Study on the influence of cathode operation parameters on the ignition voltage boundary of Hall thrusters

IEPC-2019-220

Presented at the 36th International Electric Propulsion Conference
University of Vienna • Vienna, Austria
September 15-20, 2019

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Abstract: The hollow cathode is a critical component of the discharge circuit in a Hall thruster. Different operation parameters (keeper current and mass flow rate) of the cathode will cause the electrons density and electron temperature emitted by the cathode differently, which will affect the ignition process of the Hall thruster. Thus, the ignition voltage boundaries for different operating parameters of the cathode were measured. In order to better understand how different operation parameters of cathode affect the ignition voltage boundary of Hall thruster, the plasma densities, electron temperatures, and plasma potentials under different operation parameters of cathode plume region were measured by a Langmuir probe at axial and radial directions. The results showed that both the increase of keeper current and the mass flow rate of cathode result in an increase in the electron density emitted by the cathode, while the electron temperature decreases; an increase in cathode mass flow rate results in a more pronounced effect than the keeper current. At the same time, it is found that when the mass flow rate and the keeper current of cathode increase simultaneously, the ignition voltage boundary of the Hall thruster will decrease significantly, which is mainly due to a significant increase in the electron density caused by the increase in mass flow rate and keeper current of the hollow cathode.

I. Introduction

Due to the moderate specific impulse, simple structure, and several other desirable characteristics, Hall thrusters are widely used in various space propulsion applications such as satellite station maintenance and orbital transfer[1-3]. As a critical component of the discharge circuit[4-6], the hollow cathode mainly provides high-energy

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electrons for neutralizing the ion plumes and ionizing the propellants, which have an important influence on the discharge process of the Hall thruster. Therefore, many researchers have investigated the influence of different cathode operation parameters on the steady-state discharge process and performance parameters of the Hall thruster. The influence of different heat power of hollow cathode on the performance parameters of a Hall thruster were investigated by Ning et al[7]. It was found that as the heat power of the cathode was gradually increased, the thrust increment increased first and then decreased. The effect of heat power change of a hot wire cathode on the performance of a cylindrical Hall thrusters (CHT) was investigated by Granstedt et al[8]. The results showed that as the electron emission from the cathode increases with wire heating, the divergence angle of the plume gradually reduced, however, the discharge current increased. The effect of different mass flow rates and positions of hollow cathode on the floating voltage of a laboratory BPT-4000 Hall thruster were investigated by Tilley et al[9]. The results showed that the floating voltage is a monotonic function of cathode mass flow rate. The effect of cathode mass flow rate on the cathode coupling voltage and anode efficiency of a 50 kW Hall thruster was studied by Manzella et al[10]. It was found that as the cathode mass flow rate increased, the cathode coupling voltage was observed decreased, which improved the anode efficiency. Goebel et al. studied the effects of changes in the cathode mass flow rate on the performance and cathode life of a 6 kW laboratory Hall thruster[11]. As the cathode flow fraction gradually increased, the thrust, anode efficiency and voltage utilization efficiency all gradually increased. The effect of the keeper current change of the cathode on the performance parameters of a CHT was studied by Raitses et al[12]. It was found that when the CHT was under the direct magnetic field configuration, as the keeper current gradually increased, the discharge current and propellant utilization gradually increased, and the plume divergence angle decreased dramatically. The ignition process is the first and most critical step in the safe operation of a Hall thruster[13-15]. Different cathode mass flow rates and keeper currents cause the electron density and electron temperature emitted by the cathode to differ significantly, which significantly affects the ignition process of the Hall thruster.

Since the ignition process of Hall thruster typically lasts for tens of microseconds, numerical simulation and high-speed time-resolved imaging technology were usually used to study this process. Taccogna et al. used a two-dimensional (2D) axisymmetric model to study the variation of plasma parameters at different times during the thruster ignition process[16]. The model was improved by Liu et al. and successfully reproduced the ignition pulse current, the relationship between ignition pulse current and discharge voltage and mass flow rate were also studied [17]. A high-speed charge coupled device (CCD) camera was used by Vial et al. to study the dynamic behavior of the plasma plume of a SPT-100 Hall thruster. It was found that the ion beam reveal oscillations in plasma light intensity was related to the breathing-mode instabilities[18]. A similar method was used by Ellison et al. to capture the front image of the plume during the ignition process of the Hall thruster. The results indicated that azimuthal asymmetry was introduced by the hollow cathode, which persisted for about 30 μs into the ignition process[19].

So far, the researches on different cathode operation parameters mainly focus on their influence on the steady-state performance parameters of the Hall thruster, such as the thrust, anode efficiency, and propellant utilization. However, different cathode operation parameters in the Hall thruster change the electrons density and electrons temperature emitted by the cathode into the discharge channel, which will significantly affect the ignition process of the Hall thruster. As far as we know, these related studies are still relatively lacking.

Therefore, in order to better understand how the different cathode mass flow rates and keeper currents affect the ignition process of the Hall thruster, the ignition voltage boundaries for different keeper currents and mass flow rates of the cathode were measured at a 1 kW Hall thruster. In order to analyze the changes in the plasma parameters when the cathode operated at different mass flow rates and keeper currents, more deeply, the plasma densities, electron temperatures, and plasma potentials under different operation parameters of the cathode plume region were measured by a Langmuir probe at axial and radial directions. The results showed that the changes in cathode mass flow and keeper current can significantly change the electron density and electron temperature emitted by the cathode.

II. Experiment apparatus and measurements

Our studies are carried out in a vacuum chamber with two diffusion pumps of 40000 L/s, one rotary pump, and three mechanical booster pumps, the diameter and length of the vacuum chamber are 1.5 m and 4 m, respectively. The Hall thruster used in the experiment is a 1 kW laboratory Hall thruster. The diameter of the inner insulator and outer insulator of our experimental thruster are 70 mm and 100 mm, respectively. The length of the acceleration channel is 50 mm. A self-heated hollow cathode was used to provide electrons and neutralize ejected ions. In order to facilitate the measurement of the plasma parameters in the radial and axial directions of the central plane of the cathode keeper pole, the cathode and discharge channel of thruster are arranged in parallel, and the center axis of the cathode orifice and the central axis of the thruster are parallel to each other.

And in order to analyze the changes in the plasma parameters when the cathode operated at different mass flow rates and keeper currents, more deeply, the plasma parameters under different operation parameters of the cathode plume region were measured by a Langmuir probe at axial and radial directions. The probe wires were made of 0.3 mm diameter tungsten wire, the tungsten wires are coated with alumina ceramic tubes with a diameter of 0.4 mm. In order to better measure the plasma parameters in the radial and axial directions of the central plane of the cathode keeper exit, the Langmuir probe was installed on a two-dimensional stepping motor turntable. The capacitor and resistor used in the measurement circuit of Langmuir single probe are 10 $k\Omega$ and 0.1 uF. The probe voltage and scanning voltage were measured with a Yokogawa DL850 ScopeCorder. A schematic diagram of the Hall thruster and cathode plasma parameter measurement circuit are shown in Fig. 1.

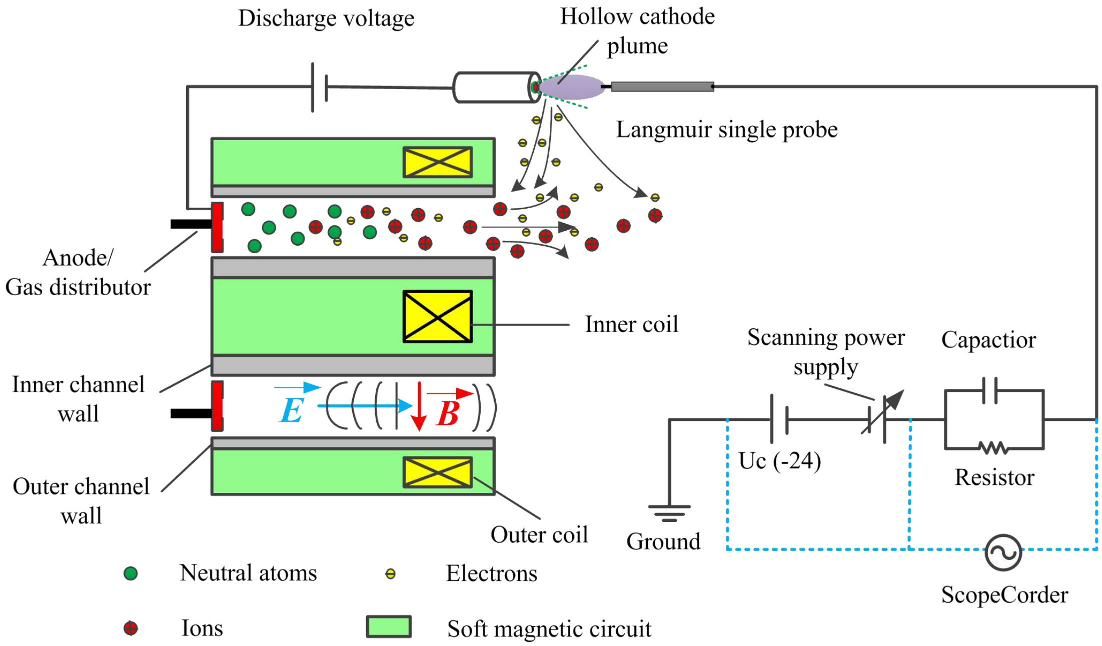


Figure 1. Schematic diagram of Hall thruster and cathode plasma parameter measurement platform.

III. Experimental results and discussion

During the experimental measurement of the ignition voltage boundary, the Hall thruster coil current is 2.0 A, the heating current of the cathode is 8.0 A, the anode mass flow rate is fixed as a certain value, and then the control variable method is used to change the cathode mass flow or keeper current. The discharge voltage of anode is continuously varied from 0 V to 1 V/s through a controllable power supply, and the maximum value is limited to 600 V. As the anode discharge voltage gradually increases, the Hall thruster will ignite successfully, and then the Labview control platform will record the discharge voltage at this time as the boundary of ignition voltage. Fig. 3 shows the boundary of ignition voltage when the cathode is operated at different keeper currents (1.5 A and 3.0 A) and at a fixed cathode mass flow rate (3.0 sccm and 6.0 sccm) . It can be seen in Fig.3 that when the mass flow rate of the cathode is constant (fixed at 3 sscm or 6 sccm, respectively), the ignition voltage boundary of the Hall thruster decreases as the cathode keeper current increases; and when the cathode mass flow rate is large (6 sccm), the effect of reducing the ignition voltage boundary of the Hall thruster will be more significant. Fig. 4 shows the boundary of ignition voltage when the cathode is operated at different mass flow rates (3.0 sccm and 6.0 sccm)and at a fixed cathode keeper currents (2.5 A and 3.0 A) . It can be seen in Fig.4 that when the keeper current of the cathode is constant (fixed at 2.5 A or 3.0 A), the ignition voltage boundary of the Hall thruster decreases obviously as the cathode mass flow rate increases. And it also can be seen in Fig. 3, when the other operating parameters during the ignition process of Hall thruster remain unchanged, when the mass flow rate of the cathode increases from 3 sccm to 6 sccm, and the keeper current of the cathode increases from 1.5 A to 3.0 A, the ignition voltage boundary of the Hall thruster is significantly reduced, and the maximum reduced voltage boundary is 72 V.

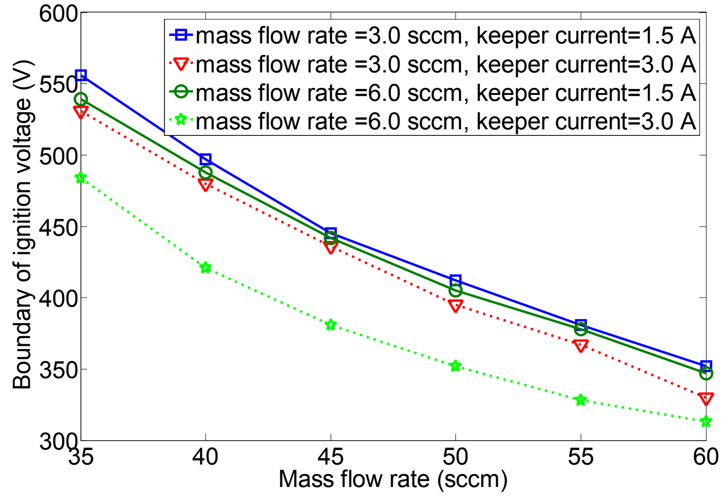


Figure 2. Ignition voltage boundary of Hall thruster with different cathode keeper currents under the same cathode mass flow rate (the cathode mass flow rate was fixed at 3 sccm and 6 sccm, respectively, and the cathode keeper current was changed to 1.5 A and 3.0 A, respectively).

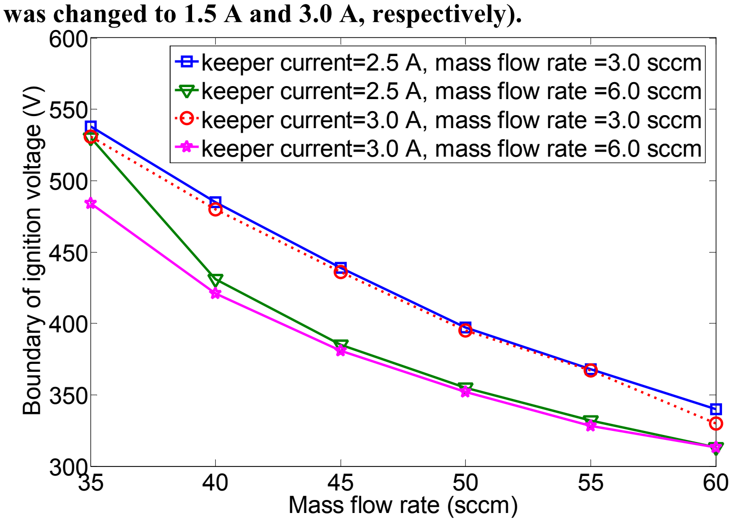


Figure 3. Ignition voltage boundary of Hall thruster with different cathode mass flow rate under the same keeper currents of the cathode (the cathode keeper current was fixed at 2.5 A and 3.0 A, respectively, and the cathode mass flow rate was changed to 3.0 sccm and 6.0 sccm, respectively).

According to the above experimental results of the ignition voltage boundary, as the keeper current and mass flow rate of the cathode increase, the ignition voltage boundary of the Hall thruster will be significantly reduced, and the effect of lowering the ignition voltage boundary when the mass flow rate of the cathode is increased is more significant. At the same time, the changes in the cathode keeper current and mass flow rate also cause changes in the plasma parameters of the cathode plume. Therefore, in order to better understand the changes in the plasma parameters when the cathode operate at different mass flow rates and keeper currents, more deeply, the plasma densities, electron temperatures, and plasma potentials under different operation parameters of cathode were measured by a Langmuir probe at axial direction (downstream of the keeper exit from 10 mm to 24 mm) and radial direction (relative to keeper center line from 0 mm to 10 mm and 0 mm to -10 mm, respectively).

The electron density contours for different keeper currents and mass flow rates of the cathode is shown in Fig. 4. It can be seen from Fig. 4 that at the same cathode mass flow rate (3 sccm or 6 sccm), the plasma density of the cathode plume increases significantly as the cathode keeper current increases (change from 1.5 A to 3.0 A), especially near the region of cathode keeper exit. At the same time, the results of Raitses et al also show that the increase of the keeper current will increase the electron emission capability of the cathode[12]. It also can be seen from Fig. 4(a) and 4(c) or Fig. 4(b) and 4(d) that at the same cathode keeper current (1.5 A or 3.0 A), the plasma density of the cathode plume increases significantly as the cathode mass flow rate increases (change from 3.0 sccm to 6.0 sccm). This is because, under the condition that the cathode keeper current is constant, when the cathode mass flow rate is increased, the initial electrons emitted by the cathode emitter can collide and ionize with more Xe atoms, so that the plasma density in the emitter barrel becomes higher, and thus more plasma bombard the emitter to produce more electrons, so the electron density of the cathode plume is greater.

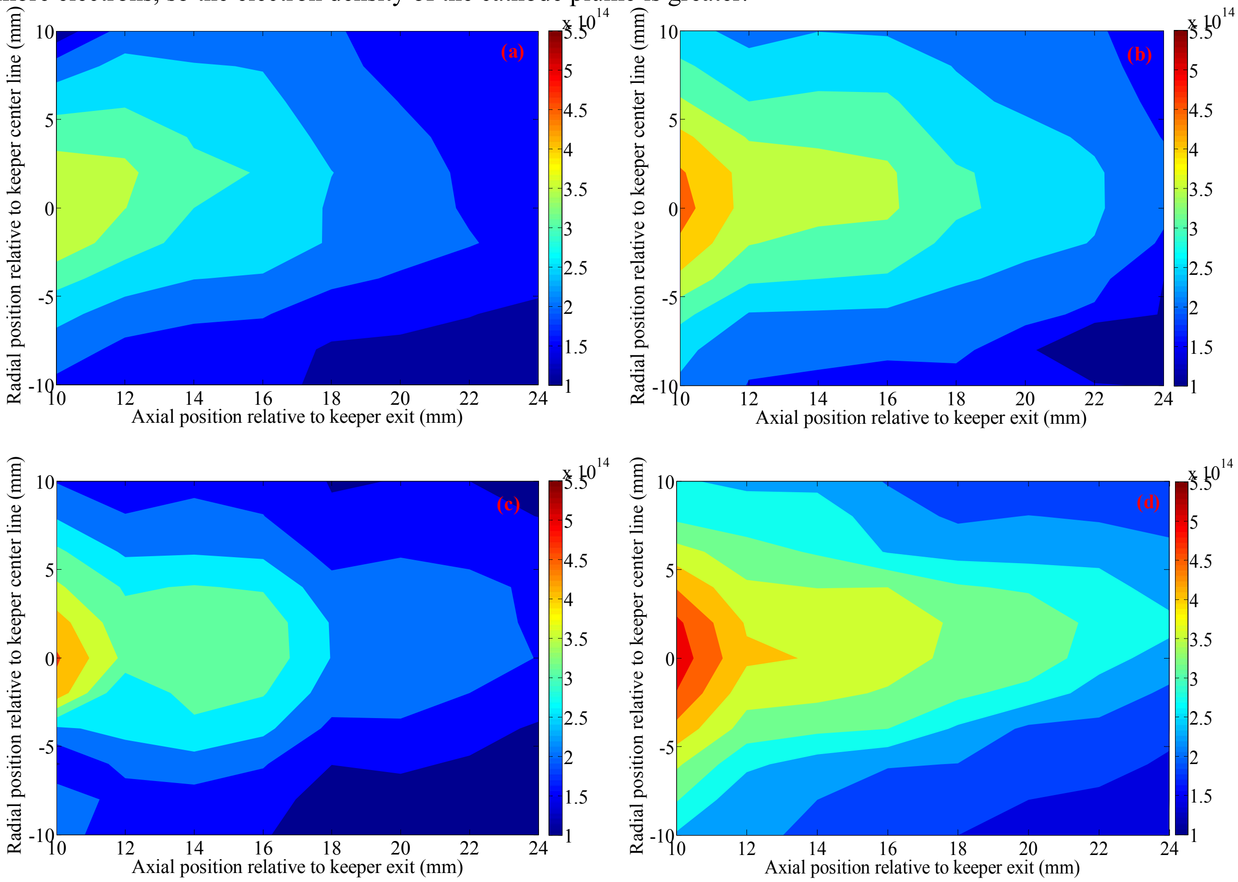


Figure 4. Electron density contours for different keeper currents and mass flow rates of the cathode. (a) the mass flow rate and keeper current of the cathode are 3.0 sccm and 1.5 A, respectively; (b) the mass flow rate and keeper current of the cathode are 3.0 sccm and 3.0 A, respectively; (c) the mass flow rate and keeper current of the cathode are 6.0 sccm and 1.5 A, respectively; (d) the mass flow rate and keeper current of the cathode are 6.0 sccm and 3.0 A, respectively.

The plasma potential contours for different keeper currents and mass flow rates of the cathode are shown in Fig. 5. It can be seen from Fig. 5 that the plasma potential of the cathode plume increases gradually as the axial distance from the cathode keeper exit increases, the change of plasma potential is similar to the result in Ref. [20]. And with the constant cathode keeper current, the plasma potential in the cathode plume will gradually increase with the increase of cathode mass flow rate. This plasma potential change may be related to the cathode coupling voltage changes observed in the Hall thruster experiments[11, 21], reducing mass flow rate of cathode will increase plasma potential in cathode plume, which will increase the coupling voltage drop between thruster and cathode.

The electron temperature contours for different keeper currents and mass flow rates of the cathode are shown in Fig. 6. The electron temperature for different keeper currents and mass flow rates of the cathode seems to be correlated to the plasma potential. As the plasma potential increases, the electrons are accelerated causing the electron temperature to rise. The similar results also can be seen in Ref. [22]. It can be seen from Fig. 6 that at the same cathode mass flow rate (3 sccm or 6 sccm), the electron temperature of the cathode plume decreases as the cathode keeper current increases (change from 1.5 A to 3.0 A), especially near the region of cathode keeper exit. It also can be seen from Fig. 6(a) and 6(c) or Fig. 6(b) and 6(d) that at the same cathode keeper current (1.5 A or 3.0 A), the electron temperature of the cathode plume decrease significantly as the cathode mass flow rate increases (change from 3.0 sccm to 6.0 sccm). The experimental results of Goebel et al. also found that increasing the mass flow of the cathode reduces the electron temperature while other parameters are constant[23]. And, increasing the cathode mass flow rate significantly reduces the electron temperature in the cathode plume region as compared to increasing the contact keeper current.

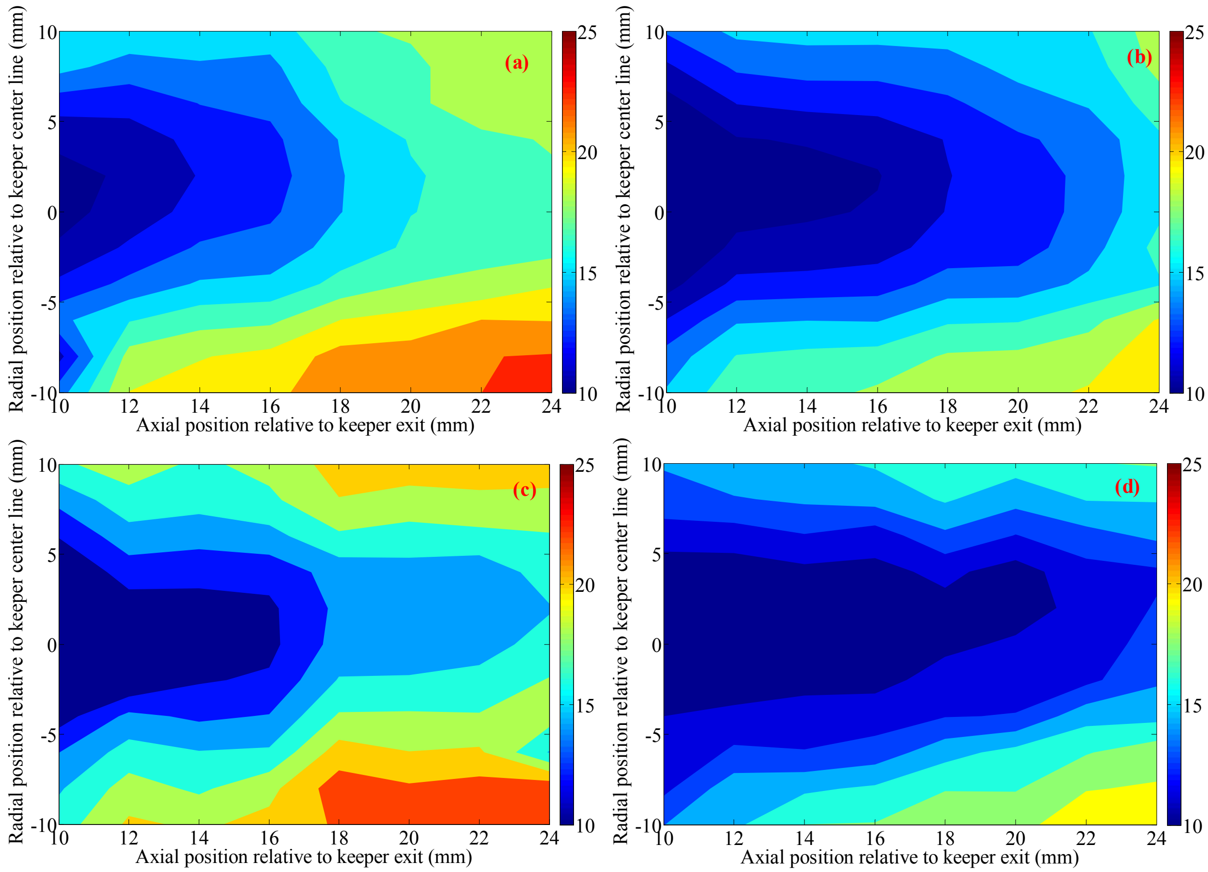
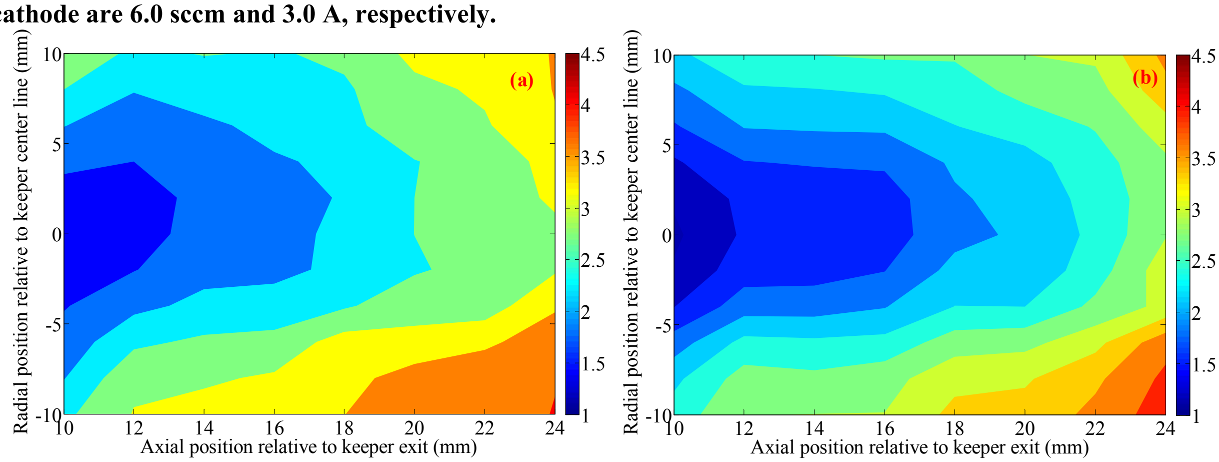
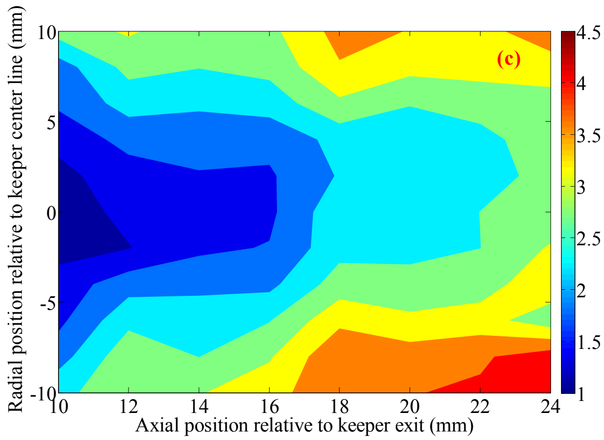


Figure 5. Plasma potential contours for different keeper currents and mass flow rates of the cathode. (a) the mass flow rate and keeper current of the cathode are 3.0 sccm and 1.5 A, respectively; (b) the mass flow rate and keeper current of the cathode are 3.0 sccm and 3.0 A, respectively; (c) the mass flow rate and keeper current of the cathode are 6.0 sccm and 1.5 A, respectively; (d) the mass flow rate and keeper current of the cathode are 6.0 sccm and 3.0 A, respectively.





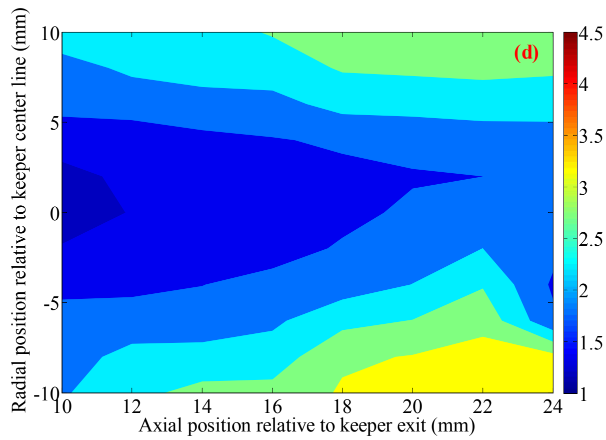


Figure 6. Electron temperature contours for different keeper currents and mass flow rates of the cathode. (a) the mass flow rate and keeper current of the cathode are 3.0 sccm and 1.5 A, respectively; (b) the mass flow rate and keeper current of the cathode are 3.0 sccm and 3.0 A, respectively; (c) the mass flow rate and keeper current of the cathode are 6.0 sccm and 1.5 A, respectively; (d) the mass flow rate and keeper current of the cathode are 6.0 sccm and 3.0 A, respectively.

From the measurement results of the ignition voltage boundary under different cathode keeper currents and mass flow rates, it can be seen that when the other parameters are constant, the increase of the cathode keeper current and mass flow rate will lead to the obvious decrease of ignition voltage boundary of Hall thruster. In particular, the effect of lowering the ignition voltage boundary is more significant when the two are simultaneously increased. Compared with increasing cathode keeper current, increasing cathode mass flow rate leads to lower ignition voltage boundary of Hall thruster. It can be seen from the measurement results of the plasma parameters of the cathode plume region under different cathode keeper currents and mass flow rates that the increase in cathode keeper current and mass flow rate will result in a significant increase in plasma density near the keeper region of the cathode. This leads to a decrease in the electron temperature in the cathode plume, especially when both are increased at the same time. Compared with the increase of cathode keeper current, the increase of cathode mass flow rate will lead to a larger increase of plasma density near the cathode keeper. According to the measurement results of ignition voltage boundary and plasma parameters under different cathode keeper current and mass flow rate, the decrease of ignition voltage boundary of Hall thruster caused by the increase of cathode keeper current and mass flow rate is mainly due to the increase of cathode keeper current and mass flow rate leading to the plasma density increased significantly in the cathode plume region. This is because when the cathode keeper current and mass flow rate increase, the plasma density in the cathode plume region increases significantly (the maximum increase is about 38%), more electrons near the cathode keeper exit can be bound by the nearby magnetic force lines, and then energy can be obtained from the axial electric field in the process of entering the discharge channel, resulting in more high-energy electrons. These high-energy electrons collide with neutral atoms that were previously concentrated in the thruster exit and discharge channels, enabling the avalanche ionization process to be established more quickly. Therefore, when the cathode keeper current and mass flow rate increase, the Hall thruster can be ignited successfully at a relatively low ignition voltage boundary. At the same time, although the cathode keeper current and mass flow rate increase will cause the electron temperature of the cathode plume to decrease, the initial electron temperature of the cathode emission is usually low, about several eV[23-25], and the electrons emitted by the cathode will gain energy from the axial electric field between the cathode and the anode during the process of entering the discharge channel. Therefore, although the cathode keeper current and the mass flow rate increase may cause the temperature of the electron emitted by the cathode to decrease, the latter may be compensated by obtaining energy in the axial electric field.

IV. Conclusion

So far, the researches on different cathode operation parameters mainly focus on their influence on the steady-state performance parameters of the Hall thruster, but it's still unknown that the influence of cathode keeper current and mass flow rate on the ignition voltage boundary of Hall thruster. Thus, the ignition voltage boundaries for different operating parameters of the cathode were measured. In order to better understand how different operation parameters of cathode affect the ignition voltage boundary of Hall thruster, the plasma densities, electron temperatures, and plasma potentials under different operation parameters of the cathode plume region were measured by a Langmuir probe at axial and radial directions. The results showed that both the increase of keeper current and the mass flow rate of cathode result in an increase in the electron density emitted by the cathode, while the electron temperature decreases; an increase in cathode mass flow rate results in a more pronounced effect than the keeper current. At the same time, it is also found that when the mass flow rate and the keeper current of cathode increase simultaneously, the ignition voltage boundary of the Hall thruster will decrease significantly, which is mainly due to a significant increase in the electron density due to the increase in mass flow rate and keeper current of the hollow cathode. In the future, PIC simulation will be used to study the effect of different initial electron density and energy distribution on the ignition process of Hall thruster.

Acknowledgments

The authors would like to acknowledge the support of the National Natural Science Foundation of China (Grant Nos. 51736003 and 51777045) and the Science and Technology Innovation Project of the Hunan Province (Project No. 2018RS3146).

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