

Study on ionization characteristics of low power hall thruster with variable cross-section channel*

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Abstract: Hall thruster with variable cross section channel is designed to meet the growing demands of low power Hall thrusters. Results obtained with krypton as propellant show this specific design expands the low power limit and improves the propellant utilization. The axial distribution of electron energy and the ionization profile were obtained by emission spectroscopy measurements in the discharge channel. Experiments indicate that the variable cross-section channel has a great impact on the distribution of electron energy. Besides, the use of a variable cross-section channel allows to control the axial distribution of the ionization.

Nomenclature

A	= Channel cross-section area;
$\dot{m}_a$	= Mass flow rate;
n_a	= Atom density;
n_e	= Electron density;
t	= Time;
V_a	= Atom velocity;
V_k	= Cathode potential;
V_i	= Ion velocity;
Z	= Axial position;
β	= Ionization rate;

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I Introduction

HALL thruster is a promising propulsion device for small satellites because of its high efficiency, specific impulse and reliability^[1]. With Deep space exploration and small satellites network and other space missions demanding, there is presently a great interest in low power hall thrusters.

The low operating power of hall thrusters can be achieved by lowering the propellant mass flow rate^[2-6], which leads to a low propellant utilization. One way to solve such problem is to extend the channel length^[5,6]. However, ion recombination losses increase in a longer channel, which, to some extent, impairs the benefits of larger propellant utilization, resulting in a limited application. Another approach, suggested elsewhere^[7], is to reduce the channel width with ceramic spacers. The obtained results demonstrated higher propellant utilization and hence better total performance using such modified channel profile. Nevertheless, there is no further research on what is happening to the ionization process in such variable cross section channel. Miniaturized hall thrusters^[8,9] are also created to achieve low power, such as BHT-200^[10] developed in BUSEK, cylindrical hall thruster (CHT)^[4,11] proposed by Raites and Fisch at Princeton Plasma Physics laboratory, etc. One of the major challenges of such small hall thrusters is space problem which prominently determines the arrangement of excitation coils, limiting the optimal design of the magnetic field which has a decisive impact on hall thruster physical processes. THT series of low power hall thrusters are created in Japan to examine stable operational conditions with variable channel length, magnetic field shape and strength^[12,13].

When the propellant mass flow rate is reduced, the weak propellant utilization is a major challenge deterring low power hall thrusters from booming. Since the decreased propellant utilization lies in the poor ionization of the propellant mass, in the paper we design one kind of variable cross-section hall thruster from the perspective of improving the ionization. Physical parameters about ionization in the discharge channel are measured to analyze the impact of variable cross-section channel on ionization process.

This paper is organized as followed. In section II, the physics of variable cross section channel and simulation results are presented. Section III describes the experimental setup and measurements of parameters. Experimental results and simple analysis are presented in section IV. Section V is a discussion about the ionization and electron energy in the variable cross-section channel. Conclusion is given in section VI.

II Methods of changing cross section channels

Magnetic field is an important method of controlling the ionization in discharge channel. In effect, only charged particles such as ions or electrons can be affected by magnetic field. However, particles like atoms which are not charged are free from magnetic field. According to the steady continuity equation of the ionization process of the propellant mass^[14], as showed in Eq. (1).

$$\nabla \cdot (n_a V_a) = -\beta n_a n_e \quad (1)$$

Obviously, although the ionization of the propellant is subject to electron density and electron temperature, atom density is of great importance to the ionization process. If the distribution of the propellant in the discharge channel is reasonably allocated, the ionization process can to some extent be improved.

Numerical result presented in Fig.1 is based on DSMC simulations; Figure 1 show the atom density in the variable cross-section channel. A schematic of the variable cross-section channel can be found in Figure 2. The atom density in variable cross-section channel is higher than that in the constant cross-section channel. The negative gradient of the atom density along the axial of the discharge channel is increased by such variable cross-section channel.

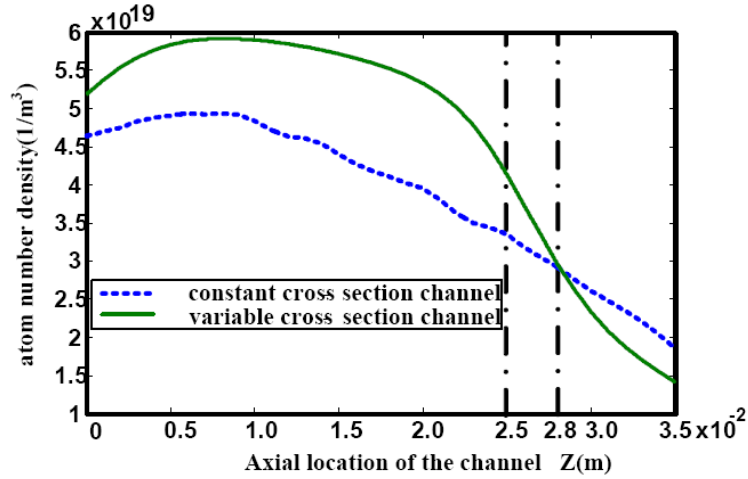


FIG 1: Distribution of atom density along the centerline in constant and variable cross-section channel. The dotted line indicates the edge of variable cross section.

Hall thrusters with variable cross section channel control the distribution of the atom density. The atom density will be increased, specifically when the cross section is reduced, increasing collision events between atoms and electrons, as a result of which, the ionization is improved.

III Experimental setup and measurement of the parameters

A Vacuum system and Hall thruster

All of the experiments were carried out in the Plasma Propulsion Laboratory of Harbin Institute of Technology (HPPL). The apparatus includes a stainless-steel vacuum chamber with a diameter of 1.5m and a length of 4m. The chamber is equipped with two diffusion pumps, one rotary pump and three mechanical boosting pumps, maintaining the operation pressure 2.7×10^{-3} Pa. More detailed introduction of the laboratory can be found in Ref.15.

The P-70 hall thruster with a nominal operation at a discharge voltage of 400V, an anode krypton mass flow rate of 3.0mg/s, and a cathode krypton mass flow rate of 0.3mg/s, was used and placed on one side of the chamber. The highly purified krypton with a purity of 99.9996% was supplied through the mass flow controllers. The outer insulator of the thruster has an inner diameter 71mm and a gap of 14mm wide. In experiments, the outer and inner insulators made of boron nitride ceramic were

designed following Figure 2.

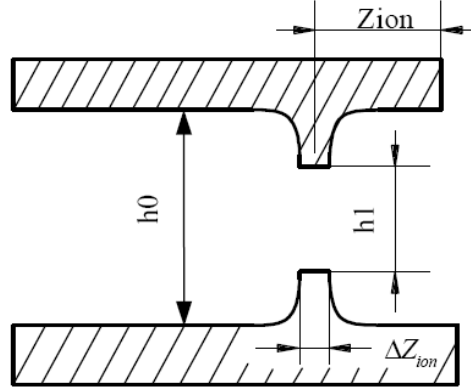


FIG 2: The design of variable cross-section channel,

$$Z_{ion} = 7.5\text{mm}; \Delta Z_{ion} = 3\text{mm}; h_1 / h_0 = 0.6.$$

B The propellant utilization

The radial distribution of ion current, the measurement process of which is given in Ref.16, is used in the calculation of propellant utilization. During the measurement process, the probe is driven to move along the radial direction. As the probe collection surface is close to the thruster exit, to minimize the influence of the probe halting in the plume to the thruster operation, we fix the probe on a high-speed, reciprocating system. The system is driven by a linear motor. Its free path is 360 mm and its highest velocity can reach 1 m/s. By using an optic grating scale built into the magnetic track to provide position feedback, its positioning resolution is 5 μm . One radial distribution of ion current density is recorded during one-time reciprocation of the high-speed system, controlled by an on off signal. In order to obtain the uncertainty level of the measured results, we drive the high-speed system eight times and record the corresponding probe signals for each chosen magnetic field topology. The discharge current and cathode potential are also recorded to justify the perturbation of the probe swept in the near-field plume. A typical example is given out in Fig. 3. In this figure, I_d is the discharge current and V_k is the cathode potential. One can find that the perturbations to the discharge current are below 14% for these reported data.

Moreover, the swept example of the ion current density profile is also given in Fig. 3, with being postprocessed by a spline smoothing. One can see that the annular geometry of the thruster channel is revealed. By integrating this profile, we obtain the axial ion current.

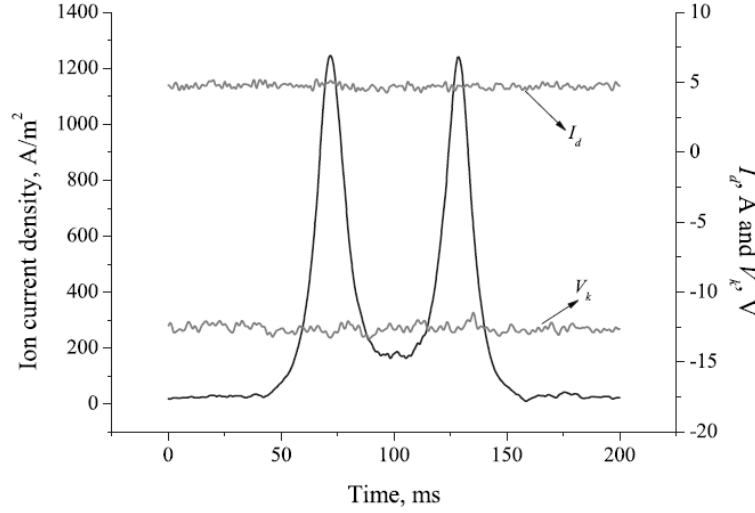


FIG 3: Single probe sweep example

C Measurement of the axial distribution of the propellant ionization in the discharge channel

Bugrova A.I. first calculated the distribution of ionization with Corona model in hall thruster discharge channel under steady state conditions. This paper uses the Kr atomic line 758.74nm and 811.29nm transitions to obtain the axial distribution of the ionization and the electron temperature along the channel. Ref.17 gives the excitation cross section of $4s^2 4p^5(^0P^o_{1/2})5p$ and $4s^2 4p^5(^3P^o_{3/2})5p$, with an error of $\pm 30\%$, Ref.18 gives the ionization cross section of one charged Kr, with an error of $\pm 6\%$. Bugrova linear results^[19] could be used to deal with the share of low energy electrons which was utilized to excite and ionize the atoms in the discharge channel of hall thrusters.

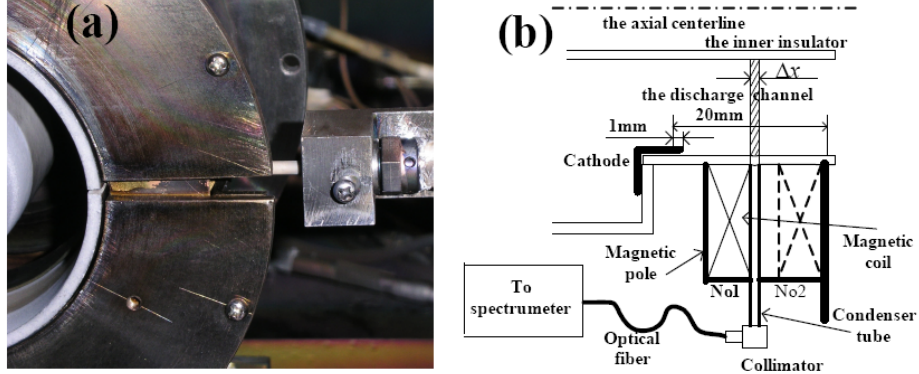


FIG 4: (a) The axial slit in P-70 and (b) schematic diagram of spectral measurement.

AvaSpec621 with a measurable wavelength 200nm~1100nm and a resolution of 0.06nm is used in experiments to record the strength of the Kr characteristic lines. To acquire the light signal inside the channel, a 1.5mm wide slit was made in the outer insulator, as shown in Fig.4a. It can be observed from Figure 4(b) that the current spectral measurement system can only collect total spectral signals from the infinitesimal volume which covers the axial distance Δx . The electron energy obtained by two-line has an error of $\pm 10\%$, the distribution of the krypton ionization calibrated with the propellant utilization has an error of $\pm 5\%$.

IV Experiment results and Analysis

A Power of the hall thruster with variable cross section

It can be seen in Fig.5, when $\dot{m}_a=2.0$ mg/s, the discharge current the variable cross section channel is close to that of the constant cross-section channel at the discharge voltage 350V, 400V, 450V, and 500V. That is to say, variable cross section channel has little effect on the discharge current .

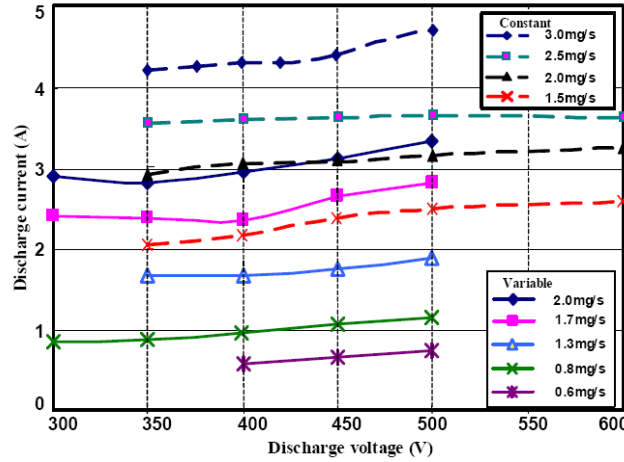


FIG 5: The discharge current versus the discharge voltage at different anode mass flow rate obtained with two different channels. Constant- represents the constant cross section channel; variable- represents the variable cross section channel.

The hall thruster with variable cross-section channel has the minimum anode mass flow rate $\dot{m}_a=0.6$ mg/s, while the constant cross-section hall thruster has $\dot{m}_a=1.5$ mg/s. the reduced mass flow rate produces a lower power. The minimum power of variable cross-section hall thruster is about 240W, the constant cross-section hall thruster has the lowest power of about 700W. Meanwhile, the maximum power of variable cross-section hall thruster is lower than that of constant cross-section hall thruster, about 1600W and 2400W respectively. To sum up, the effect of the variable cross section channel is to move the power range of hall thrusters to the lower side. When the anode propellant mass flow rate is reduced, hall thrusters could improve the density of the propellant in such variable cross-section discharge channel to an extent which is enough to maintain the stable discharge progress. Besides, when the anode propellant mass flow rate is increased, variable cross section hall thruster is easily overheated because of larger surface-to-volume ratio. Eventually, hall thrusters with variable cross section channel are suited to low power.

B Propellant utility of variable cross section hall thruster

As showed in Fig.6, when the anode mass flow rate is 1.7mg/s, the propellant utility of variable cross section is higher than that of constant cross section at the same discharge channel. And according to the trend at the same discharge voltage, the propellant of variable cross section is also higher than that of constant variable section

between the anode mass flow rates 1.2mg/s and 1.7mg/s. While when the anode mass flow rate is below 1.2mg/s, the propellant utility can be higher than 50%. Obviously, the variable cross section can improve the propellant utility, especially at low mass flow rates. When the cross section is reduced, we believe that not only the atomic density increases, but also the electron density is also increased. As a result, the ionization probability increases along with the increased rate of ionizing collisions.

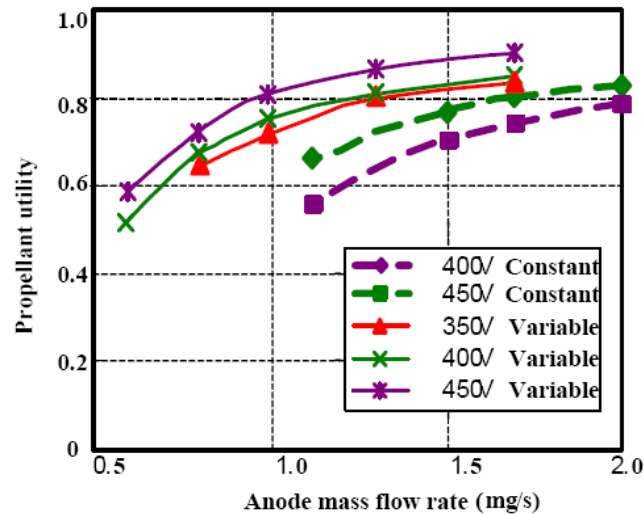


FIG 6: The propellant utilization versus the anode mass flow rate at different discharge voltage.

C The distribution of ionization with variable cross section channel

It can be seen in Fig.7 that, with the variable cross section channel, the peak position of the electron temperature almost maintains at the downstream edge of the variable cross section part, when the mass flow rate is 0.6mg/s, 1.5mg/s, 2.0mg/s at the discharge voltage 400V. Additionally, the distribution of electron energy along the axis at the variable cross section part has a larger slope than that at the same location in the constant cross section channel. Furthermore, when the mass flow rate is 1.5mg/s, 2.0mg/s for both the variable and constant channel, the maximum value of electron energy for the variable channel is larger than that for the constant channel.

About the ionization, at the discharge voltage 400V, the peak position of the distribution of the ionization at the variable cross section channel almost stays at the same location, when the mass flow rate is 0.6mg/s, 1.5mg/s, 2.0mg/s, and the distribution line becomes thinner in comparison with the case at the constant cross section channel. While the peak position in the constant cross section channel moves downstream with decrease of the mass flow rate, namely 2.5mg/s, 2.0mg/s, 1.5mg/s. Additionally, at the same mass flow rate 1.5mg/s, 2.0mg/s, the maximum value of ionization for the variable channel is larger than that for the constant channel.

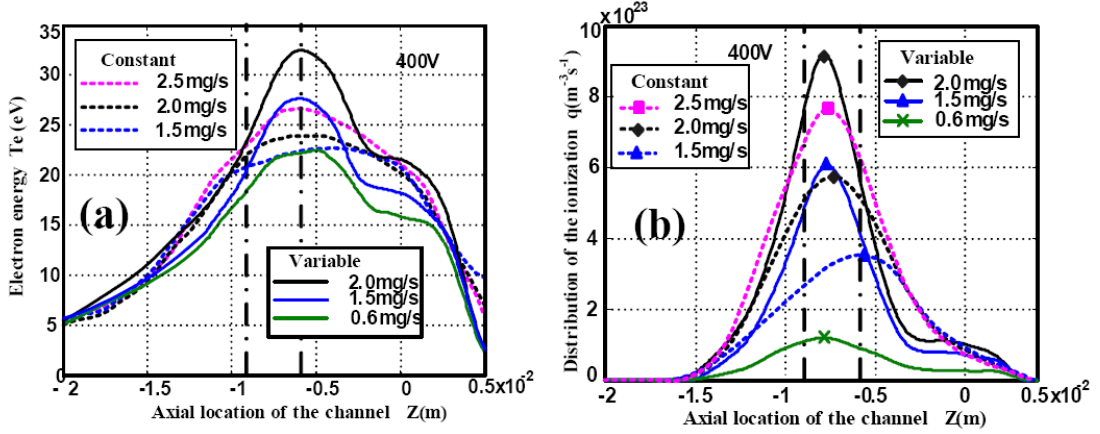


FIG 7: Distribution of (a) electron temperature and (b) the ionization along the axial location of the channel at the discharge voltage 400V. The dotted line indicates the edge of the variable cross section channel as showed in Fig. 2.

V Discussions

A The distribution of electron energy

Electric field is the dominant electron gain source, while electron-neutral collision and electron-wall collision are the main electron loss source. Electron-neutral collision can be measured by the intensity of ionization, while surface-to-volume ratio has great deal with electron-wall collision. Electric field is set up by the electron conductivity, which means higher electron conductivity makes low electric field.

For the variable cross section part, the surface-to-volume rate increases abruptly, causing the electron energy loss due to electron-neutral collision to increase abruptly. Meanwhile, the higher ionization in the channel brings about two facts. On one hand the electron energy loss due to electron-neutral collision increases, on the other hand the electron conductivity increases, leading to small electric field. As a result of all, the electron energy gain increases marginally due to small electric field and the electron energy loss increases abruptly due to two loss factors from the edge of the variable part. Sequentially, the peak position of the electron temperature maintains almost at the downstream edge of the variable part. When the mass flow rate is different, the fact that the peak positions almost stay at the same location might give us a hint that during the two electron energy loss factors, the electron-wall collision might play the dominant role.

B The distribution of ionization

Given the variable cross-section channel, the ion continuity equation and continuity equation for atoms in Ref. 14 can be modified, as showed in Eq. (2) and (3)

$$A(z) \frac{\partial n_i}{\partial t} + \frac{\partial A(z) n_i V_i}{\partial z} = A(z) \beta n_i n_a \quad (2)$$

$$A(z) \frac{\partial n_a}{\partial t} + V_a \frac{\partial A(z) n_a}{\partial z} = -A(z) \beta n_i n_a \quad (3)$$

According to the steady distribution of ionization, the distribution of gas atom, ion

current, and electron current along the axial location can be obtained, as showed in Fig.8

Here, we will give a qualitative explanation about the distribution of ionization. From the continuity equation for atoms, the steady distribution of ionization along the axial location can be expressed as minus gradient of gas distribution along the axial location if the velocity of atom is constant. So, the peak position of ionization in the discharge channel is the peak position of minus gradient of gas distribution.

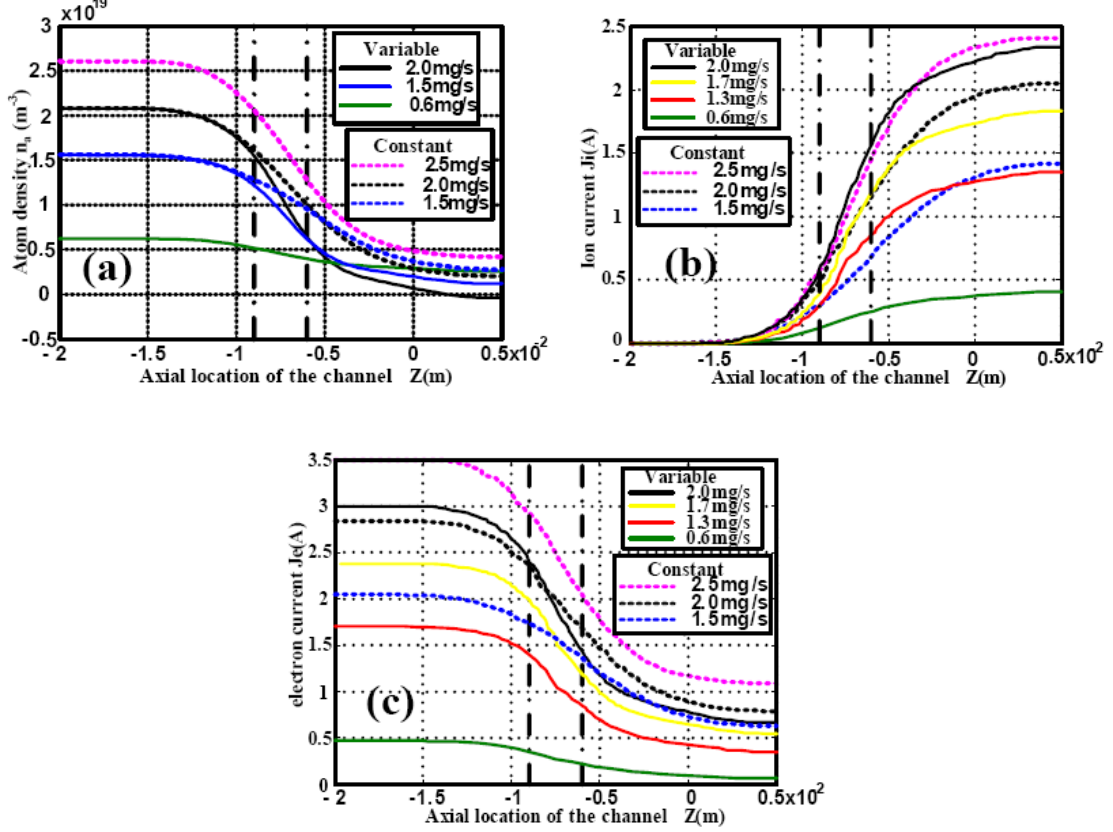


FIG 8: Distribution of (a) atom density, (b) ion current, and (c) electron current along the axial location of the channel at the discharge voltage 400V. The dotted line indicates the edge of the variable cross section channel as showed in Fig. 2.

In the variable cross-section channel, the variable part not only promotes the density of atom there, but also promotes the negative gradient of gas distribution, which can be seen from the DSMC simulation and the atom density in Fig. 8. As a result, at the same mass flow rate 1.5mg/s, 2.0mg/s, the ionization in the variable cross-section channel is bigger than that in the constant cross-section channel.

Since the negative gradient is promoted, the distance from one atom density point to another atom density point in the ionization zone will be smaller. So, the ionization process occupies smaller axial distance. This might be the reason why the ionization distribution becomes thinner in the variable cross-section channel. Furthermore, when the mass flow rate is different, the peak position of minus gradient of gas distribution will vary little along the axial location because of the promoted minus gradient. This might be the reason why the peak position of distribution of ionization of different mass flow rate almost maintains at the same axial location.

As a conclusion, the variable cross-section has great impact on the electron energy and can control the distribution of ionization through changing the gas density and the gradient of gas distribution.

VI Conclusions

A new kind of low power hall thruster is designed by changing the profile of the discharge channel. The experimental results show that the hall thruster with variable cross section channel can operate at low power, along with the increase of the propellant utility. What is more, the variable cross-section channel has a great impact on the distribution of electron energy. Also, the peak position of the ionization maintained almost at the same location when the mass flow rate changed, which differs from the case at the constant cross section channel. This predicts the possibility of optimization of the axial distribution of ionization. A qualitative expression is proposed to explain the effect of variable cross-section channel on the electron energy and ionization. But more detailed physical process in variable cross-section channel needs much work about measuring the parameters in the discharge channel which depends on the improvement of the diagnostic methods.

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