Interaction Effect Analysis of Ion Thruster Plume on GEO Satellite by using DSMC Method and Measurement Evaluation Method

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Abstract: Ion propulsion system may have a serious impact on the satellite, including force torque effects, thermal effects, sputtering effects, electromagnetic radiation and surface potential effects, and so on. This thesis represents an impact assessment study of the plume produced from a 1.3 kW ion thruster. A numerical analysis with a Direct Simulation Monte Carlo (DSMC) method using unstructured three-dimensional meshes is conducted. Based on numerical simulation and relevant test results, the plume effect of force torque and thermal on solar panel of communtcation satellite was been analyzed and the sputtering deposition effect on the satellite is proposed. The design configuration of the present SJ-13 commuication satellite is verified sufficiently by the numerical simulation and test of the plume interaction effect.

Key words: electric propulsion; plume; torque effects; thermal effects; sputtering deposition effects; evaluation Method

Section I overview

The ion thruster plume consists of propellant beams, such as xenon ion, neutralizing electrons, unionized neutrals, non propellant efflux, and low energy CEX xenon ions. The singly charged ions (Xe^+) are the basic species in an ion thruster plume.A beam expansion cone is 15^o , which is primarily due to the fringe electric fields in the grid apertures and secondarily due to the curvature of the grid surface.

It is significance to evaluate the influence of plume on the high orbit satellite. At present, a lot of research results about the plume effect of ion thruster have been made. Ground test conditions and Plasma diagnostic equipment are limited, and the measurement error come from unstable vacuum equipment is unavoidable, for example Previous experiments have found that ion density measurements by Langmuir probes with the probe axis set at different angles with respect to the plasma flow direction led to different results, so the probe measurement results are difficult to analyze. But still, experiment is the most important method to evaluate plume effect on the satellite. A corresponding numerical simulation model will be an indispensable diagnostic tool for the application of electric propulsion.

This paper is organized as follows: Section II describes the experimental results including the diagnostics which consists of a Langmuir probe, a Faraday probe, and a RPA. The simulation results of the CEX ion parameters are also presented and the measured values are reasonably consistent. Section III displays the preliminary evaluation results about force, heat flux, charging and discharging, deposition effect on the satellite, and the data sources come from the section II. Finally the analysis of the modified simulation model and experimental data gives us a thorough understanding of the effectiveness of the plume effect measurement.There is a deeper study and understanding of the mechanism of the interaction between the plume and the high orbit satellite.

Section II Simulation and experiment results of Ion Thruster Plume

This chapter provides lots of experimental data which effectively support the engineering application of ion electric propulsion technology.In order to make more effect evaluation, repeated experimental measurements are carried. The ion thruster provides a thrust of 40 $\pm$ 2mN under a measured beam current of 800 mA and a beam voltage of 1030 V ,and the experimental facility is a vacuum chamber of 5.5m in diameter and 12.8m in length, which could maintained at 5×10^{-3} Pa, and Several different types of techniques have been utilized to determine the beam ion density such as Langmuir probes, Faraday cups, and Retarding Potential Analyzers (RPA) . The components that contribute to the total ion density are the beam ion density, the CEX ion density, and the background ion density.

Fig. 1 shows the collected probe current profiles along radial positions at the axial distances of 200 mm − 900 mm away from the grid surface of the ion thruster.The plume properties are axisymmetric about the centerline of the thruster; the integrated beam current was calculated at each axial location. A three-dimensional PIC method is proposed to solve the particle trajectories of the charge-exchange plasma and the electric field surrounding the satellite. The density distribution of the ion beam is modeled by an analytical profile of the parabolic axisymmetric core and an exponential decay hypothesis. The density distribution of the neutral plume is modeled analytically as that of a free molecular flow from a point source located at one thruster radius behind the thruster exit. Electrons are commonly assumed to be isothermal in plasma plume modeling and the density is modeled by the Boltzmann distribution.

The density distribution of the charge particle given by

$$n_{bi0} = \frac{I_b}{e v_{bi} \pi r_T^2}$$

The density distribution of the neutral particls given by

$$n_{n0} = \frac{2 I_b}{e \bar{C} A_n} \left(\frac{1}{\eta_p} - 1 \right)$$

where A_n is flow area behind the thruster acceleration-grid exit, $A_n = \beta \pi r_{\mathrm{T}}^2$,and β is penetrant proportion of neutral particls, r_{T} is the radius of thruster acceleration-grid exit, η_p is utilization ratio of Xeon propellant, I_b is current density of the ion,$V_{bi}$is the vector aligned along direction of incident ion beam.

$$\bar{C} = \sqrt{8kT_w / \pi m_i}$$

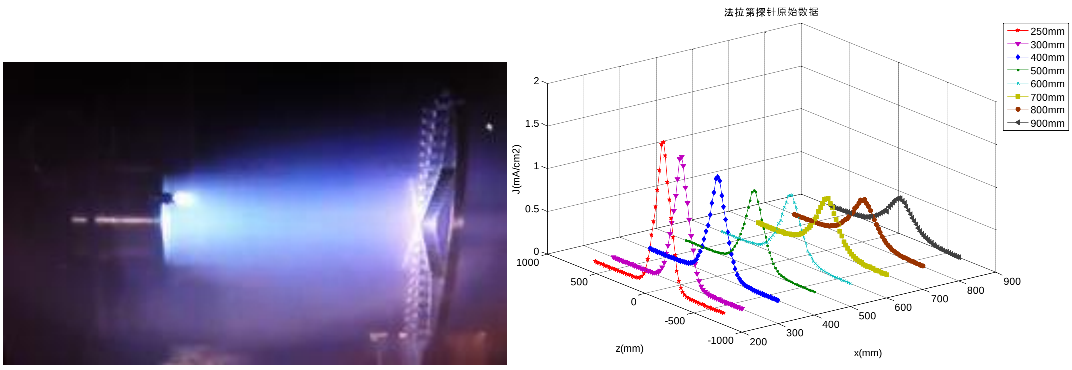

Fig. 1 Faraday current density testing result on different radial direction

According to experimental data, electron temperature is changed obviously along radial positions at the axial distances. This means isentropic model of electron temperature is more reasonable than being considered as isothermal model. The electron temperature distribution given by

$T_e/T_{\mathrm{ref}} = (n_e/n_{\mathrm{ref}})^{\gamma-1}$

Where T_{ref} is electron temperature and γ is the ratio of specific heat of electron, γ is modified by using experimental data. n_{ref} is electron desity relevant to the electron temperature. As seen in Fig. 2, the charge-exchange plasma density ranges from 10^{12} to 10^{10}/ m^3 near the downstream side from the thruster, and plasma density ranges from 10^{15} to 10^{13} / m^3 during the axial scans. Compare the simulation results and the collected probe current profiles along radial positions at the axial distances of 300 mm; the maximum relative error is 27.4percent, the collected ions decrease rapidly because of the effective collection area of Faraday probe, and also because of the unstable vacuum.

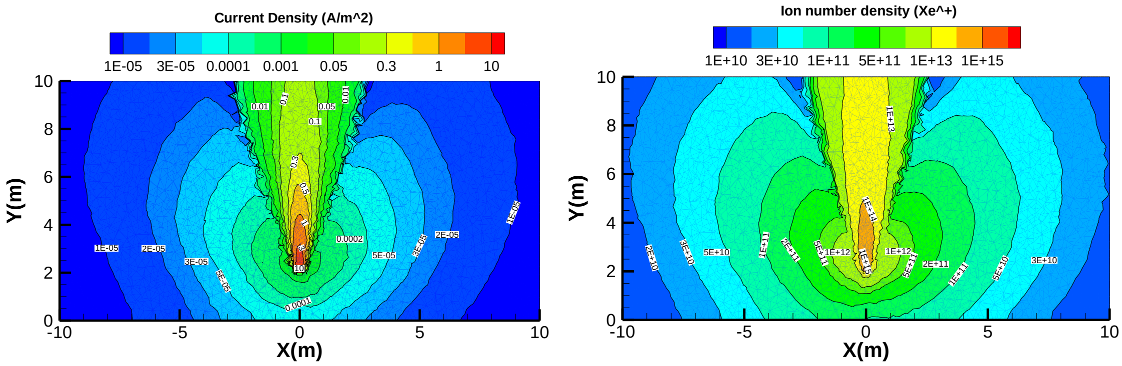

Fig. 2 Simulation results of ion density and current density distribution of LIPS200

This section Calibrated ion density profile by compare with the experimental data and the simulation results, ion potential (velocity), and plasma potential profiles measured by the diagnostics of a Faraday probe,which is suitable to analsys the plume effect on satellite.

Section III preliminary evaluation results of plume effect on the satellite

Particle energy, particle density, particle speed, particle quality are acquired from Section II, as is shown in the figure 3 and What we concert is focus on the impact of disturbance torque to the Solar arrays, the sputtering effect to the connection of metal silver material and the deposition effect to the surface glass of of the solar arrays and the oar（oxide-stable resin）coating.

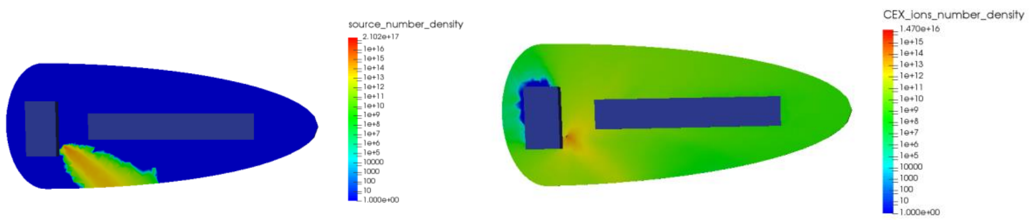

Fig. 3 Simulation results of ion density and CEX_ions density distribution of satelliete geometric model base on three-dimensional FEM method

Kinetic energy and momentum loss are calculated through particle parameter statistics colliding to the target surface. Energy flux, heat flow density distribution value and the heat adaptation coefficient being considered .The analysis method is based on different layout position and different angle。Model calculation and geometry method can calculate the plume cumulative impact on the surface of the satellite.

We assume that the mesh boundary area of solar is S, and ε_i represent the energy of ion particle, v_i is the vector aligned along direction of incident ion beam, $v_i^{\perp}$ is the normal velocity component. m_i is the particle quality. The energy flux of particle given by

$$\Gamma_{\varepsilon}^{i} = \frac{\varepsilon_i}{\frac{V}{S} \Big/ v_i^{\perp}} = \frac{1}{2} m_i v_i^2 v_i^{\perp} \left(\frac{S}{V} \right)$$

The total energy flux of the particles given by

$$I_{\varepsilon} = \sum_{i}^{N} I_{\varepsilon}^{i} = \sum_{i}^{N} \frac{1}{2} \frac{m_i v_i^2 v_i^{\perp}}{V} =$$

$$\sum_{i}^{N} \frac{1}{2} \frac{m_i v_i^2 v_i^{\perp}}{N \big/ n} = \frac{mn}{2} \left[\frac{1}{N} \sum_{i}^{N} v_i^2 v_i^{\perp} \right]$$

Fig. 4 shows Caculation process and the results of maximum moment and thermal flow, as shown in the fig.4 that the maximum surface additional pressure of the plume interfere to the solar array is 3.0×10^{-6}Pa,the maximum moment is 0.0279mN·m and the maximum heat flow is 0.025W/m^2.under the assumption of the thermal accommodation coefficient is 1,when the solar array rotate to 30 digree.

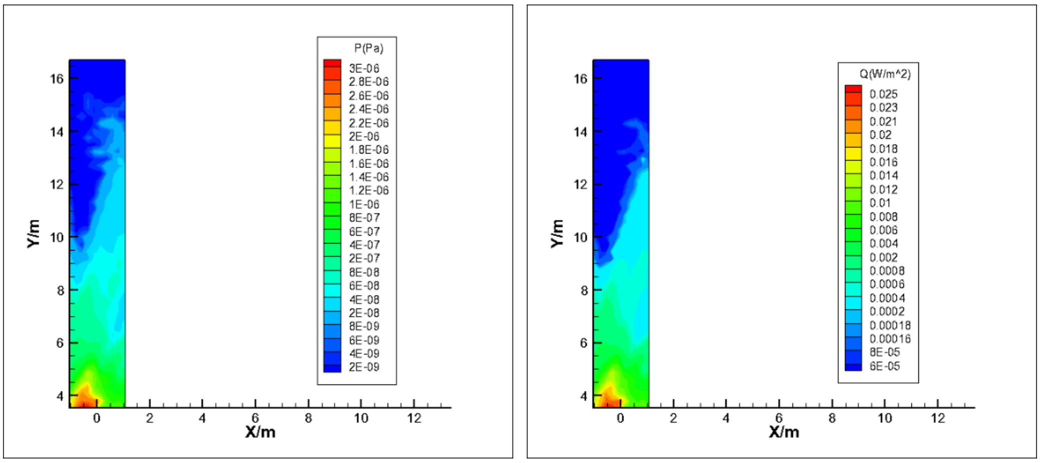

Fig. 4 Caculation process and the results of surface pressure and thermal flow

Influence factor of Plume sputtering effect including Beam energy, the density distribution of the plume and sputtering yield of the particle from difference angle. Caculation process of sputtering effects regularity is that: first of all, we acquired the sputterging data acting on the solar array by rely on piezoelectric quartz crystal microbalances (QCMs), which could used as a means of determining the mass loss of thin films, The material removed from the coating by etching may be correlated to a shift in the resonance frequency of the QCM(see fig.5).sencondly, we calculate the sputtering yield at action spot of the solar array using analytic geometry method and according to the energy gradient.

The analysis method is based on the following hypothesis: 1) when the solar arrays turns 360 degrees in one day, only half of the position is affected by the particle of plume.2) In the worst case to estimate, sputtering yield is inversely proportional to the square of distance.3) Total accumulated time is 11 thousand hours, that is the Orbiting work time of the electric propulsion.

Fig.6 and fig.7 show On-orbit sputtering effects on the solar panel of silver-interconnect structure and cover glass structure.the Maximum value of Sputtering thickness is distributed mainly in side angle of solar arrays of silver-interconnect structure, is about 0.0104mm. This sputtering area account for 0.12% of the impact to the whole wing.the thickness of the silver material which connects the solar cell array is triple thicker than the sputtering position.Similarly; the area of Sputtering thickness value more than 0.0001mm only accounts 1.57 percent of the whole solar arrays.

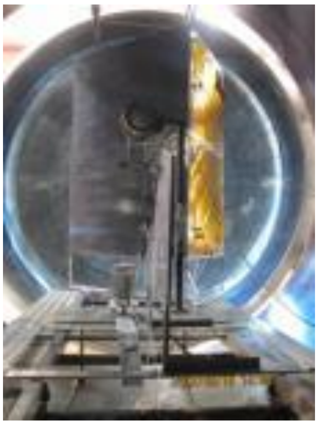

Fig. 5 Erosion rate test by QCM

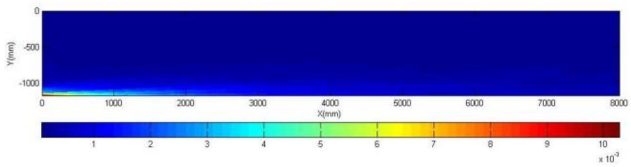

Fig. 6 On-orbit sputtering effects on the solar panel of silver-interconnect structure

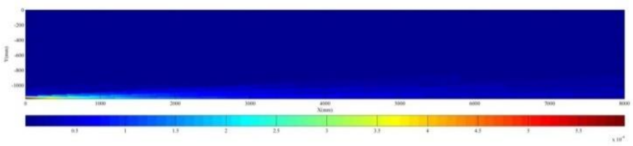

Fig. 7 On-orbit sputtering effects on the solar panel of cover glass structure

Deposition effect come from the atoms Mo and xenon ions Mo+, we could analysis the Deposition effect by static the mass loss, we could also Evaluated base on Accelerating current of grid electrode.

First of all, Evaluation mass loss base on Accelerating current of grid electrode.

Sputtering yield of Mo and Accelerator grid impingement current can be used to calculate the mass loss of atoms Mo as following:

$$\dot{m}_{\mathrm{Mo}} = \lambda_e \lambda_y \frac{Y J_{\mathrm{a}} M_{\mathrm{Mo}}}{e}$$

where J_{a} is Accelerator grid impingement current,e is unit charge, Y is the Sputtering yield of Mo, M_{Mo} is the quality of Mo atoms, λ_e is the proportion coefficient of Mo in all the corrosion, λ_y is modifying factor between the Accelerator grid impingement current and the Sputtering yield of Mo, which is impact by the difference of electric potential .

Sencondly, Evaluation deposition thickness base on mass loss.

Ward model method can be used to describe the distribution of atoms Mo. and percentage mass loss of grid electrode of unit time is calculated by

$$\nu = \frac{\dot{m}_{\mathrm{tot}}}{\pi} \cdot \frac{\cos\theta}{R^2} atoms/(cm^2 \cdot \mathrm{s})$$

$$\dot{m}_{tot} = 10.81\mathrm{g}/8200\mathrm{h} =$$
$$0.00132\mathrm{g}/\mathrm{h} = 2.30\times10^{15}\,\mathrm{atoms/sec}$$

Where ν is numbers of particls per second to the specifc surface, and $\dot{m}_{\mathrm{tot}}$ is mass loss of atoms Mo, R is the position between the Deposition point on the satellite and the thruster. Atomic mass of Mo is $95.94\mathrm{g/mole}$, diametral $2.8\,\mathring{\mathrm{A}}$,each square centimeter area contains the number of Atomic Mo is $1.65\times10^{15}/\mathrm{cm}^2$.

As we know, two QCM devices are installing on the DS-1 Deep space detector.the distance between QCM0 and axial line of the thruster is 75cm, included angel is 85degree, the other OCM1 arrange out of field range of the thruster. Deposition quantities are calculated as

$$\nu = \frac{\dot{m}_{\mathrm{tot}}}{\pi} \cdot \frac{\cos\theta}{R^2} = \frac{2.3\times10^{15}\times0.08716}{3.14\times75^2} =$$
$$1.13\times10^{10}\,\mathrm{atom/s{\times}cm^2}$$

$$1.98\times10^{-5}\,\overset{\mathrm{o}}{\mathrm{A}}/\mathrm{s} = 0.0712\,\overset{\mathrm{o}}{\mathrm{A}}/\mathrm{h} = 71.2\,\overset{\mathrm{o}}{\mathrm{A}}/\mathrm{kh}$$

The testing rusults acquired from the telemetry parameter of QCM is that during 2750 hour of the testing, the Thickness of QCM0 is $250\,\mathring{\mathrm{A}}$, deposition rate is $160\,\mathring{\mathrm{A}}/\mathrm{kh}$ and the Thickness of QCM1 is $25\,\mathring{\mathrm{A}}$ which may come from the other extraneous component.the other reason of the different deposition quantities may come from the screen-grid of the thruster.

As for the LIPS200 ion thruster, Thickness or quality variations of atoms can be seen by lift test of thruster, as seen in the 11000 hour wear test of the ion thruster.Accelerator grid impingement current is 4mA,the Accelerator grid volt is -185V,and the Sputtering yield can calculate as 0.259, mass loss of atoms Mo as following:

$$\dot{m}_{\text{Mo}} = 0.75 \times 0.22 \times \frac{0.259 \times 4 \times 10^{-3} \times 1.59 \times 10^{-25}}{1.6 \times 10^{-19}} =$$
$$1.7 \times 10^{-10}\,\text{kg/s} = 1.07 \times 10^{15}\,\text{atom/s}$$

After 11000h life test, the total mass loss of atoms Mo is 6.727g,and $\theta = 36.5^{\circ}$, $R = 1211\text{mm}$, The different position n of rate of deposition for the LIPS200 list at the table1 as following:

Table 1 Different position of rate of deposition for the LIPS200

distance L/m		0.5	1	2
angle $\theta(^{\circ})$		85	85	85
rate of deposition $(\overset{\circ}{\text{A}}/\text{kh})$	Atom Mo	75.4	18.8	4.7
	Ion Mo+	0.123	0.033	0.007
11000h thiness of deposition（nm）	Atom Mo	82.9	20.7	5.2
	Ion Mo+	0.036	0.135	0.0076

The above section show the qualitative analysis about the deposition effects on the satellite, but during fifth year's woring, the solar arrays turns 360 degrees in one day, which means the total thiness of deposition on solar arrays is half of the average value.So the conclution is made that the final thinness above 10A of deposition on the solar arrays occupy only 2 percent as show in fig.8.

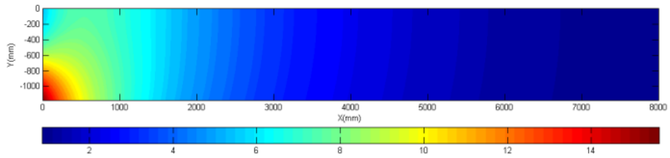

Fig. 8 Results of on-orbit deposition effects

Finally, this thesis represents an impact assessment study of the plume produced from a 1.3 kW ion thruster. The conclution is made this LIPS200 Ion propulsion system have a slight impact on the solar panel of communtcation satellite, the force torque effects, thermal effects, sputtering effects and deposition effects is acceptable.

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