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Simulations of momentum transfer process between solar wind plasma and bias voltage tethers of electric sail thruster

Guangqing Xia[a,*], Yajie Han[a], Liuwei Chen[a], Yanming Wei[b], Yang Yu[b], Maolin Chen[c]

[a] State Key Laboratory of Structural Analysis for Industrial Equipment, Dalian University of Technology, Dalian, 116024, China
[b] Beijing Institute of Control Engineering, China Academy of Space Technology, Beijing, 100080, China
[c] Science and Technology on Combustion, Internal Flow and Thermo-Structure Laboratory, Northwestern Polytechnical University, Xi'an, 710072, China

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ABSTRACT

The interaction between the solar wind plasma and the bias voltage of long tethers is the basic mechanism of the electric sail thruster. The momentum transfer process between the solar wind plasma and electric tethers was investigated using a 2D full particle PIC method. The coupled electric field distribution and deflected ion trajectory under different bias voltages were compared, and the influence of bias voltage on momentum transfer process was analyzed. The results show that the high potential of the bias voltage of long tethers will slow down, stagnate, reflect and deflect a large number of ions, so that ion cavities are formed in the vicinity of the tether, and the ions will transmit the axial momentum to the sail tethers to produce the thrust. Compared to the singe tether, double tethers show a better thrust performance.

1. Introduction

Electric sail thruster is a new concept propulsion device, which produces thrust through the interaction between the electric field of the sail tethers and the solar wind [1]. The tether layout of the electric sail thruster includes cross structure [2] and parallel structure [3], as shown in Fig. 1. For both parallel and cross structure, a positive bias in the sail tether is applied, then the high velocity ions in the solar wind are reflected or deflected under the effect of the sail electric field, the axial momentum is transmitted to the sail tether to form the thrust.

Because of the lack of reliable experimental conditions, the theoretical analysis and numerical simulation are mainly used to study the interaction between the electric field of the sail tethers and the high velocity solar wind plasma flow. The theoretical analysis mainly includes the potential distribution of the single tether in the solar wind environment, the trajectory of the ion flow around the tether, and the force analysis of the tether and so on [2–4]. Because it is difficult to give the exact profile and position of the electric tether sheath, we can only determine the approximate range of the electric tether force by the theoretical analysis [5], and we cannot obtain the accurate thrust parameters. Obviously, numerical investigation is a reliable method for accurate simulation of the interaction between the electric field of the sail tethers and the solar wind, furthermore the force of the sail tethers. The existing research work includes: the electric potential of tether sheath and electron number density distribution based on 1-D PIC method [4], the ion flow deflection process simulation based on 2-D PIC method [6], and the tether sheath distribution based on 3-D PIC method [7].

Some numerical results have been obtained for the analysis of the thrust characteristics of a single tether under a certain bias voltage, but the study of different tether bias voltage and multiple tethers has not been carried out. In this paper, the simulation of the interaction between the electric field of the sail tethers and the solar wind plasma is carried out. Based on the full-particle 2-D PIC simulation, the sail tether sheath formation process, the ion deflection trajectory and the force of the sail tether are compared under different tether bias voltage conditions. At last, the momentum transfer characteristics between the solar wind plasma and the electric sail with single tether and double tethers are analyzed.

2. Model description

2.1. Calculation region and parameters

The calculation region is set as a rectangular domain. As shown in Fig. 2, the sail tether is located at the center of the calculation region, and the potential is set as the sail tether bias voltage $\phi = V_{cable}$. The boundary potential is the space plasma potential $\phi = 0$. The solar wind plasma enters from the left side and is reflected or deflected because of the electric field of the tether sheath. When the ions enter and leave the

* Corresponding author.
E-mail address: gq.xia@dlut.edu.cn (G. Xia).

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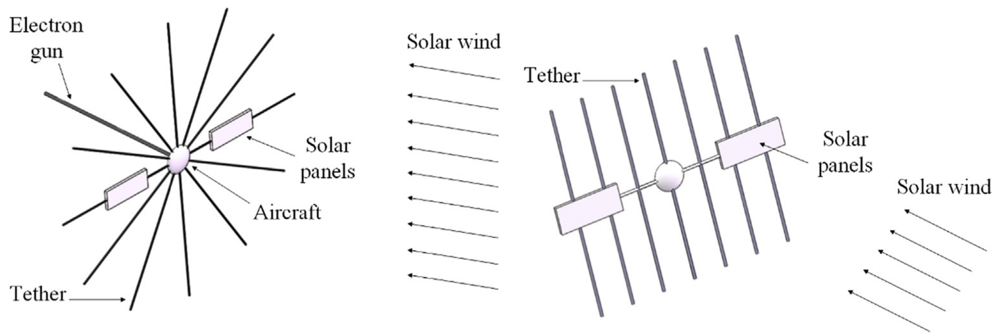

Fig. 1. Structure of E-sail thruster. (a) Cross structure; (b) parallel structure.

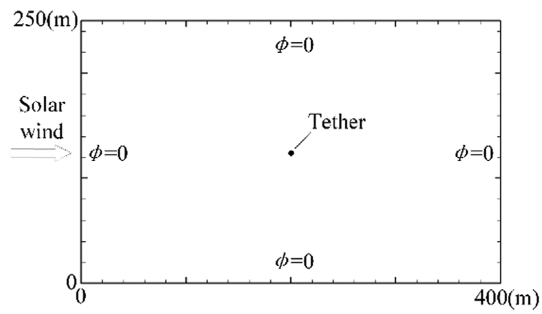

Fig. 2. Calculation region.

Table 1
Calculation parameters.

Calculation parameters	Value
Number of tethers	1–2
Number of grids	161 × 101
Space step	2.5 m
Time step	162.5ns
Solar wind plasma density n_0	$7.3 \times 10^6 \mathrm{m}^{-3}$
Solar wind speed v_0	400 km/s
Ion temperature	8eV
Electron temperature	8eV

calculation region, the axial momentum will change obviously. The momentum transfer between the ion and the sail tether can be calculated by the ion momentum entering and leaving the calculation region in unit time. Thus we can obtain the thrust of electric sail thruster.

The solar wind plasma parameters are derived from reference [1], calculate its Debye length as:

$$\lambda_D = \left(\frac{\varepsilon_0 k T_e}{n_e e^2}\right)^{1/2} = 7.78m \tag{1}$$

Where k is boltzmann constant, T_e is solar wind plasma electron temperature which is 8eV, n_e is solar wind electron number density, $n_e = n_0 = 7.3 \times 10^6 m^{-3}$, e is the unit charge.

In order to ensure the accuracy, set the space step to $\Delta x = \Delta y = 2.5m$, which is about one third of Debye length. The setting of time step Δt satisfies both the CFL condition and the limitation of plasma frequency, as:

$$v_{\max} \cdot \Delta t < \Delta x \tag{2}$$

$$\Delta t < \omega_p = \left(\frac{n_e e^2}{\varepsilon_0 m_e}\right)^{1/2} \tag{3}$$

where $v_{\max}$ is the maximum velocity of the simulated particle, which can be considered as $v_{\max} = v_0 = 400km/s$, ω_p is the frequency of solar wind plasma. Integrating the CFL condition and the limitation of plasma frequency, we set the $\Delta t = 162.5ns$".

The parameters of the grid and the solar wind plasma parameters used in the calculation are shown in Table 1.

2.2. PIC method and calculation process

We use the full-particle PIC method in the simulation. PIC method is a common numerical method for the simulation of low-temperature plasma. It is a coupled method of solving particle motion and self-consistent electric field [9–12].

In PIC model, the ion motion follows Newton - Lorentz law, the equation of motion is as follows:

$$M\frac{d\vec{v}}{dt} = q(\vec{E} + \vec{v} \times \vec{B}) \tag{4}$$

$$\frac{d\vec{x}}{dt} = \vec{v} \tag{5}$$

where M is the particle mass, q is the particle charge, $\vec{v}$ and $\vec{x}$ are the speed and the position vector of the particle respectively, $\vec{E}$ and $\vec{B}$ are the electric field and the magnetic field strength at the particle location respectively.

The magnetic field in the solar wind is ignored since it is very small. The electric potential and electric field can be solved by the Poisson equation:

$$\nabla^2\phi = -\frac{e}{\varepsilon_0}(n_i - n_e) \tag{6}$$

$$\vec{E} = -\nabla\phi \tag{7}$$

where ε_0 is the vacuum dielectric constant, the poisson equation is solved by the successive overrelaxation method.

The specific calculation process is shown in Fig. 3. In the figure, the subscript$i$, $j$denote the particle and grid numbers, respectively, T is the particle temperature (in this paper $T = T_e = T_{ion}$), $\vec{F}$ s the force of the particle.

3. Results and discussion

3.1. Self-consistent potential and plasma parameters

3.1.1. Simulation of the number of particles

The solar wind plasma is distributed throughout the calculation region and the tether bias voltage is set to 1 kV as the initial condition. Attracted by the positive bias voltage of the tether, the electrons have a tendency to move toward the tether, and the ions leave far from the tether. Thus the number of ions decreases and the number of electrons increases at the initial stage, as shown in Fig. 4. With the development of solar wind motion and plasma self-consistent electric field, the number of ions and the number of electrons tend to be stable after 10000 time steps (t = 1.625 ms), and the number of electrons is slightly