Monte Carlo Simulation of Gas Flows in SPT-ATON

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Abstract: There is a buffer volume, which ensures the working material into the channel. The direct simulation monte carlo method is adopted to simulate gas in buffer of Stationary plasma thruster, the distribution of gas along the channel's radial direction is changed with the different size of the buff's structure, and there exits an optimization size which can make the destiny of the gas along the radial most uniformly. The paper also proposes the method of choose the buffer size in order to achieve uniform gas, the buffer designed by this method agrees well with that of ATON. The average density of gas coming into the accelerating channel is approximately proportioning to the mass flux: the velocity of gas changes little with the change of mass flux.

Nomenclature

Φ_T	=	the thermalized potential
Φ	=	the electric potential
n_{eo}	=	constant
n_e	=	electron number density
w	=	the width of buffer
i	=	the number of cells at the exit
L	=	the length of buffer
σ	=	the coefficient of gas ununiformity
$\dot{m}$,qm	=	the mass flux of gas
h	=	the position of the ejecting hole
A	=	the channel area
b	=	the width of buffer
m	=	the mass of gas molecule

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I. Introduction

Stationary plasma thruster is one of the most eminent electric thrusters. Compared with other electric thrusters, its structure is simple, and the efficiency is high. SPT can work stably with a long life time, and simple electrical source. Since its specific impulse is at the little satellite's span, it is suitable for controlling the orbit and adjusting the pose for little aircraft.

SPT is base on the unite work of electric field and magnetic field. The electrons controlled by the magnetic field collide with the propellant (xenon) to ionize the gas. Then the ions are accelerated by the electric field and ejected out to generate thrust. So the SPT demands electric equip potential lines toward the anode in the accelerating channel, which can ensure the ions are focused to the middle of the channel and avoid the collision of the ion with the channel wall.

Assume the energy distribution of electron is maxwell. We have [1,2]

$$\Phi_T = \Phi - \frac{kT_0}{e} \ln \frac{n_e}{n_{e0}} \qquad (1)$$

In this equation, Φ_T is the thermalized potential. It is constant along the magnetic line; Φ is the electric potential; n_{e0} is a constant. If the distribution of electron density is uniform, the last item tends to be zero, then the electric equip potential line is coincide with the magnetic line (thermalized potential line). We can draw a conclude that there are two important points to insure ion focusing and improve the performance of SPT[1].

1. Designing a proper magnetic field with convex lines toward the anode.
2. Generating uniform flow of ions.

In order to generate uniform ion flow, firstly we must ensure the uniform flow of the propellant coming into the ionization area. In ATON-SPT, there is a buffer (figure1) which can ensure the uniformity of the gas come into the acceleration channel, then the performance of the thruster will be improved.

Shown in Figure 1 is the structure of buffer, the propellant from gas tank comes into the gas distribution through the control valve and gas supply pipe. Then it ejects into the buffer through a number of holes in the gas distribution. After uniformed in the buffer, the gas comes into the working channel. The gas distribution and a large number of ejecting holes along the azimuthal direction make sure the propellant uniformly come into the accelerating channel along the circle.

In order to evaluate the uniformity of the gas, we define the coefficient of gas ununiformity σ, it equals to the ratio of the difference of the max value and min

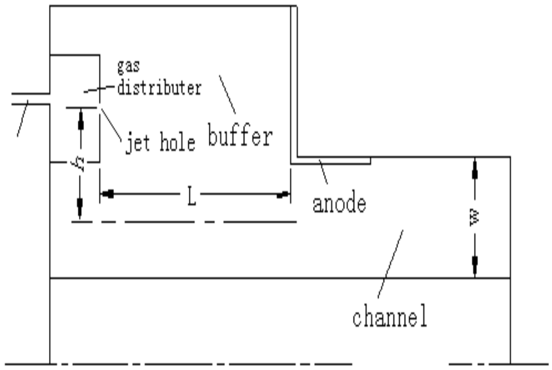


Figure 1. The structure of buffer

value of the density to the mean density. It is a guideline to evaluate the gas uniformity.

$$\sigma = \frac{n_{\max} - n_{\min}}{n} \qquad (2)$$

The mean value of the particle density at exit is

$$n = \frac{\int_0^w n dw}{w} = \frac{\sum_i n_i w_i}{w} \qquad (3)$$

where： w is the channel width; i is the number of cells at the outlet along the radial.

With optional buffer structure, we can get the most uniform density when the gas come into the channel, the structure we design based on the principle of min σ agrees well with that of ATON.

Very little of xenon is ionized in the buffer[3], the effect of magnetic field is little, so we can calculate the distribution on the assumption of no magnetic filed and optimize the structure.

The density of gas in the buffer is very small, kundsen number is about 0.1～1.2, then the flow belongs to transition flow[3], so we use the direct simulation monte carlo method（DSMC）to calculate the gas flow in the buffer.

II. The simulation of gas flows with the DSMC in the buffer

DSMC is a microcosmic method, which is based on the mechanism of molecule movement, Finite simulation molecules are used to simulate large number of the real molecules. After following the track of simulated molecules and recording the state of them, we do some statistics, then we can get the macroscopic parameters.

Using DSMC method, the size of cell is about one third of the mean free path, it is required there should be about 10～20 simulated molecules in every cell. One simulated molecule represents lots of real molecules. The larger number of the simulated molecules is large the computing time is longer. However, if the number is too small, the stability of calculation will be bad and exits large errors because of the molecule fluctuation. In order to insure the suitable number of molecules in cell, we can use the method of calculating subarea, drawing the grids, and calculating the weight of the simulated molecules in subarea to solve this problem. The buffer and anode section of Stationary plasma thruster can be divided into ten rectangle section, as shown in Figure 2.The forth section is the inlet section of xenon with smaller size, the grid is smaller too. We can choose littler weight of the simulated molecules to make every cell have suitable number of molecules.

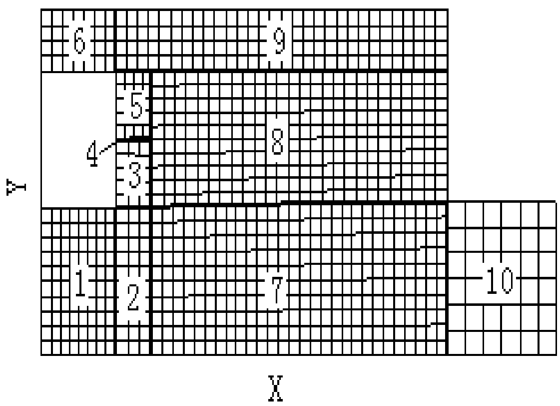


Figure 2. The section and cells in calculation.

The collision model of xenon molecules with the buffer wall is diffuse refection model. The temperature is fully accommodated, the model of molecule is VHS model。

The mass rate is 1.5 mg/s, the velocity isolines in x direction of A4 thruster's buffer are shown in Figure 3. The isolines of number density n are shown in Figure 4. The uniformity of providing gas is very important in ionization zone, so the outlet of the calculating zone can be approximately thought as the inlet of the ionization zone. Gas is ionized and ejected out when they reach the ionization zone, so the outlet is defined as vacuum, which is in accord with the fact. The gas near the outlet has a process of acceleration.

Figure 5 shows the radial distribution of the gas in ionization area with buffer and without it. Curve 1 is the situation without buffer. Because the ejecting holes are in the middle of the channel, density is large in the

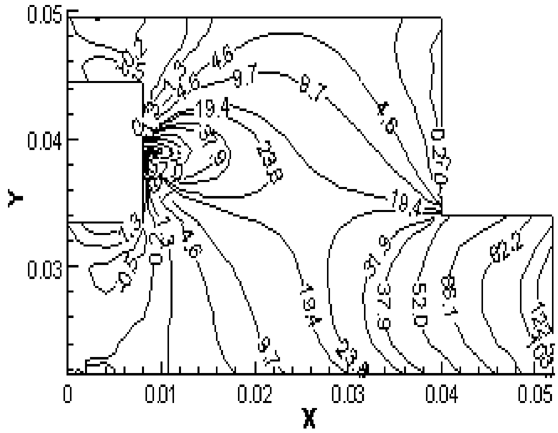


Figure 3. The isolines of velocity in x.

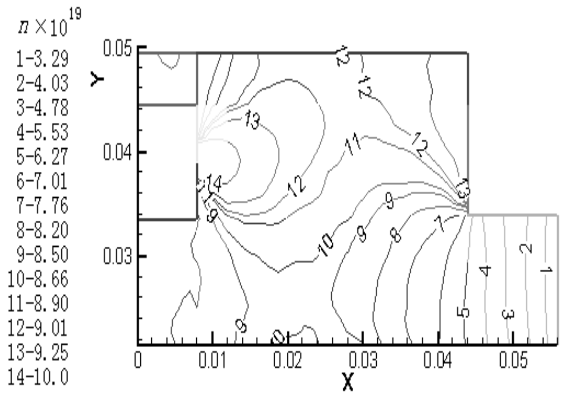


Figure 4. The isolines of number density n.

middle of the channel. And the density in inner and outer wall is a little larger because of the reflection near the wall. The density distribution is a "W" shape along the radial and σ is large with this structure. Curve 2 is the situation with a buffer, we can see the effect of buffer on uniformizing the gas.

III. The optimization of buffer

When the buffer size is changed, density uniformity is also changed, the uniformity of propellant's distribution have an optimum value if we design buffer reasonably. The size of buffer include length L, position and width of the eject hole and width of the channel W（figure1）.By iteration and optimization, we can get the buffer size when the σ is least.

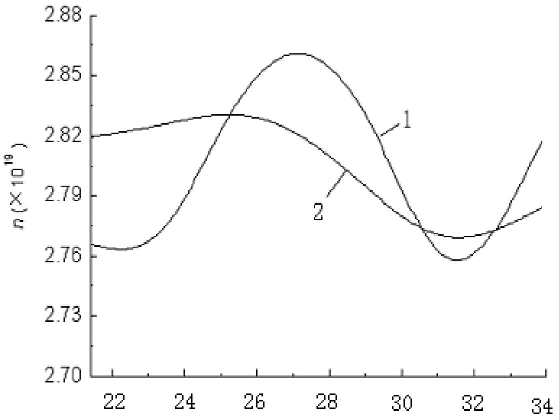


Figure 5. The radial distribution of the gas in ionization area with buffer and without it.

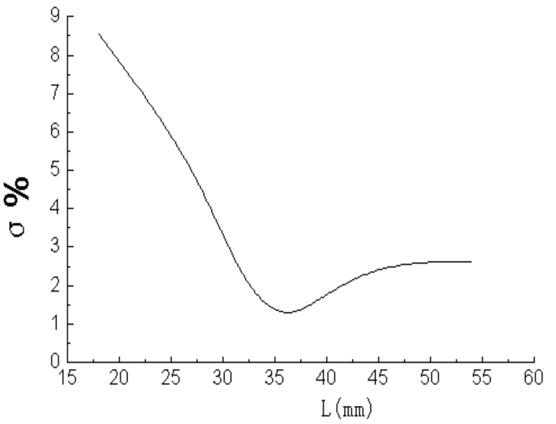


Figure 6. The relation of σ and the length of buffer L.

A. The length of buffer

Figure 6 shows the rule of σ changed with the buffer length. We can see that the length of buffer has an optimum value, at this value, σ is at least. The structure we calculated agrees well with that of A40 thruster of Russia.

When the length of buffer is less, the ejecting holes are near to the wall. After the gas is reflected from the wall, direction of the gas changes largely. For this reason, the radial velocity near the anode outlet changes largely and the density near the anode outlet is asymmetry. The less of the buffer length, the more of gas ununiformity along the radial (figure 7, curve 1).

When the buffer is longer, the gas nearly direct ejects into the entrance of the channel, the distribution of atom along radius is similar with that of having no buffer,(figure 7 curve 5), the coefficient σ is larger, but σ is smaller compared with no buffer because of the effect of buffer.

The size of different power stationary plasma thruster can be denoted by the width of channel. With different width there is a optimum size of buffer making σ least, as shown in figure 8. In the range, the length of buffer is in proportion to the width of channel.

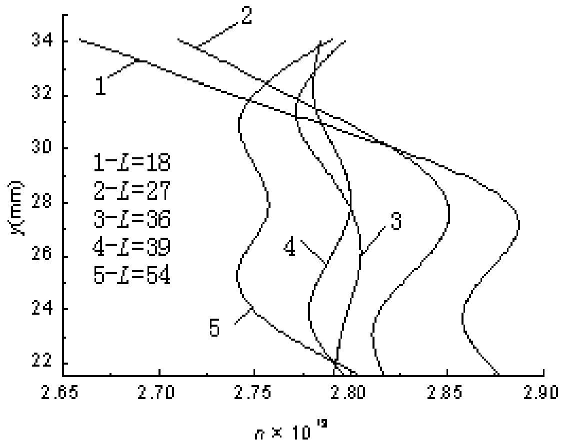


Figure 7. The radial distribution of density.

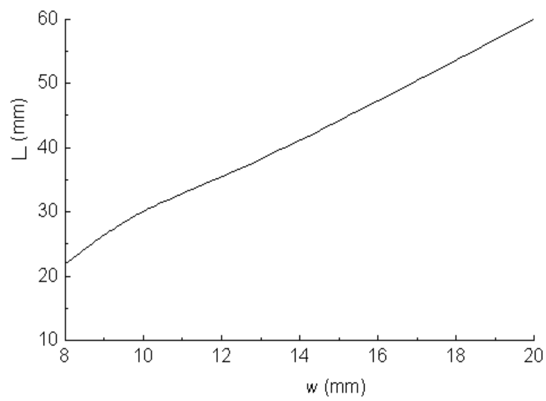


Figure 8. The relation of L and W.

When the mass flux is given, for every ejecting hole, the product of number density and speed are constant, for different ejecting gas density, the particle number density is nearly fixed, in other words, if the mass flux is fixed, we can't change the particle number density by the method changing the eject density. Because the velocity of gas at the outlet of anode is invariability, the particle density of number is in proportion to the mass flux, as is show in figure 9.

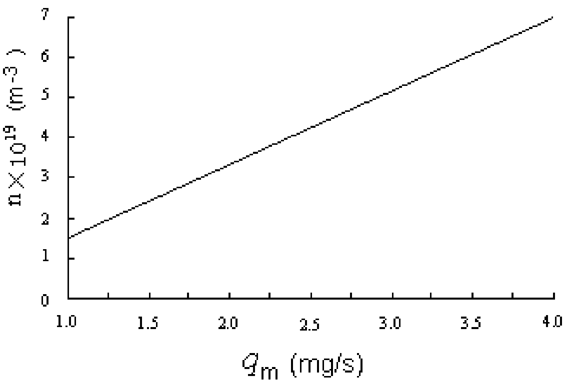


Figure 9. The relation of number density and mass flux.

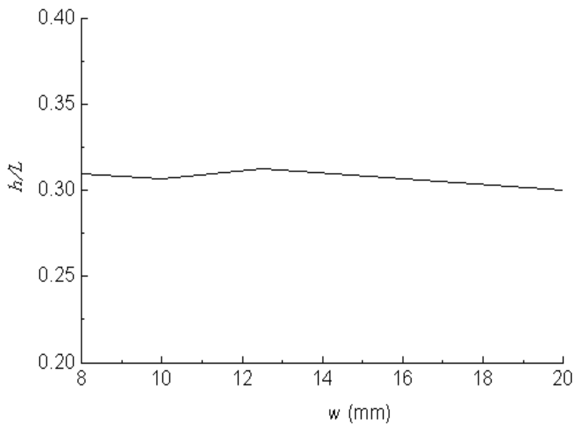


Figure 11. Optimal h/L changes with *w*.

B. The position of ejecting hole

When the position of the ejecting holes change in the radial direction, σ will change with it, and there exits a optimized value, as shown in figure 10, the x-axis is the distance between the center of ejecting hole and the center of accelerating channel. The interpretation why there exits optimum value of h is

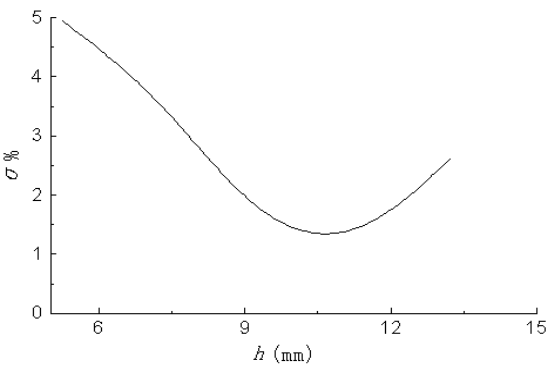


Figure 10. σ changes with the position of hole.

coherent with that why there exits optimum value of L.

When the width of the channel is changed, there is a optimized buffer length and position of the ejecting holes making σ least, the ratio of "h" to "L" is in proportion to the width of channel as shown in figure 11.

C. The width of buffer

When the width of buffer changes, σ will change with it and has a least value, as shown in figure 12.

The rate of optimization buffer width to length changes with the channel width changes little with the width of buffer, the curve is close to a line, as shown in figure 13.

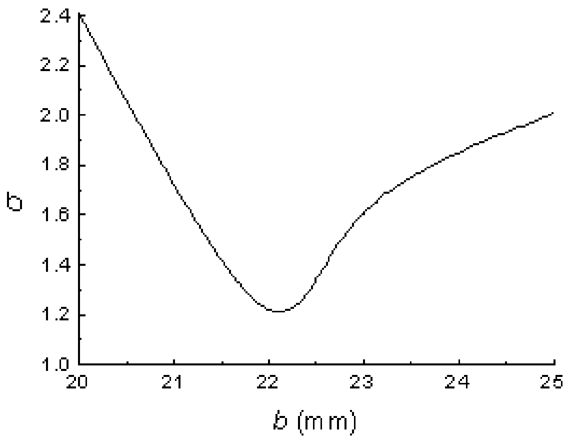


Figure 12. σ changes with b.

IV. The radial distribution of atom coming into the channel

The radial distribution of gas density and velocity in the channel affect the performance of thruster. When we calculate the characteristic of SPT, we also need the density and velocity of gas.

Figure 14 and15 show the radial distribution of the gas density and the axis velocity at different mass flux of A40, We can find the radial distribution and value of axial velocity is invariable, the average is 125m/s, so the number density is approximately in proportion with mass flux.

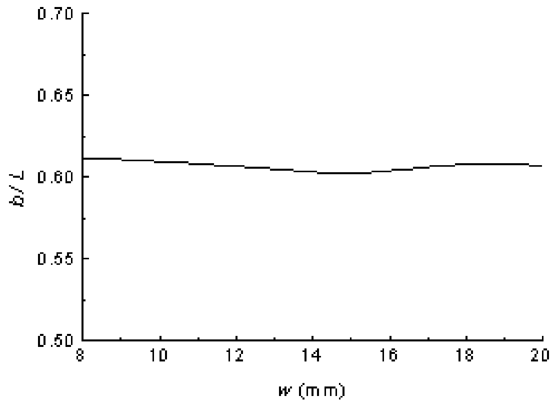
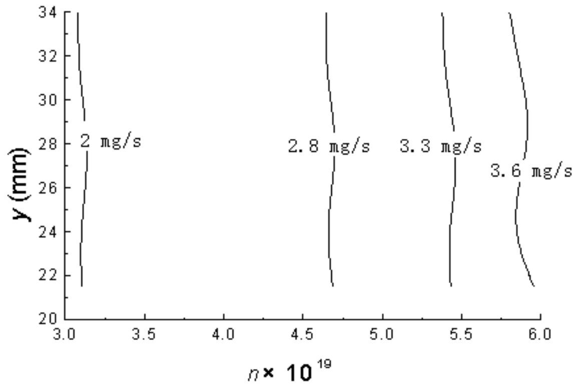


Figure 13. Optimal b/L changes with w.



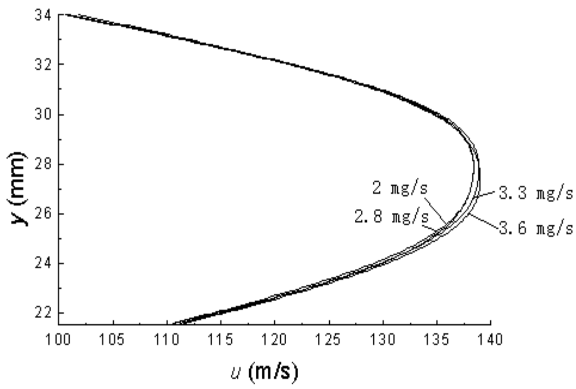


Figure 15. The radial distribution of axial velocity.

V. Conclusion

（1）For stationary plasma thruster the structure of buffer can make the gas uniform in the accelerating channel efficiently and the efficiency of thruster will increase largely. The uniform of gas along the radial have something to do with the size of buffer and there is a optimization size making the most ununiformity.

（2）The optimal length of buffer is approximately in proportion to the width of channel. We can take L=(2.5～3)w;

（3）According to the calculation, b/L=0.60～0.62 and h/L=0.3～0.32 can be a good choice when we design a new thruster.

（4）The gas density in the anode section is in proportion to mass flux approximately. It is not affected by the eject velocity and eject density with the same mass flux.

（5）According to the results of the simulation, the velocity of the gas in accelerating area is about 120～130 m/s, the velocity is irrelative with mass flux $\dot{m}$ and the structure of the buffer. Then we can get the density of gas in the accelerating channel is

$$n = \frac{\dot{m}}{(120 \sim 130)mA} \qquad (4)$$

VI. References

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