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GAS-PLASMA COUPLING IN MINIATURIZED SPACES

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Abstract. *Attention is drawn to plasma-neutral gas interaction in miniaturized spaces as micro technology systems grow to be the key components in a wide range of products including small spacecrafts. This study details 3D self-consistent model of charged and neutral particle dynamics inside a microthruster used for nanosatellites applications. The model includes the conservation equations of the charged species and the fluid with the Poisson equation – as described by the formalism in the Royal Military College Self-Consistent code (R*SCPC). Those equations will be solved by three-dimensional numerical schemes for both species transport and electric field in a partial differential solver and the results compared to 2d results. Different electrode configurations will be investigated in order to optimize the system. Time dependent plasma evolution starting from an initial cloud confined between a cathode and an anode very close to one another will be investigated. We will study the neutral gas dynamics and its suspected dependence on the plasma interaction. Gas heating and will be discussed to highlight the interaction between neutral gas and charged species in governing the evolution of the miniaturized space.*

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1 INTRODUCTION

Under normal conditions a gas is an almost perfect insulator. If, however, a sufficiently large potential difference is applied between electrodes in a gas, it undergoes a transition from an electrically insulating state to a conducting state (plasma) including free-moving electrons and ions in which a small ionization current may be amplified. It is only recently, however, that a firm basis has been given to the theory of the ionization growth, and it is with these theoretical analyses that we will be concerned in the present paper. Simulation of direct-current surface plasma discharge phenomena in high-speed slow actuation has been introduced in [1] and the thrust measurement of a miniature electrothermal thruster using microwave-excited microplasma has been conducted in [2]. This study introduces dynamics of plasma and neutral gas interaction. Under normal conditions the plasma will be macroscopically neutral, an equal mix of electrons and ions in equilibrium. However, plasma can be accelerated and steered if an external electric field is applied. Gas discharge will take place if plasma is accelerated between a cathode and an anode in an atmospheric pressure neutral gas reservoir. Secondary electrons are emitted from the cathode mainly due to positive ion impact, sustain the discharge. The secondary electrons are accelerated in the direction of the anodes by the electric field, and obtain such high energies that they start ionizing neutral gas particles. New electrons thus created and accelerated and an ionization squall formed. In this paper we introduce a model for a miniature electrothermal micro meter thruster. The thruster is composed of alternative dielectric – metal electrodes with atmospheric pressure helium gas propellant. The thruster generates plasma to increase the heat of the bulk propellant. Thrusters in this class give very small specific impulse and thrust. The model first solves the conservation equations for charged and metastable species with the Poisson equation to determine the spatial distribution of the electrical potential and calculates electrons and positive ions number density and calculates the neutral gas number density by solving the conservation equation of the neutral gas. Joule heating and momentum transfer terms are included in the conservation equations to exemplify the relation between neutral and charged species. The model presented is a 3-D, different electrode configuration, to the 2-D self consistent formalism of the Royal Military College self-consistent plasma code (R*SCPC) [3, 4] that describe the 2-D interaction between plasma and the neutral gas inside an atmospheric microthruster. Fluid equations of the neutral gas and the plasma are described. Time dependent plasma evolution starting from an initial cloud confined between a cathode and an anode 0.4 mm apart is investigated. The microthruster height is 1.2 mm and 5.2 mm wall to wall. A 300 V potential is applied to the anodes. Results in this work show charged species evolution and infer gas-plasma interaction at a later evolution stage of the discharge. The microsthruster is practical as a propellant for a micro and nano satellites [5]. Higher thrust efficiency and more controllable and uniform impulse characteristics are possible with a larger array of microthrusters.

2 ELECTRODES AND GAS EQUATIONS

In order to study different ionization processes that can take place at an electrode surface in a gas we consider two plane parallel plates 0.4 mm apart each composed of a metal cathode and anode flanked by a dielectric material as shown in Figure 1. A potential difference 300 V is applied between the cathode and the anode producing a uniform field *E* in the gas. Drifting electrons will colloid with gas molecules and produce new electrons and ions. Ions will drift towards the cathodes and if they collide with sufficient kinetic energy with the cathodes or the dielectric electrodes they will eject secondary electrons. Each ion incident on the cathode will have a

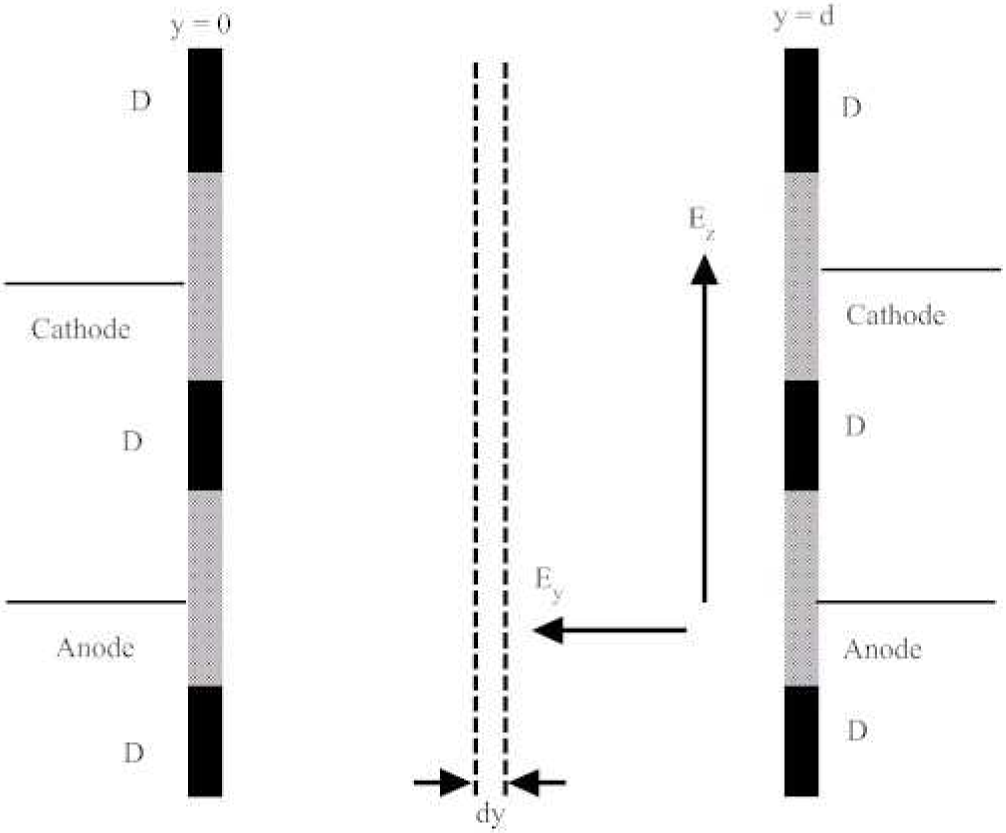

Figure 1: Two dimensional representation for the microthruster.

probability of ξ_i producing a secondary electron in the gas. Excited and metastable atoms produced in the gas body will diffuse and eventually collide with the cathode or the dielectric electrodes where they may produce secondary electrons. For their longer lifetime metastable atoms have a higher probability to hit the cathode and the dielectric electrodes prior to decaying. The coefficient ξ_m, ξ_{ex} are used to describe the probability of secondary emission production due to the metastable and excited atoms collision with the cathode or the dielectric surface. Secondary electros emission due to the incidence of photons on the cathode will be neglected in this study.

The plasma and neutral gas dynamics are described by the following equations:

Poisson equation

$$\nabla \bullet \nabla \psi = -\frac{\rho}{\varepsilon} \tag{1}$$

The conservation equation for charged species is represent by

$$\frac{\partial n_c}{\partial t} + \nabla\left[n_c \mu_c \vec{E} - D_c \nabla n_c \right] = \alpha_{i0} \mu_c n_c n_0 \vec{E} + k_{cm} n_c n_m + k_{pm} n_m n_p , \tag{2}$$

The conservation equation for the excited atoms (metastable) is given as:

$$\frac{\partial n_m}{\partial t} + \nabla\left[n_m \mu_m \vec{E} - D_m \nabla n_m \right] = \alpha_{ex} \mu_e n_e n_0 \vec{E} + k_{em} n_e n_m - k_{pm} n_m n_p - k_{rm} n_m - k_{2m} n_m n_0^2 \tag{3}$$

where n_c, μ_c and D_c correspondingly represent particles density, mobility and diffusion coefficient with the subscript c denotes e (electrons), *i* (ions), *m* (exited atoms). The initial density of the neutral helium gas and the exited atoms $n_0 = 2.5 \times 10^{25}$ m^{-3} and $n_m = 2.5 \times 10^{21}$ m^{-3} respectively; $De = 0.543$, $D_i = 0.354 \times 10^{-4}$ m^2/s and $D_m = 6.0 \times 10^{-5}$ m^{-3}. The ionization and excitation coefficient $\alpha_{ex}\ n_0$ and $\alpha\ n0$ are calculated as in [6, 7], $k_{rm}n_m$ and $k_{2m}n_m n_0^2$ indicate excited atom loss due to the escape of radiation and the conversion of metastable atom to metastable molecule.

The electron density at the cathode - dielectric surface is defined by the relationship

$$n_e = \left(\frac{\xi E}{V_e} \right) \left(\mu_i n_i + \mu_m n_m + n_{e0} \right) \tag{4}$$

where $\xi = 0.1$ is the electron yields attributable to ions and excited atom flux to the absorbing cathode and dielectric surface, $n_{e0} = 10^6$ m^{-3} is the initial electrons and ions density and V_e is the electrons velocity. The initial electron cloud is described as

$$n_e = \begin{cases} n_{e0} \exp\left(-\dfrac{1}{20} \left[x^2 + \left(\dfrac{3}{8}(y-16) \right)^2 \right] \right) & 10 \le z \le 20 \\ 10^6 & z < 10 \quad or \quad z > 20 \end{cases} \tag{5}$$

The conservation of mass, momentum and energy equations for the neutral gas take the form:

$$\frac{\partial m_g n_g}{\partial t} + \nabla\left(m_g n_g V_g \right) = 0, \tag{6}$$

$$\frac{\partial m_g n_g V_g}{\partial t} + \nabla.\left(m_g n_g V_g V_g \right) = n_c \frac{m_g m_c}{\left(m_g + m_c \right)} \nu_{cg} \left(V_c - V_g \right) - \nabla P + \nabla \tau, \tag{7}$$

$$\frac{\partial \varepsilon}{\partial t} + \nabla\left(\varepsilon V_g \right) = \nabla Q - \nabla\left(V_g \cdot (P + \tau) \right) + J.E, \tag{8}$$

where m_g, $n_g(x, y, z, t)$, $V_g(x, y, z, t)$, P, τ are the mass, density, velocity, pressure and viscosity of the gas. The subscript *c* corresponds either to electrons or ions in collision with gas atoms. The collision frequency υ_{cg} between charged and neutral species is determined by $m_g \upsilon_{cg} = K_B T_c / D_c$, where K_B is the Boltzman constant, D_c is the diffusion coefficient and $P = K_B n_g T_g$, where T_g is the temperature of the gas.
The term $n_c m_g m_c/(m_g + m_c)\ \upsilon_{cg}(V_c - V_g)$ in equation 7 represents the momentum transfer due to convection between the plasma and the neutral gas and the term *J.E* represents the energy transfer due to Joule heating. This implies that the neutral gas dynamics is conditioned by the plasma dynamics. The equations are discretized by the method of finite control volume with the approximation of centered difference at the frontiers and solved by the flux corrected transport (FCT) algorithm [8, 9]. The Poisson equation is

solved by an efficient fast Fourier transform algorithm [10] following x, y and z directions.

The boundary conditions at the anode are $\partial n_e/\partial y = 0$ and $n_i = n_m = 0$; $n_m = 0$ and $\partial n_i/\partial y = 0$ at the cathode. The initial gas pressure and temperature are 760 torr and 293 K respectively in the plasma simulation. The mesh has 2 million points and the microthruster is 1.2 mm height and 5.2 mm wall to wall with 0.4 mm distance between the upper and lower electrodes. The electron distribution at the cathode in the helium microplasma is determined by assuming that the total flux from the cathode n_{ev} is equal to the total density of the cathode emission frequency.

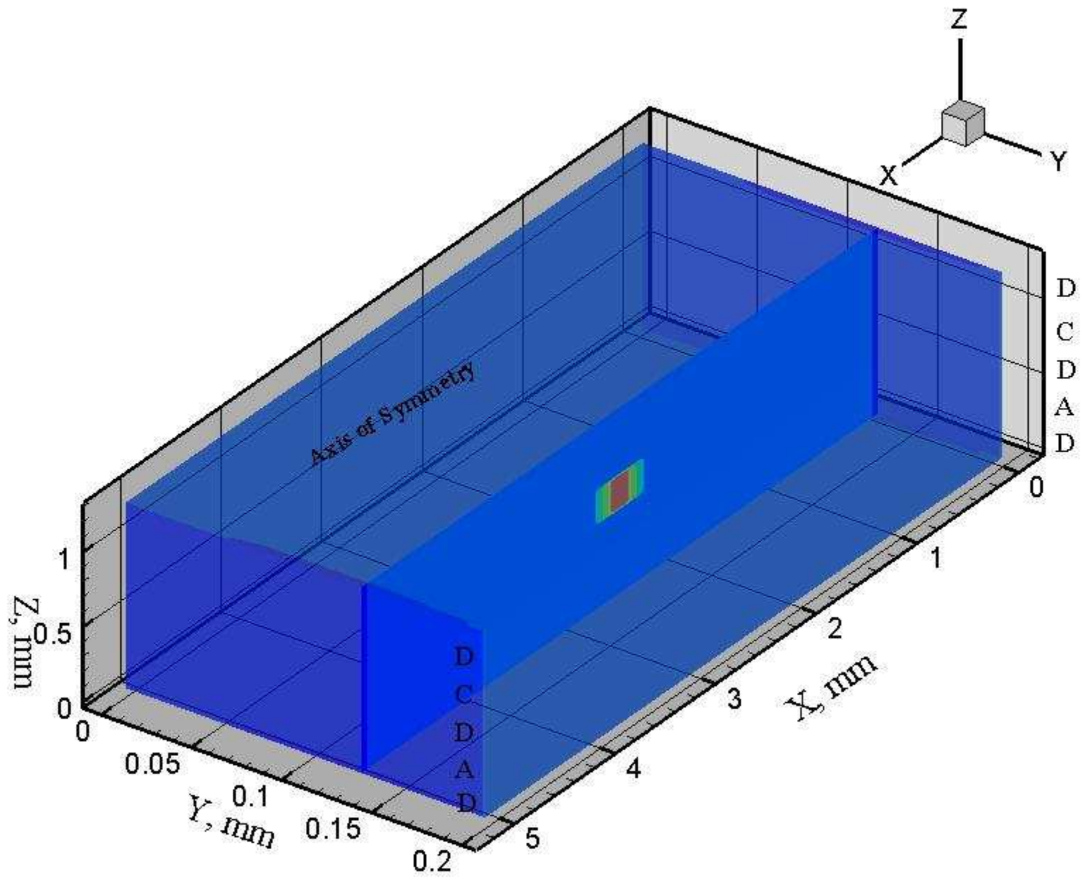

Figure 2: Schematic three dimensional representation of the evolution of electrons densities inside the microthruster

Alternative metallic-dielectric electrodes have been used in the simulation. The contribution of secondary emission due to photons has been neglected.

3 RESULTS

The calculations begin with the acceleation of an intial electron cloud in the electric field with a time step $\Delta t \approx 0.02$ ns. After about 6 ns the intial electrons disappears but more electrons are created by secondary emission when ions bombard the cathode and the dielectric material. Initial stages of the charge evolution are described in [11]. A three dimensional scehmatic representation of the charge evolution in the microthruster is shown in Figure 2. The electron cloud is drived by the electric field produced in the y –direction between opposite electrodes and between the cathode and anode in the z-direction in the opposite sides of the microthruster. Electrons ionize atmospheric pressure helium gas in the microthruster producing ions which will be accelerated towards cathodes. In the vicinity of the cathode, the electron density is determined by several effects cathode emissions flux, gas ionization and strong electron transport effects which can sweep away electrons, while ion density is dtermined by the rate of gas ionization. Figure 3 represents electrons amplification at 12, 62, 112 ns respectively. Secondary electrons are created when ions smash into the cathode and electrons density of 5×10^{17} m^{-3} is reported at 112 ns. Figure 4 represents ions amplification at 12, 62, 112 ns. Ions density of about 2×10^{19} m^{-3} is found at 112 ns. Ions have larger mass and move slower than electrons producing a significant difference between electrons and ions population producing a space charge which creates an additional electric field between the electrodes as shown in Figure 5. The electric field increases to about 80% of its orginal value in 112 ns as shown in the figure. The additional electric field sustains the plasma gas interaction process and helps creating more ions and electrons.

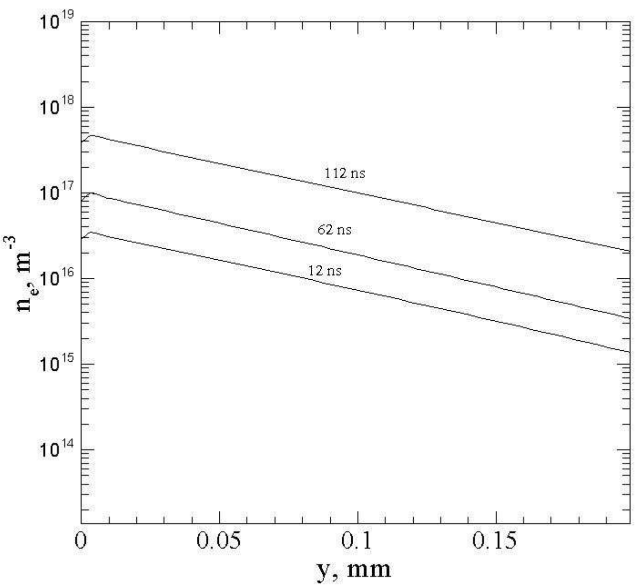

Figure 3: Axial values of electrons densities; electrodes at 0.2 mm.

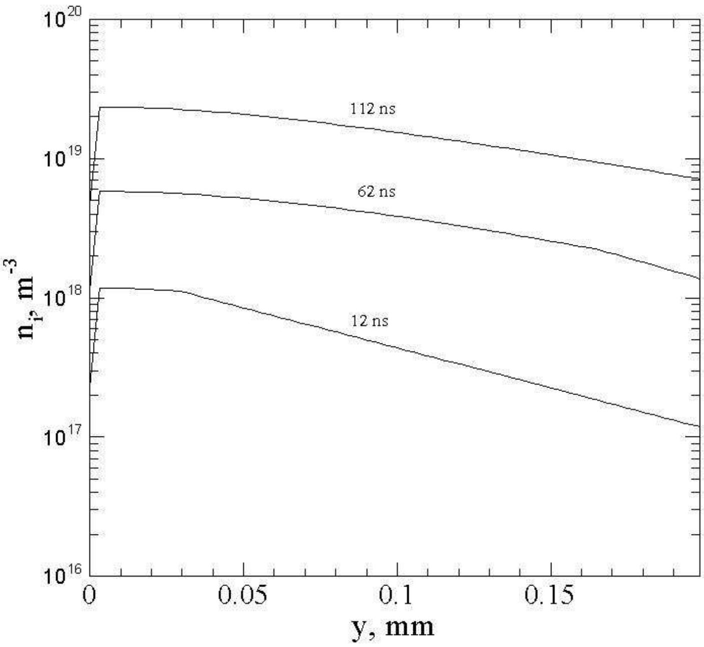

Figure 4: Axial values of ions densities; electrodes at 0.2 mm.

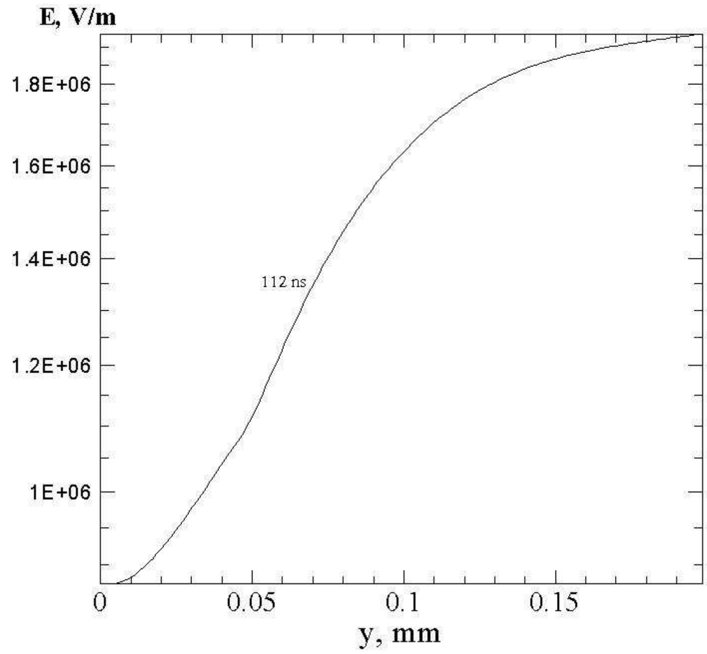

Figure 5: Electric field evolution in the microthruster.

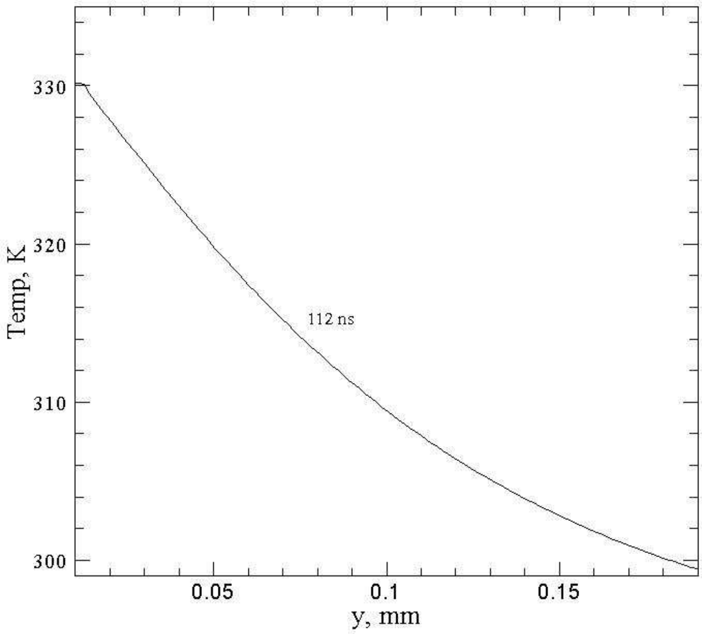

Figure 6: Distribution of gas temperature at 112 ns.

Momentum transfer and joule heating results in gas heating near the cathode as a result of collision between charged and neutral species as shown in figure 6. Results described in [3] using opposite metallic electrodes at 240 and 449 V shows higher electron amplification due because of the potential drop between the cathode and the anode across the dielectric material which is expected to distinguish the ionization process in the part of the cloud near the dielectric. Longer computational time is needed to simulate the field distortion at later time and its effect on the charged species population and the neutral gas parameters.

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5 CONCLUSIONS

In this paper we presented a three dimensional self consistent plasma model to describe the interaction between charged species (plasma) and atmospheric pressure neutral gas in a microthruster. The model is a expansion of the two dimensional Royal Military College self consistent plasma model (R*SCPS). The model includes using alternative metal – dielectric electrodes. Simulations show significant amplification of both electrons and ions and gas heating in the microthruster.

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