STUDY OF THE INTERACTION OF SATELLITE WITH ION THRUSTER PLUME USING 3D PIC SIMULATION

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ABSTRACT

We use a simplified spacecraft model to study the interaction between a satellite, surrounding space plasma, and charge exchange ions associated with an ion thruster. The model includes the satellite body, two solar panels, a xenon ion thruster and a neutralizer cathode. Our study is based on simulations made with PTetra [1], a fully kinetic time-dependent electrostatic particle in cell (PIC) model. In our model the ion thruster is represented as a surface from which a prescribed ions flux in ejected into space. Concurrently the neutralizer cathode emits a neutralizing electron current in order to maintain the spacecraft at a low net charge and potential. PTetra is also used to simulate neutral xenon gas with which the ion beam exiting from the thruster, interacts and generates charge exchange ions directed away from the beam. A particular attention is paid to charge exchange ions which are back scattered and directed toward the solar panels. Estimates are made of the fluxes of such ions on the solar panels and of ways to alleviate their effects.

1. INTRODUCTION

With the characteristics of high-specific impulse, ion propulsion devices play an increasingly important role in the domain of spacecraft [2]. However, the ion beam ejected from the thurster will greatly change the electromagnetic field around the spacecraft, and it will have a significant impact on microwave transmission and in-situ measurement in particular. In support of experiments and in order to better understand the physics of ion thrusters, several simulations of this process have been made. Many scholars have done related research, and have achieved remarkable results [3] [4] [5]. In this paper we use a combination of PIC and finite element method (FEM) to solve electrostatic fields surrounding high density electrons and ions.

2. SATELLITE GEOMETRY

An idealized spacecraft geometry is shown in Fig. 1, which includes the satellite body, two solar panels, a xenon ion thruster and a neutralizer cathode.

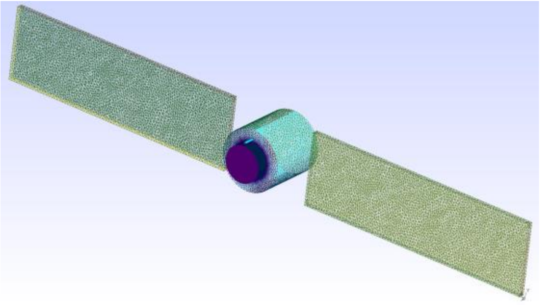

Figure 1. Geometry with surface meshes

The detail parameters of geometry are shown in Tab. 1.

Table 1. Geometry parameters

Radium of satellite	0.5m
Length of satellite	1.0m
Radium of ion thruster	0.3m
Radium of neutralizer cathode	0.02m
Solar panels	4.0m×1.2m×0.1m

The simulation domain is discretized with an unstructured tetrahedral mesh and it is delimited by an outer boundary located sufficiently far from the spacecraft.

3. SIMULATION PARAMETERS

3.1. Initial Condition of Particles

The parameters used to simulate the thruster and electron gun are shown in Tab. 2.

Table 2. Simulation parameters

Ion beam current	2.0A
Ion total accelerating voltage	1500V
Electron beam current	-2.0A
Electron total accelerating voltage	-10V

According to the total accelerating voltage of ions and electrons, the initial speed of ions and electrons are $v_{ii} = 4.69 \times 10^4$ and $v_{ei} = 1.875 \times 10^6$ respectively.

Assuming that all the xenon ions are singly ionized positive Xe^+, in the area very close to the emitting surface, the density of ion can be calculated from Eq. 1. And the ions flux ejected into space is given by Eq. 2.

$$n_i = \frac{I}{S v_{ii} |q|} = 9.4 \times 10^{14} \tag{1}$$

$$\Gamma = \frac{I}{|q|} = 1.25 \times 10^{19} \tag{2}$$

where the I, S, v_{ii} and q denote the ion beam current, the emitting area of the ion thruster, the initial velocity and the charge of ions, respectively.

3.2. Particles Implantation Conditions

As shown in figure 1, ions and electrons are emitted from the end surface. Due to this high density, the ion beam can produce up to tens of thousands of volts in space charge potential. In order to ensure that the ions and electrons can smoothly enter the calculation region, we set a high potential on the ion's emitting surface and a low potential on the electronic emitting surface. The potential can be calculated from Gauss Law. The initial velocity of the ions and electrons follow Maxwell distribution, and the most probable speeds are above mentioned v_{ii} and v_{ei}.

3.3. Particles Motion Equation

As mentioned above, the high density particles lead to a high space charge potential, so it is necessary to consider relativistic effects in the calculation of particle motions, especially for electrons. According to the impulse theorem, the momentum after a time step can be obtained from the Eq. 3.

$$\vec{p}(t + \Delta t) = \vec{p}(t) + q\vec{E}\Delta t \tag{3}$$

The effective mass of particles equals the rest mass m_0 times the relativistic factor γ.

$$m = m_0 \gamma \tag{4}$$

From the mass-energy relation, we can derive the relation between the relativistic factor and the momentum as Eq. 5.

$$\gamma = \sqrt{1 + \left(\frac{p}{c m_0} \right)^2} \tag{5}$$

where c is the speed of light, and p is the amplitude of the vector momentum. Finally, the velocity after a time step can be obtained from the Eq. 6.

$$\vec{v}(t + \Delta t) = \frac{\vec{p}(t + \Delta t)}{\sqrt{m_0^2 + \left(\frac{p(t + \Delta t)}{c} \right)^2}} \tag{6}$$

3.4. Charge Exchange

A fraction of the un-ionized neutrals can also escape out of the thruster with a thermal speed corresponding to the thruster wall temperature. The velocities of xenon atoms also follow Maxwell distribution, and the most probable velocity can be calculated from Eq. 7.

$$v_{ni} = \sqrt{\frac{8kT_i}{\pi m_i}} \tag{7}$$

where k is Boltzmann's constant, T_i and m_i are the temperature and mass of ions in SI.

Then the distribution of neutral particles can be quickly simulated without considering the electric field. In order to reduce the amount of computation, neutral particles are regard as the background particles, and their distribution will not be changed in the calculation process. The distribution is shown in Fig. 2.

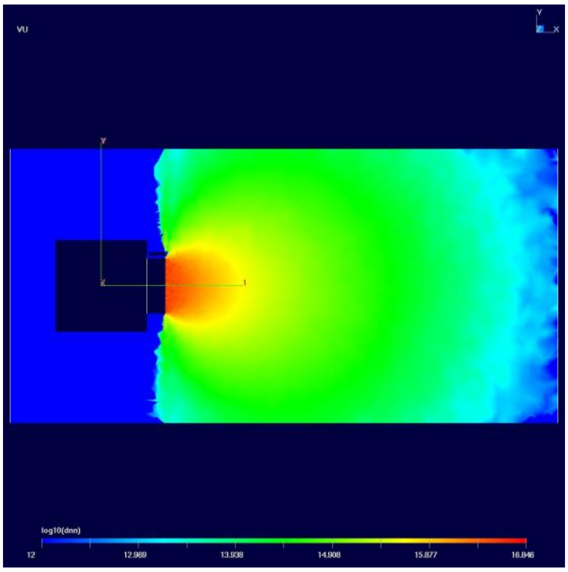

Figure 2. Cross section of the neutral particle profile.

When we track ions, the charge-exchange ion collision cross section should be calculated firstly by using Eq. 9 [3].

$$\sigma = \left(k_1 \ln\left(v_i\right) + k_2\right)^2 \times 10^{-20} m^2 \qquad (9)$$

where v_i is the ion speed, k_1=-0.8821 and k_2 = 15.1262. Then a random number is generated to determine whether the charge exchange collision occurs. If there is no collision, the PIC method is adopted to advance the ions. If on the other hand a charge exchange event occurs, the velocity of the ion is changed to that of a randomly selected neutral particle; thereby creating a low energy ion.

4. SIMULATION RESULTS

Based on the above mentioned setting, we compare two calculation results; one in which charge exchange collision are taken into account, and another in which they are not. The simulation mesh contains 1 666 195 tetrahedral elements and 332 194 nodes. The mesh is adaptive and it is refined near the emitting surfaces. There are approximately 800 000 particles in the computational domain. Fig. 3 shows the variation in the surface potential of the satellite versus time, and Fig. 4 shows the deposition charge on the surface of the satellite versus time. In these figures, the red and green lines refer to results obtained with and without charge exchange collision respectively.

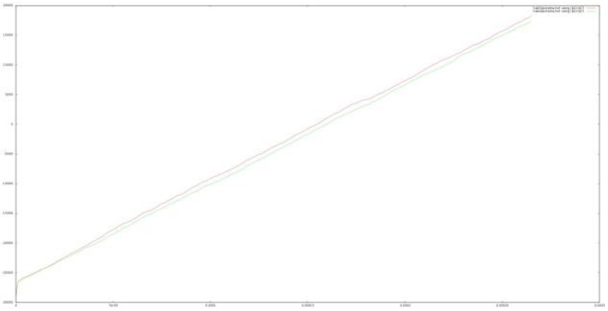

Figure 3. Temporal variation of the satellite surface potential. the red and green lines refer to results obtained with and without charge exchange collision respectively.

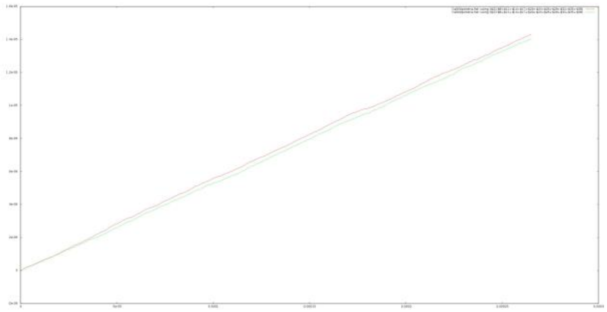

Figure 4. Charge collected by the satellite surface as a function of time. the red and green lines refer to results obtained with and without charge exchange collision respectively.

Firstly, we find that the surface potential of the satellite has increased to very large values. The change in the satellite surface potential is mainly caused by two reasons: 1) Ion and electron beams produce very high space charge potentials which lead to changes in the potential on satellite's surface; 2) ions are reflected back to the surface of the satellite to form a net charge accumulation.

Early in the simulations, there were no ions on the satellite surface, and the satellite potential was still growing, which was due to the first reason mentioned above. With the ion beam gradually stabilizing, the increase in the surface potential of the satellite was mainly due to the second cause. As the simulation progresses, a high potential develops on the surface, thus preventing charged particles from further depositing, which leads to anticipate that the steady state potential will be even larger.

Secondly, we find that the main composition of reflux ions does not consist of low energy ions produced by charge exchange collisions, although it could make the potential increase slightly faster. The main reason for the return flow is a large number of low energy ions coming from the initial velocity distribution, which change their trajectory under the influence of the high space charge potential. Fig. 5 shows a cross section of the potential profile. Fig. 6 shows a cross section of the ion density distribution. All of the images are displayed on the XY plane.

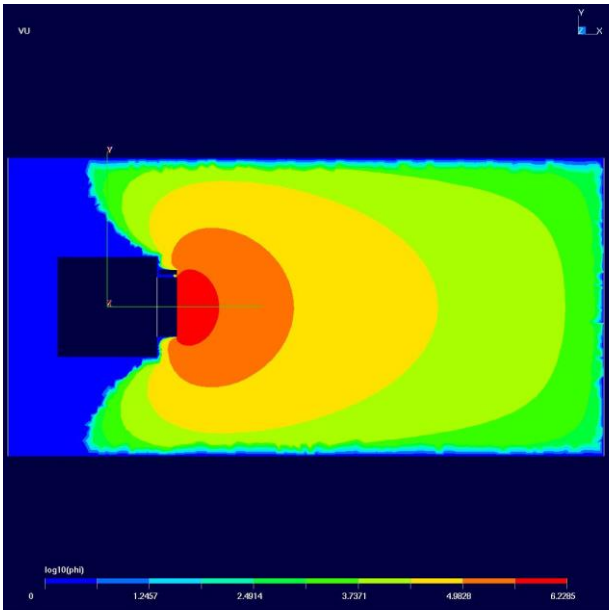

Figure 5. Cross section of the potential profile.

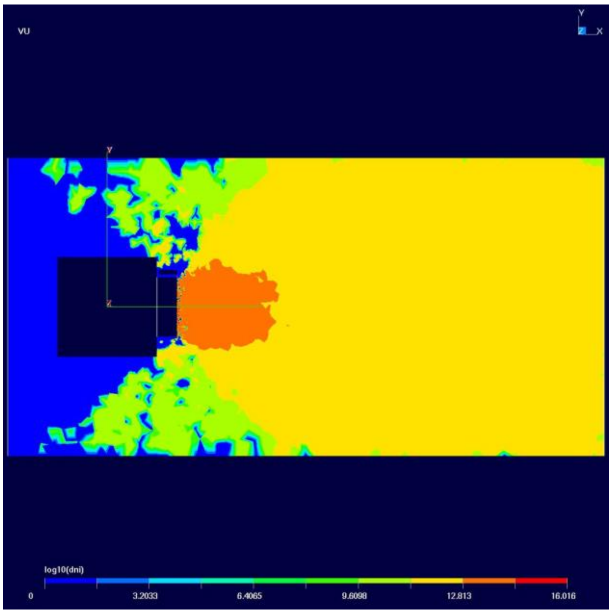

Figure 6. Cross section of the logarithm of the ion density.

Fig. 7 and Fig. 8 show the cross section of v_x and v_y profile respectively. From these figure we can see that a large number of ions change their original initial velocities which are along the x direction.

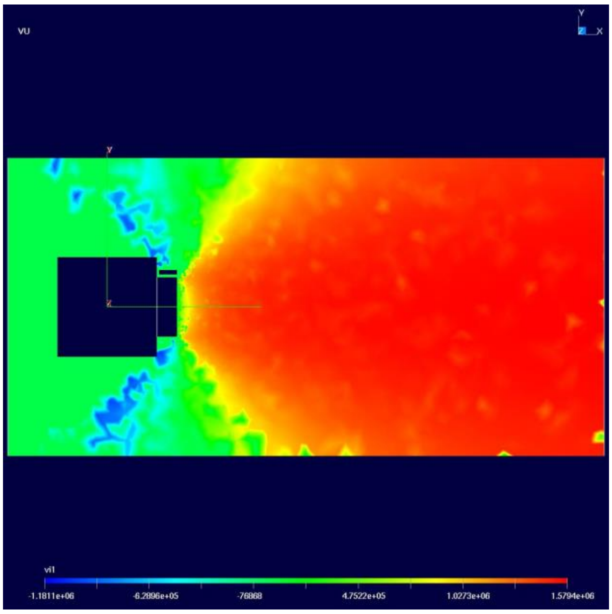

Figure 7. Cross section of the v_x profile

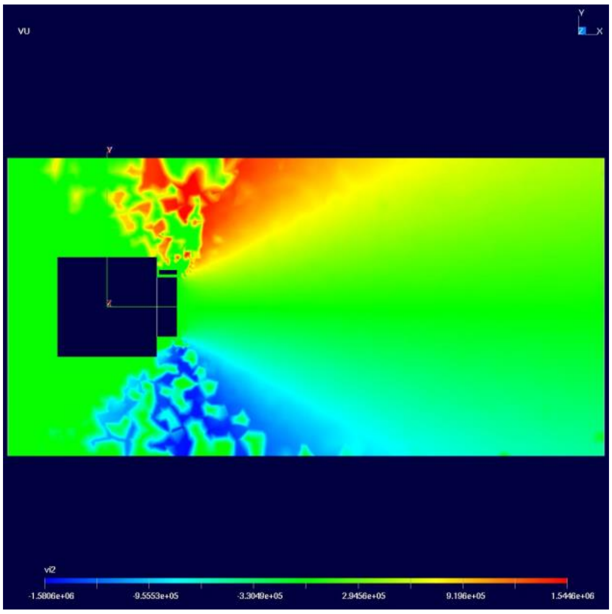

Figure 8. Cross section of the v_y profile

5. CONCLUSION

Our study is based on simulations made with PTetra [1], a fully 3D kinetic time-dependent PIC model. The simplified geometry is used to represent the main components of a satellite. In order to ensure that particles can smoothly enter the calculation region, we set a high potential on the ion emitting surface and a low potential on the electron emitting surface. In tracking particle motion, we consider relativistic effects and charge exchange collisions. As a conclusion, we find: 1) the surface potential of the satellite can reach very large values; 2) The main reason for the return flow is a large number of low energy ions coming from the initial velocity distribution, which are deflected in their trajectories by the high space charge potential.

6. REFERENCES

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