V/\partial t + V\partial V/\partial x = -\partial P/\partial x \quad (2)$$

where ρ is the plasma density, P is the pressure, V is the plasma velocity and $\Gamma(t,x)$ is the ablation rate. The energy balance equation can be written in the form:

$$\frac{3}{2}n_e\left(\partial T/\partial t + V_z\partial T/\partial z\right) = Q_J - Q_r - Q_F \quad (3)$$

where Q_J is the Joule heat, Q_r is the radiation heat and Q_F is the heat associated with particle fluxes. This equation depends on the coordinate along the cavity. However, our estimation and previous calculations show[14] that the arc temperature varies only slightly with axial position and therefore we further assume $\partial T/\partial z=0$. The Teflon surface temperature is calculated from the heat transfer equation with boundary conditions that take into account vaporization heat and conductivity. The solution of this equation is considered for two limiting cases of substantial and small ablation rate very similar to that described in Ref. 11. For known pressure and electron temperature one can calculate the chemical plasma composition assuming LTE[11,15,16]. The Saha equations are supplemented by the conservation of nuclei and quasi-neutrality.

Electrostatic sheaths

The electrostatic sheath near the cathode provides the current continuity from the cathode to the plasma bulk as shown in Fig. 1. We assume that the cathode emission plays a small role in the current balance. The total current density in the sheath consists of electron J_e and ion J_i current densities:

$$J = J_i + J_e \quad (4)$$

In the case of a planar sheath in front of the cathode (the Debye radius is much less than the cathode length) J_i is determined by the Bohm relation:

$$J_i = 0.4en(kT_e/m_i) \quad (5)$$

where n is the plasma density at the plasma-sheath interface (see Fig. 1). The electron current is due to high energy electrons that penetrate the electrostatic barrier:

$$J_e = \tfrac{1}{4}\, en(8kT_e/m_e)\exp(-e\Delta\phi/kT_e) \quad (6)$$

where $\Delta\phi$ is the potential drop across the near-cathode sheath. For given current density one can calculate the potential drop:

$$\Delta\phi = T_e \ln((m_e/m_i)^{0.5} - J/en(kT_e/m_e) \quad (7)$$

One can see that the potential drop depends upon current density, plasma density and electron temperature.

In the cavity near the Teflon surface, the electrostatic sheath potential drop is negative in order to repel the excess thermal electrons, so that the electron current J_e is equal to the ion current J_i. It was concluded previously that during the discharge pulse, a quasi-steady sheath structure is formed and that under typical PPT conditions this sheath is unmagnetized in the self-magnetic field generated during the pulse[11]. Under the conditions mentioned above, the potential drop in the sheath is calculated as:

$$U_d = -T \ln (J_{eth}/J_i) \qquad (8)$$

Where J_{eth} is the random electron current density and J_i is the ion current density also determined by the Bohm condition.

Ablation model

The ablation model employed here is based on a kinetic model of the Knudsen layer near the ablated surface, which was analyzed using the distribution function moment method[17,18,19]. This method employs an approximation of the distribution function within the non-equilibrium Knudsen layer as a sum of the distribution functions before and after this layer with a coordinate dependent coefficient. In our problem of evaporation, it is only important to know the parameters on the boundaries and not their variation between the boundaries. This means that the problem is reduced to the integration of the conservation equations of mass, momentum and energy:

$$\int V_x f(V)\, dV = \text{const}$$
$$\int V_x^2 f(V) dV = \text{const} \qquad (9)$$
$$\int V_x V^2 f(V) dV = \text{const}$$

After integration of equation (9) we obtain a set of equations in which parameters at the external boundary of the Knudsen layer depend upon velocity at the Knudsen layer edge. Applying mass and momentum conservation between the edges of the hydrodynamic layer, one can find the velocity at the outer boundary at the Knudsen layer. Velocity and density at the outer boundary of the Knudsen layer determine the ablation rate. The system of equations is closed if the equilibrium vapor pressure can be specified. In the case of Teflon, the equilibrium pressure formula is used[1]:

$$P = P_c \exp(-T_c/T_o) \qquad (10)$$

where P is the equilibrium pressure, P_c and T_c are the characteristic pressure and temperature, respectively.

Nozzle and Plume models

The plasma flow through the conical nozzle is modeled by a quasi-one-dimensional continuum approach similar to that used previously (Ref. 7). We have assumed that the main part of the plasma generated in the cavity accelerates in the nozzle by the gasdynamic mechanism. We have considered the quasi-neutral plasma where ions and electrons are assumed to be ideal gases. This model also relies on the assumption that the flow is sourceless and plasma losses to the wall and wall evaporation are small and can be neglected.

The plume model is based on a hybrid fluid-particle approach similar to that used previously (Refs. 7, 20). In this model, the neutrals and ions are modeled as particles while electrons are treated as a fluid. Elastic (momentum transfer) and non-elastic (charge exchange) collisions are included in the model. The particle collisions are calculated using the direct simulation Monte Carlo (DSMC) method[21]. Momentum exchange cross sections use the model of Dalgarno et al.[22], while charge exchange processes use the cross sections proposed by Sakabe and Izawa[23]. Acceleration of the charged particles in the self-consistent electric fields is computed using Particle-In-Cell method (PIC)[24]. We have assumed quasi-neutrality that allows determination of the electron density. The plasma potential with respect to the thruster exit plane is calculated using the Boltzmann relation. The plasma potential at the thruster exit plane with respect to the cathode varies with time and is calculated using the near-cathode sheath model. The grids employed in this computation are similar to those used previously (Ref.7).

Results

In this section we present results of the calculation of the plasma parameter temporary and spatial variation in the Teflon cavity of the PPT-4 and also plume flowfield based on the boundary conditions provided by the device model. In addition, some thruster performance characteristics (thrust impulse and ablation mass) are calculated and compared with available experimental data. In this paper we also show how the improved thruster model and boundary conditions at the thruster exit plane affect the plume simulation.

Firstly, we present results for the thruster device modeling. These results later will be employed as boundary conditions for the plume simulation. All results are presented for PPT-4 with the following geometry and discharge parameters: anode radius R_a=3 mm and cavity length L=8.3 mm, current peak of about 8 kA and pulse duration of about 10 μs (Refs. 4, 25).

To illustrate the effect of the new ablation model on the ablation rate calculation, the trajectory of the ablation rate in the plasma density - Teflon surface temperature plane during the PPT-4 pulse is shown in Fig. 2. One can see that the ablation rate peaks at about 110 kg/m^2s at 3 μs and then rapidly decreases. It should be noted that in the experiment the average ablation rate was estimated to be about 30 kg/m^2s (Ref. 4).

The time evolution of the temperature and ionization degree (at the exit plane, x=L) is shown in Fig. 3. It can be seen that the electron temperature initially increases rapidly and peaks at about 3 eV and then decreases to 1 eV toward the pulse end. The model predicts that initially plasma in the cavity is strongly ionized while after about 3 μs the ionization degree decays substantially.

To demonstrate the different ion and neutral species temporal and spatial variation, their distributions are shown in Fig. 4. Both ion species peak at early times (about 3μs) while neutral species peak later. The relative concentration of the species changes along the cavity length and also during the discharge pulse.

The spatial and temporal distribution of the Teflon surface temperature is shown in Fig. 5. The temperature sharply increases during the first 2 μs of the discharge pulse and peaks at about 640 K. One can see that the temperature varies only slightly along the cavity.

To illustrate the ability of the model to predict some thruster performance characteristics, we calculate the thrust impulse bit and ablation mass per pulse as a function of cavity geometry and compare with experimental data. The gasdynamic thrust impulse is generated due to the pressure force on the anode. We integrate the pressure during the discharge to calculate the thrust impulse bit. In the case of PPT-4 nozzle with the area ratio of about 100, the nozzle may increase the thrust by a factor of 1.5 (Ref. 26). The thrust impulse bit dependence on the cavity length is shown in Fig. 6. One can see that it increases by a factor of 2.5 when L increases from 3 mm up to 25 mm. A similar trend was also found in the experiment[25]. The calculated Teflon mass ablated per pulse is shown in Fig. 7 as a function of cavity length and radius. Generally, the ablated mass increases with increasing cavity length and decreasing cavity radius. From comparison with experiment it can be shown that the model underpredicts the ablation mass by about 25%. However, it should be noted that some mass can be ablated in the form of large particulates. This effect for one particular PPT was estimated to be up to 40% of the total ablated mass[27]. The ablation in the particulate phase was not considered in the present paper.

The near-cathode sheath model allows of calculation the potential drop between the plasma at the thruster exit plane and the cathode. The plasma has a positive potential with respect to the cathode which decreases initially with time. This happens because the current pulse is essentially gone after 5 μs when the main plasma cloud arrives at the exit plane. Therefore the plasma density at the exit plane increases while the current decreases and this leads to decreasing $\Delta\phi$.

As mentioned earlier, one of the reasons for development of the 1D cavity model is to produce more accurate boundary conditions for the plume simulation. The temporal variation of the plasma density at the thruster exit plane is shown in Fig. 9. In comparison with previous results, the plasma density significantly increases at later times since plasma parameter variation along the cavity length is taken into account. These new boundary conditions are employed in the particle simulation of the plume. As expected, there is an effect on the plume structure at later times as shown in Fig. 10. It can be seen that the simulation predicts well the initial rise and the actual peak of the potential data. To generate the results shown in Fig. 10 we assumed that the potential at the thruster exit plane is constant throughout the simulation. However, it was shown (Fig. 9) that this potential varies with respect to the cathode. The measurements of plasma potential were made with respect to the cathode[4,25] . To illustrate this effect we combine the plasma potential in the plume (Fig. 10) with variation of the plasma potential at the thruster exit plane (Fig. 8). These results are shown in Fig.11 where the electron temperature near the cathode is used as a parameter. One can see that this approach is able to predict the drop of the potential from 5 μs and the minimum before the rising part. In making this comparison with the experimental data, it is expected that the measurements collected over the first 5 μs (before main plasma cloud arrives at the thruster exit) cannot be reproduced in the frame of the present model. This is due to dependence on the ignition plasma introduced by the igniter spark, which is not modeled in present work. In the present model we assume that all plasma parameters are radially uniform while really the electron temperature near the nozzle edges may be smaller than that at the axis[28]. Therefore we introduce the electron temperature as a parameter.

The new thruster exit boundary conditions provided by the physical models presented in this study do not significantly affect the main aspects of the plume structure that were reported in Ref. 7. It is found that the overall distribution of the chemical species in the plume is almost unchanged. The main conclusion from Ref. 7 still holds, that for the PPT-4, the main component of back flow onto the spacecraft will arise from the highly mobile carbon ions.

Summary

An end-to-end device/plume model has been developed to describe plasma generation, acceleration and plume expansion for an electrothermal pulsed plasma thruster. As an example, we have studied the Teflon fed PPT-4 developed at the University of Illinois. The modeling strategy was based on a one-dimensional fluid unsteady model for the plasma generation and acceleration processes and a particle simulation of the plume. A new kinetic ablation model was employed to calculate the Teflon ablation rate as a function of the plasma parameters. Predicted results were compared directly with data for PPT-4 performance characteristics and plume flowfield. In general, the agreement between data sets was good.

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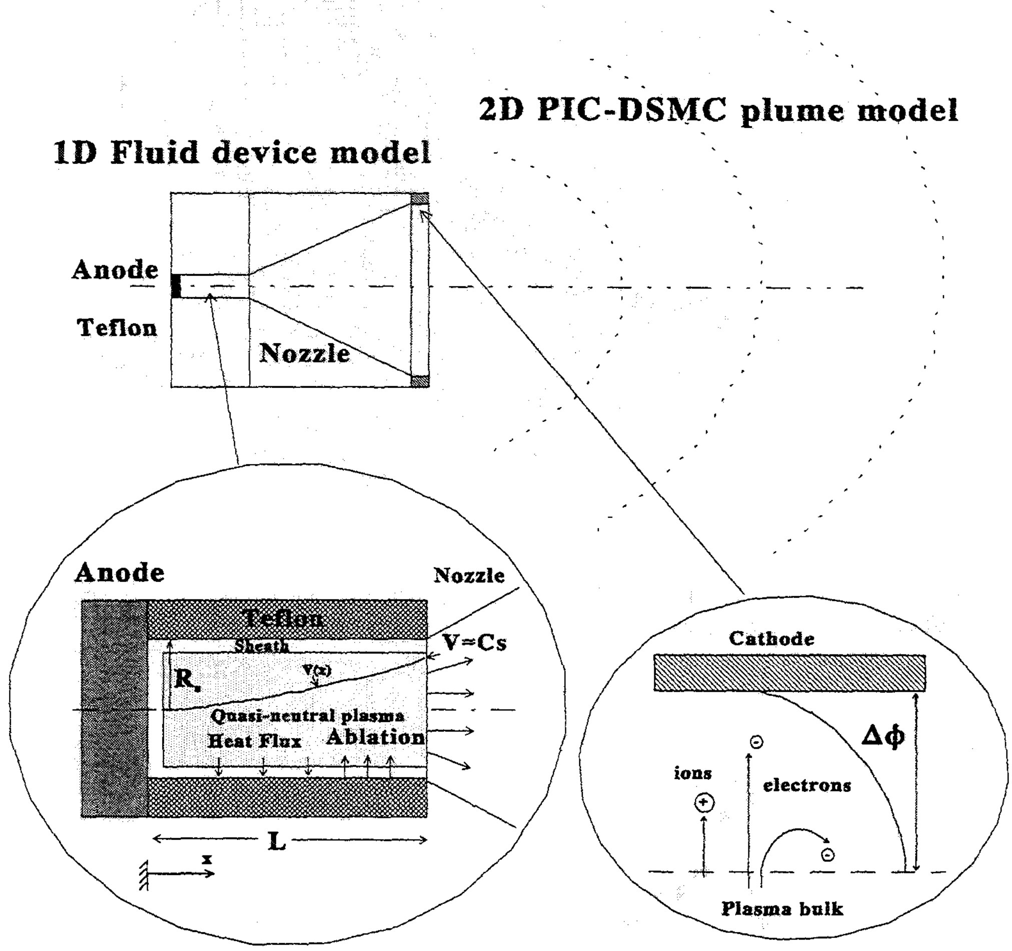


Figure 1. Schematic diagram of the PPT-4 and plume

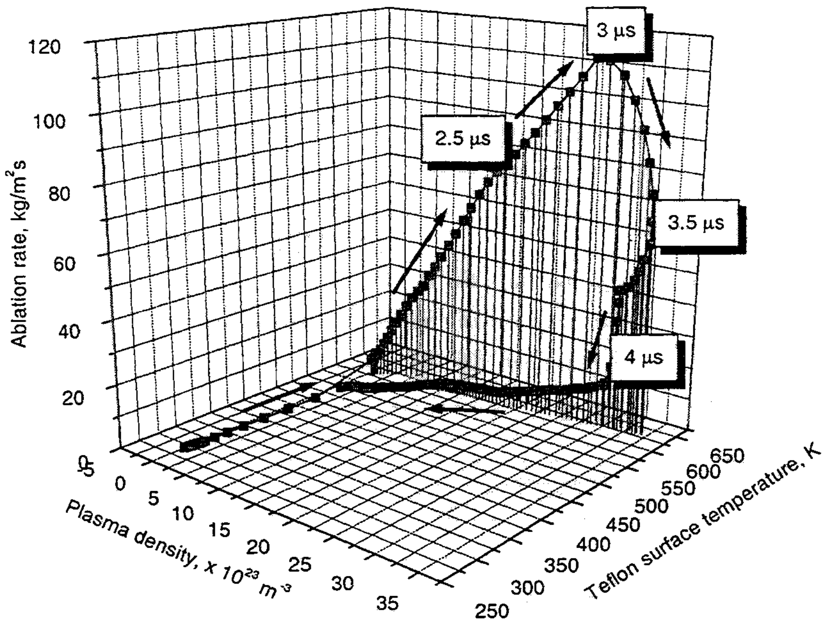


Figure 2. The ablation rate as a function of plasma density and Teflon surface temperature. The arrow indicates the direction of ablation rate evolution during the pulse.

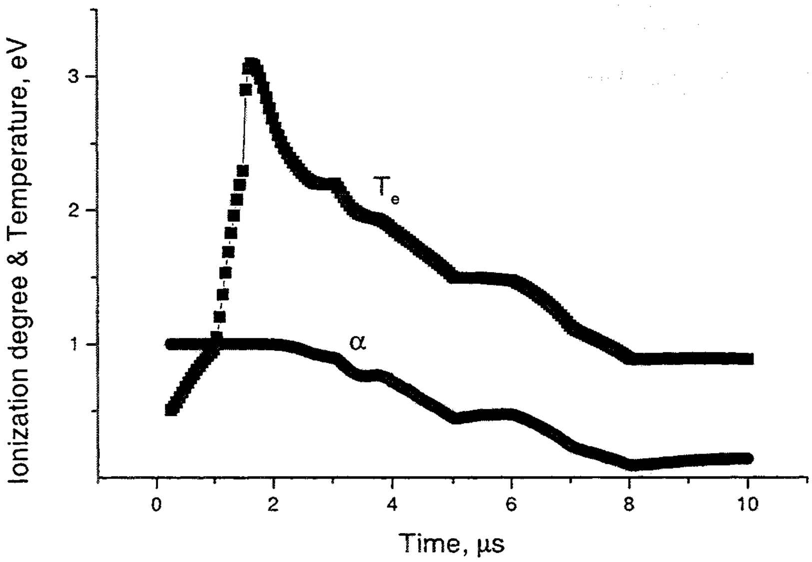
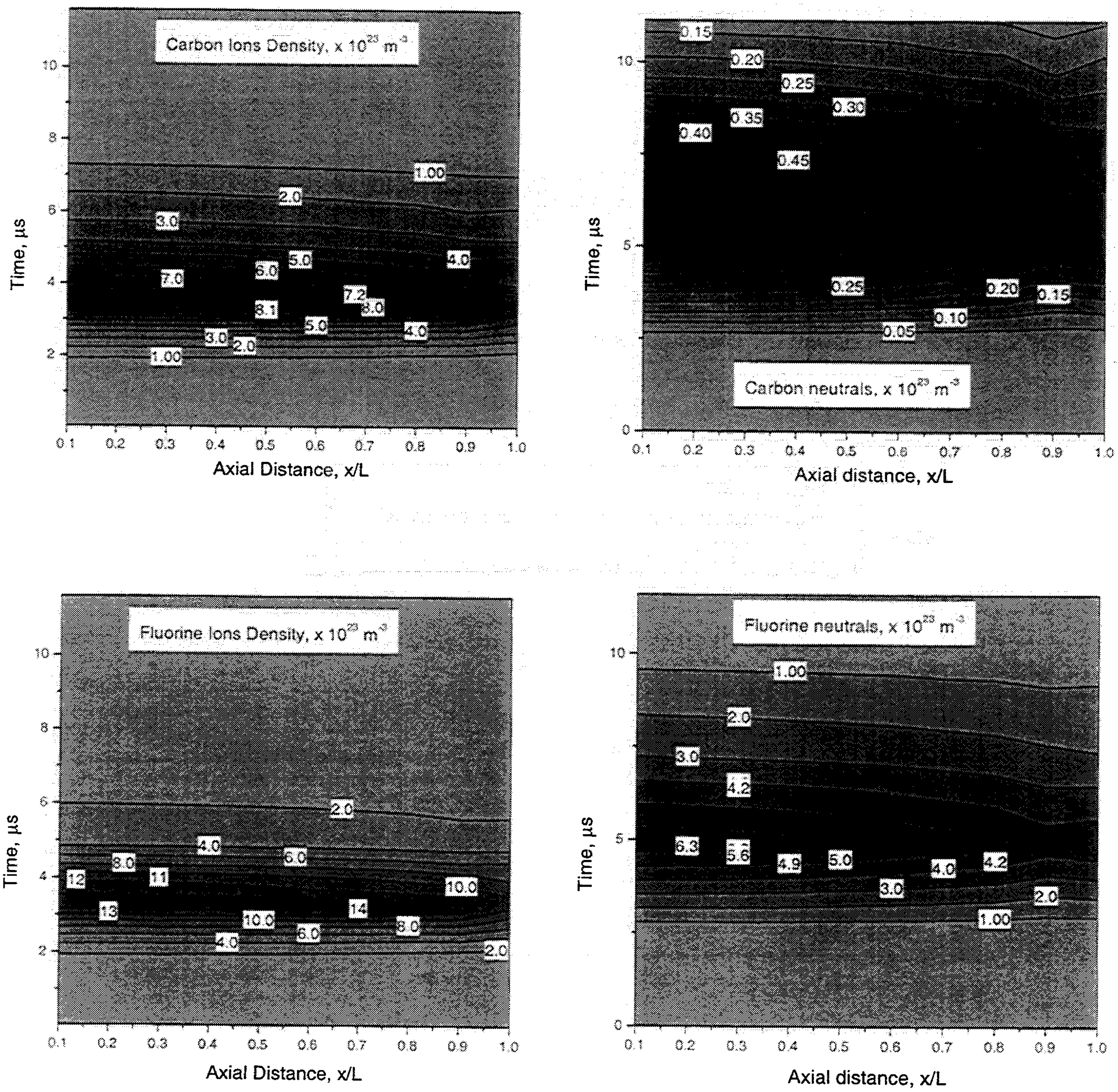


Figure 3. Variation with time of electron temperature and ionization degree in the cavity

Figure 4. Temporal and spatial variation of the chemical species during the discharge pulse



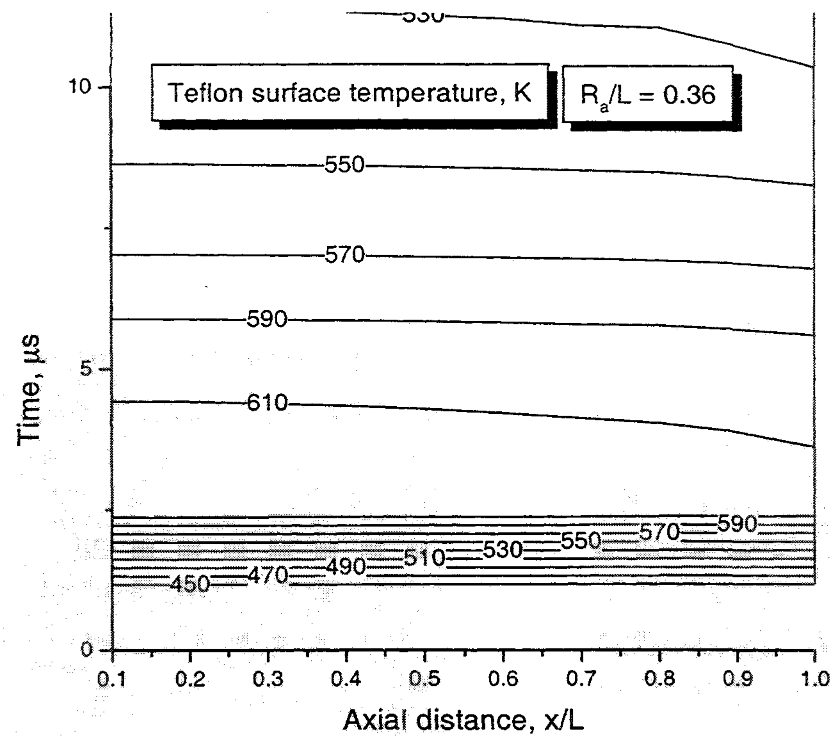


Figure 5. Temporal and spatial variation of the Teflon surface temperature

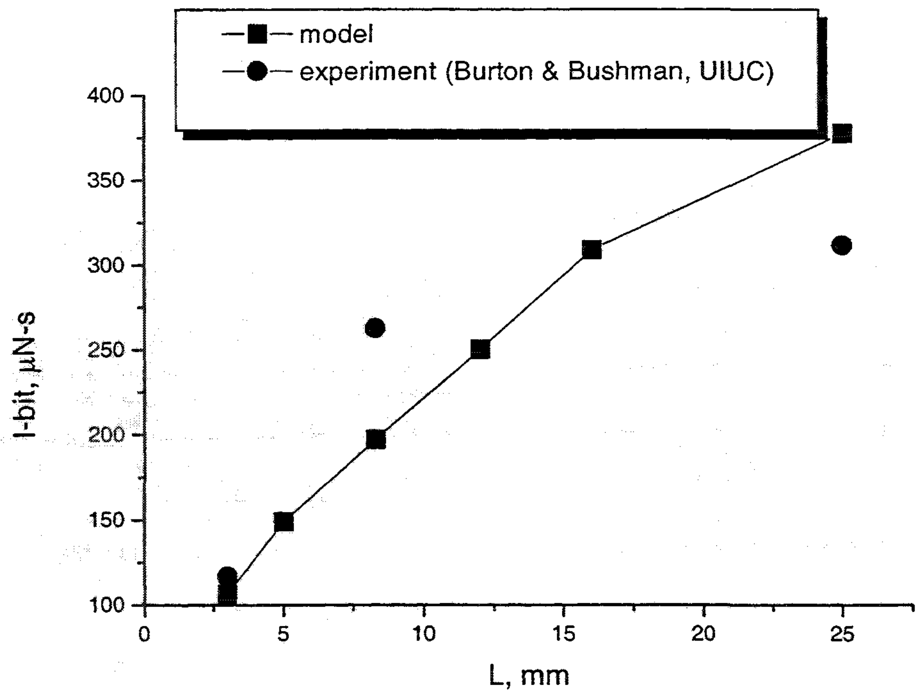


Figure 6. Thrust impulse bit variation with cavity length and comparison with experiment

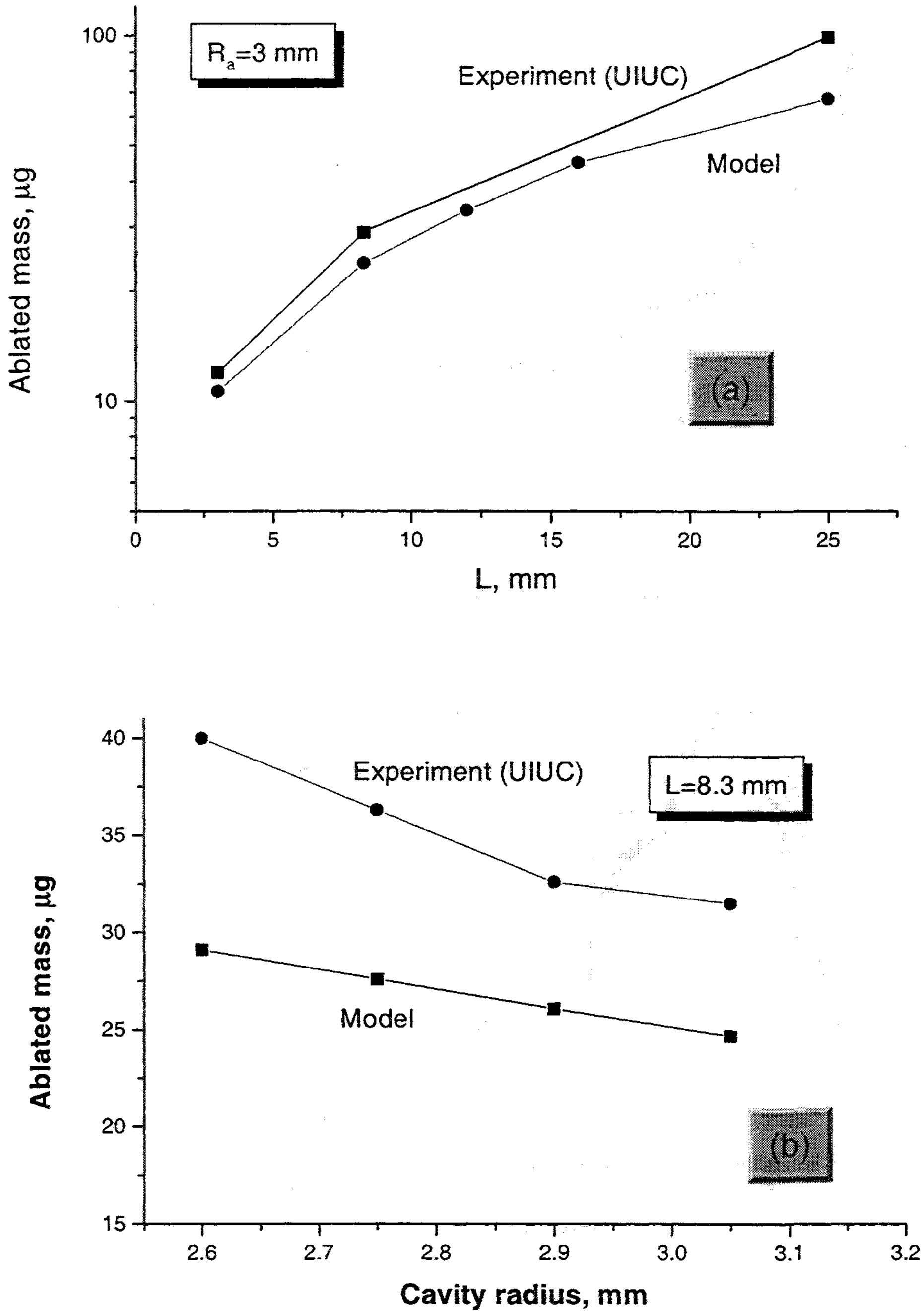


Figure 7. Ablated mass as a function of cavity geometry and comparison with experiment. a) constant cavity radius R_a; b) constant cavity length L.

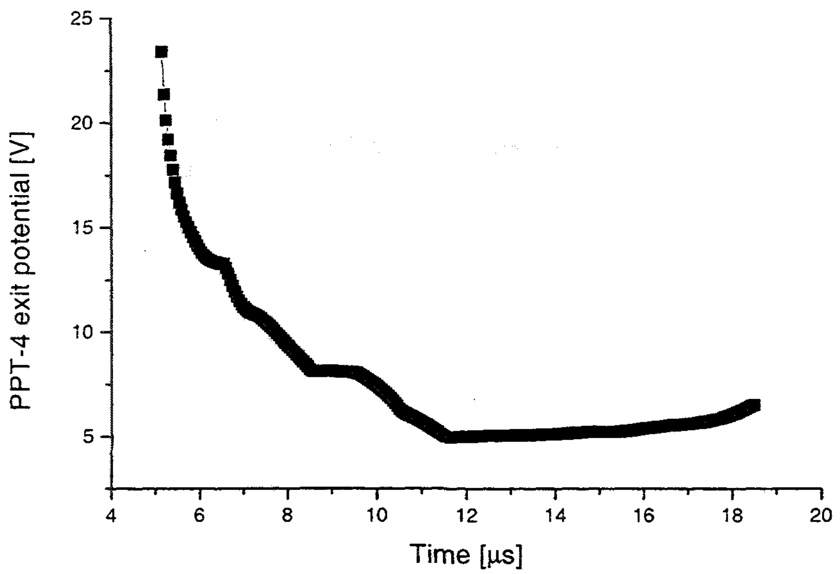


Figure 8. Temporal variation of the plasma potential at the thruster exit plane with respect to the cathode

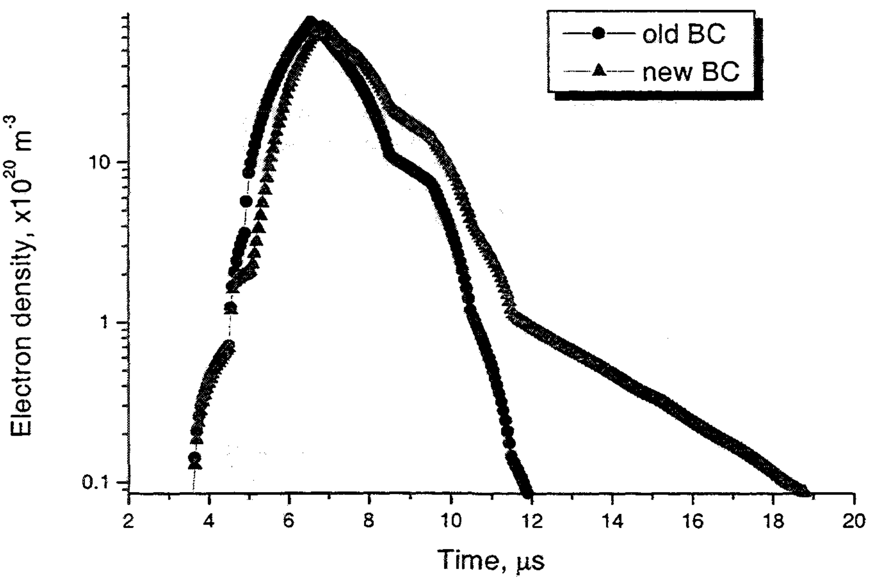


Figure 9. Variation with time of electron density and comparison with previous results

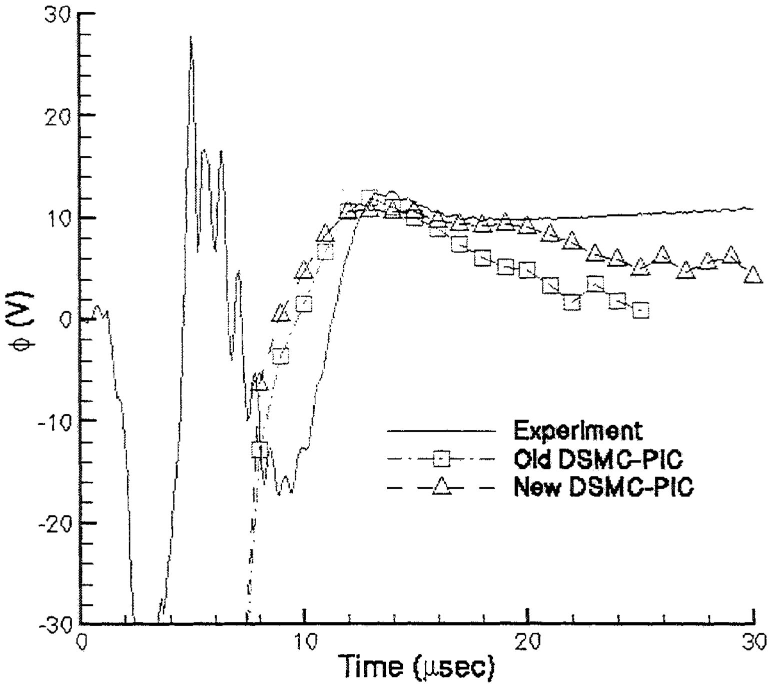


Figure 10. Variation of the plasma potential on the plume centerline at 10 cm from the thruster exit plane and comparison with experiment

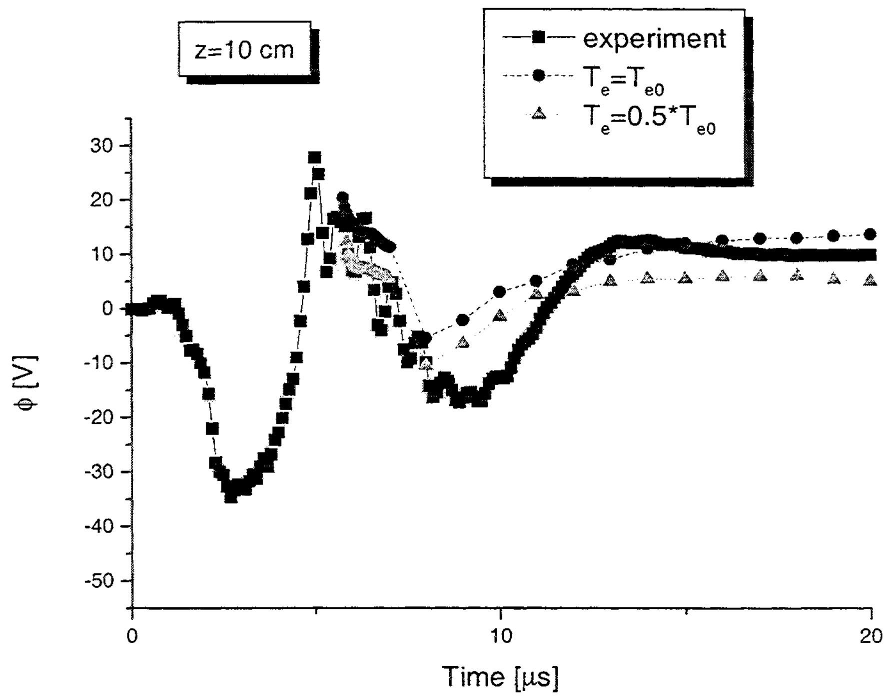


Figure 11. Variation with time of the plasma potential in the plume at 10 cm from the PPT-4 exit plane with electron temperature near the cathode as a parameter