Mechanism Analysis of Cathode Low Frequency Oscillation

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Abstract: The hollow cathode used for electric propulsion is always accompanied by oscillation during operation, and the amplitude of the low-frequency oscillation between 30 kHz and 80 kHz is the largest. The discharge oscillation of the cathode has a bad influence on the stability of the thruster and can generate high-energy ions in plume, which make severe erosion of the keeper and plate, limiting the normal working life of the cathode. Therefore, it is important to study the mechanism of low-frequency oscillation to reduce cathode oscillation and extend cathode life. it is considered that cathode low-frequency oscillation is related to cathode discharge instability but lacks clear mechanism explanation.In this paper, a 4-10A variable working condition of lanthanum hexaboride heatless cathode was measured. The combination of three-probe diagnosis and spectroscopy was used to measure the change of neutral gas density in the plume and found it is consistent with the discharge oscillation. Therefore, it is considered that the neutral gas oscillation in the cathode plume region is related to the low-frequency oscillation. The photo of the plasma ball in the cathode plume is photographed by a high-speed camera and found to be periodic on the low-frequency oscillation scale of the cathode discharge oscillation, and the position will also change. Combined with the simulation analysis, it is found that the plasma density in the cathode orifice region is higher when the current is higher in the cathode discharge oscillation period. At this time, the throttling effect of the orifice is higher, resulting in the accumulation of neutral gas in the cathode tube. The neutral gas density in the plume region is lower and the impedance is higher. The discharge voltage of the cathode increases due to the regulation of the discharge, the discharge current of the cathode decreases, the plasma density of the cathode pore region will also decrease, which will make the throttling effect decrease, and the neutral gas in the cathode tube is ejected, the density of the gas in the cathode plume region will be increased, and the phenomenon of reionization in the cathode plume region will cause the plasma density increased, the impedance decreased, the voltage decreased, and the discharge current rised. This results in low frequency oscillations of the cathode. The neutral gas velocity in the plume region is the sound velocity scale, and the cycle is calculated in accordance with the geometry to coincide with the period of the cathodelow-frequency oscillation.

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I.Introduction

SINCE the beginning of the concept of electric propulsion by Tsiolkovsky and Dr. Godard, many country have already made the application and development of electric propulsion technology be real [1]. Compared with traditional chemical propulsion, electric propulsion systems have high specific impulse characteristics, which can alleviate the quality of spacecraft, increase the payload of spacecraft, and have advantages in long-life satellites and deep space exploration, but at the same time, the longer life and the more complicated structure put forward higher requirements for the reliability of the electric propulsion device [2]. The hollow cathode as an electron source and neutralizer plays an important role in the entire electric propulsion system. Due to the particularity of the aerospace system, the hollow cathode requires a reliable life of at least 10,000 hours [3]. Under normal working conditions, the temperature of the cathode is up to thousands of degrees Celsius. The erosion of the cathode material caused by high temperature and plasma sputtering will lead to cathode failure and eventually cause the thruster to fail to start normally. Therefore, the study of erosion failure mechanism of the cathode is Significant.

At present, the international research on hollow cathode erosion is mainly verified by long life test experiments. In 1988, Hohn R. Brophy and Charles E. Garner of the California Institute of Technology's Jet Propulsion Laboratory (JPL) conducted a high-current hollow cathode life test on an ion thruster at 100A and 150A with 170 hours and 24 hours respectively, the experiment found that this large current discharge mode has a certain erosion phenomenon on the cathode orifice (tungsten tip hole) [4]. The Lewis Center of the United States conducted a 27,800h life test on a hollow cathode and found that the cathode orifice pore size increased by 14% due to ion bombardment erosion [5]. The JPL laboratory in the United States conducted an 8112h life test on the cathode used in Deep Space No. 1, and found that the keeper hole of the cathode of the neutralizer was significantly corroded and reamed by 70% [6]. After the 30,000h life test, the keeper level was found to be in the direction of the inferior plume. The most serious place reached 20%, and the top of the touch level also experienced obvious erosion, which was significantly more in the hole area [7-8]. From June 2005 to February 2014, NASA proposed the NEXT (NASA's Evolutionary Xenon Thruster) program for 51,184 hours on the basis of Deep Space No. 1, and found that the orifice of the cathode showed obvious erosion. Corrosive deposits have also appeared in the top region. Erosion of the entire orifice is not very serious, the minimum diameter of the cathode orifice is reduced by 13%, some deposition occur in the pore area, and the chamfered portion at the downstream produces inconspicuous erosion [9]. DanM. Goebel, IoannisG et al. started the 16000h experiment on the cathode of the 25cm-Xe ion propulsion system neutralizer from 2009. The first 2880h worked at the point mode of high power 4.5kW, and the erosion was slow; after 13370h at 2kW Working at the plume mode, the erosion rate is relatively faster. At the end of the experiment, the orifice of the cathode was corroded from the original straight holes without chamfering to the hemisphere in the downstream [10-13].

I.K et al. of the University of Colorado in the United States used the RPA probe to measure the ion energy distribution in the high current hollow cathode plume [14]. RPA probes placed radially in the plume of the cathode measure high-energy ions far exceeding the anode discharge voltage, followed by Dan M. Goebel et al. in the JPL laboratory [15], Dan M. Goebel believes Low-frequency oscillations are the main reason. By measuring the phase relationship between the ion current and the discharge voltage, they find that the ion current oscillation is consistent with the voltage oscillation. But they only made simple surmise, the test verification was not perfect and did not explain the source of the oscillations. Nelsion et al. of the University of California proposed the principle of ion acoustic acceleration, which is believed to be caused by high-energy ion bombardment, and high-energy ions are mainly caused by ionic turbulence effects. Emily et al. at JPL Laboratories have found that adding additional gas flow can effectively reduce high-energy ion production from the cathode [17].

This paper focuses on a 200-hour life test of a cathode in different working modes, and combines probe measurement, high-speed camera photography and other measurement methods to measure the relationship between ion energy and cathode oscillation in the cathode plume region, and the cathode. The evolution of the plasma characteristic parameters with the cathode discharge oscillation explains the mechanism of the low-frequency oscillation of the cathode.

II.Experiment

A. Instrument and set up

The cathode is a heatless hollow cathode, the flow rate is 3sccm, the current is 4-10A, the vacuum tank is 40cm in diameter 60cm in length . The ultimate vacuum of the experimental equipment is 10-4Pa. The vacuum of the cathode is in the range of 1.2-1.7*10-2Pa, the anode power supply is 10A/250V and the ignition power is 0.3A/1000Vm, the ignition control and data acquisition of the whole experiment are passed through the computer.

A total of 300 hours of life test was carried out on the cathode. The first 150 hours were operated at a flow rate of 3 sccm and an extraction current of 10 A. The extraction current was reduced to 8 A at 150-200 hours, and a new keeper was replaced at 200-300 hours. During the experiment, the cans were opened every 50 hours, and the cathode was subjected to a pole-to-electrode treatment to analyze the erosion of the cathode. To analyze the cathode erosion mechanism, the probes used in the experimental design mainly include three-probe and RPA. The three-probe is mainly used to measure the oscillation of electron temperature and plasma density in the plume region. RPA is mainly used to measure the ion energy distribution in plasma.

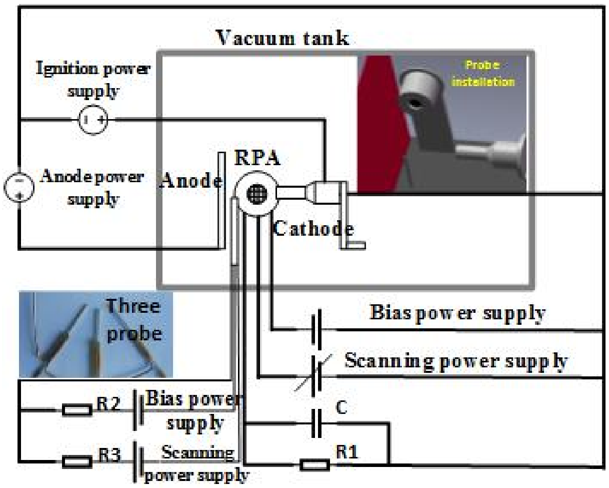

Figure 1. Experimental device used in the experiment

B. Diagnostic method

The traditional Langmuir probe can obtain a series of parameters such as the electron temperature and electron density of the plasma, but only for a steady-state average parameter. While the three-probe can measure time-varying signal of the parameter [18]. The three-probe used in the experiment are shown in Fig. 1, which Placed in the cathode plume area 15mm away from the cathode keeper, the time-varying signal collected by the oscilloscope can obtain the oscillation waveform of the plasma characteristic parameters in the cathode plume. During the experiment, the current and bias voltages on the three-probes were measured to calculate the electron temperature and electron density. The oscilloscope was used to collect the signal fluctuations on the three-probes, and the three-probe can be used to measure the parameter at each moment, then the plasma characteristic parameters at this moment can be obtained, and the relationship between the plasma density and the discharge oscillation can be obtained. During the test, the acquisition resistance of the three-probes was chosen to be 10k ohms, and a 1nF capacitance was chosen to eliminate the high frequency noise. The bias voltage is selected from 20V and 30V respectively.

By using an RPA to diagnose and analyze ion energy, the relationship between ion energy and oscillation in the plume region can be measured, and the ion current at bias voltages V1 and V2 can be measured with the RPA probe. The current, which can represent the ion energy between eV1 and eV2, uses an oscilloscope to capture the RPA probes at different bias voltages, simultaneously acquires the waveform of the current oscillation, and adjusts the collected different signals to the current signal. The ion energy distribution in the oscillation period of one current can be obtained. The signal collected in the experimental process generates high-frequency clutter due to the interference of the power supply and the circuit, we removed it by digital filtering. Using RPA to get signal, the scanning voltage is 20V-120V, and the interval is adjusted by 10V. A total of 11 groups of data are measured, use the higher one to subtract the lower one, the current of the ion energy between the two voltages can be obtained, and the mean value of the two voltages is multiplied by the elemental charge as the ion energy, thereby we can obtain an ion energy distribution in one cycle.

The high-speed camera is used to capture the shape of the cathode plume, and the synchronous trigger is used to synchronize the current oscillation with the high-speed camera to capture the oscillation of the plasma density and distribution in the plume during the current oscillation period, which can be verified with the results of the probe measurement

III.Result

A. Effect of Cathode Oscillation Amplitude on Cathodic Erosion

In the case where the extraction current is 10A, the image of the top of the keeper after 200 hours of experiment is shown in Fig. 2(b). At this time, the inner hole of the keeper is obviously enlarged, and the apparent chamfer is corroded. The surface changed roughly. After replacing the new keeper, the extraction current is reduced to 8 A. At this time, the oscillation of the cathode is significantly lowered, and the erosion of the keeper top is as shown in Fig. 2 (a), and the keeper is substantially free of erosion. The method of resin expansion is used to perform the sectioning of the keepers every 50 hours. The changes of the apertures observed under the microscope are shown in fig. 2 (c) and (d). In the case of 10A, the orifice erosion is not tight. However, there is a significant erosion condition at the chamfer and it becomes larger and larger over time

In the 10A working mode, the cathode operation is biased to the plume mode due to the large current drawn. At this time, the oscillation is relatively large, and the extraction current is reduced in the 8A operating mode, and the discharge oscillation of the cathode is significantly reduced. The waveforms of the experimental oscillations are shown in Fig. 3(e) and (f), and the root mean square of the oscillation is used as the oscillation measurement value of the cathode. The voltage oscillation at the extraction current of 10 A is 0.1, and in the case of 8 A, the oscillation is 0.025. The changes in oscillation during the test are shown in Fig. 3 (g) and (h).

Among the hollow cathodes, the erosion of the material is mainly caused by two main factors of high temperature evaporation and plasma sputtering. During the experiment, the infrared thermometer was used to measure and monitor the temperature on the cathode keeper. It was found that the temperature of the top of the cathode keeper was stable between 600 and 700 during the whole experiment. The rate at which the cathode material is lost due to high temperature evaporation is extremely low and can be ignored. Therefore, it can be judged that the erosion of the keeper is mainly caused by the bombardment of ions.

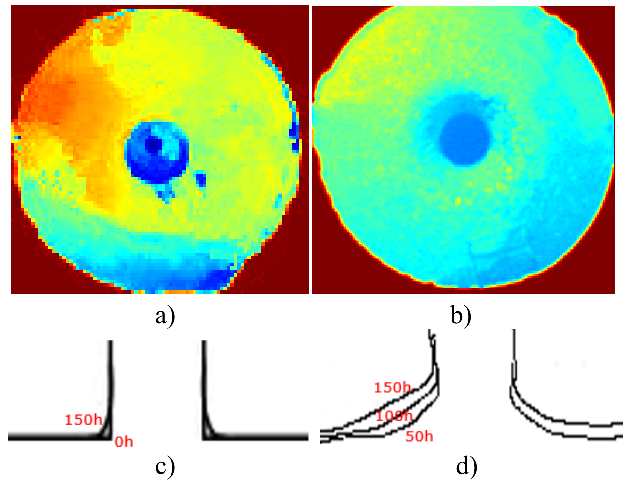

Figure 2. Erosion of the keeper after 50h and 200h（a, b). The orifice of keeper after 150h in point mode and plume mode (c, d).

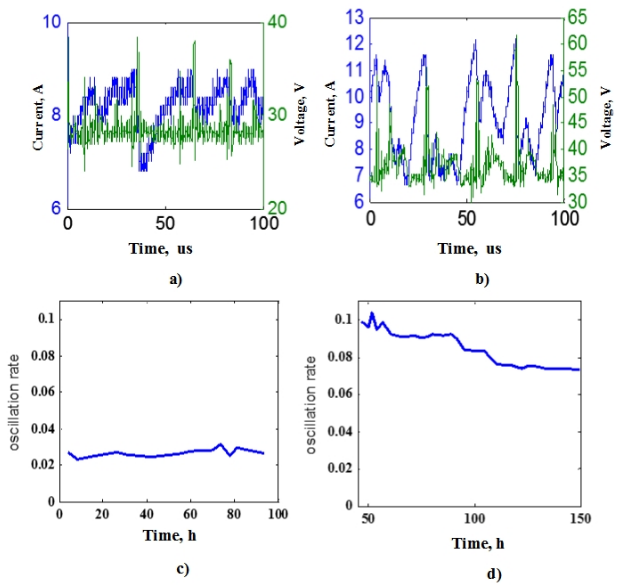

Figure3. The oscillating waveform of point mode and plume mode (a, b). The **oscillation of point mode c) and plume mode (c, d).**

B. Effect of oscillation on Ion energy

In order to verify the effect of cathodic oscillation on the high energy ion generation of the cathode, the RPA probe was used to measure the tendency of the ion energy in the cathode plume region to change with the cathode oscillation. The current is adjusted to 5-10A, and the gas supply flow rate is 2-5sccm. It can be seen from the experimental results that in the case of small extraction current, the oscillation increases with the increase of the flow rate, and in the case of the large extraction current, with the flow rate The increase and the oscillation gradually decrease, and the case where the oscillation is maximum occurs when the flow rate is small and the current is drawn.

The experimental measurement of the ion energy distribution of the cathode under different working conditions is shown in Fig. 4. Taking 3sccm as an example, in the case of fixed flow rate, as the extraction current increases, the oscillation of the cathode gradually increases, and the ions of the corresponding cathode. The peak of the energy distribution gradually shifts to the right, and the generated high-energy ions increase obviously. The change of the highest energy ion generated by the cathode with the oscillation of the cathode is shown in the figure, at the same supply flow rate, along with the cathode. As the oscillation increases, the high-energy ions generated by the cathode gradually increase. It can be seen from experiments that the larger the oscillation of the cathode, the more high-energy ions are generated.

C. Plasma characteristic parameter oscillation

The collected ion current is measured by three-probes. The oscillation of the characteristic parameters of the plasma in the cathode plume is shown in Fig. 6. As the current is increased, the space potential oscillation in the cathode plume increases. The electron density oscillation increases, which means that the plasma density oscillation increases. The electron temperature oscillation, the electron temperature, the electron density and the current oscillation are at the same frequency. The anode voltage is high while the anode current is low, the plasma density is low, the electron temperature is high, and the plasma potential is high.

Increase the bias voltage of the RPA, the relationship between the collected ion current and the cathode current and voltage oscillation is shown in the Fig. 5. In the case where the bias voltage is relatively low, the collected ion current is relatively large. In the absence of when the bias voltage is applied, all the ions of the energy are collected. At this time, the oscillation of the current and the voltage is reversed, and the oscillation of the ion current is consistent with the oscillation of the current. As the bias voltage increases, the ion current gradually increases. The decrease is that the ions collected at this time are mainly high-energy ions. At this time, the ion current has almost no oscillation, which proves that the flux of low-energy ions changes with the oscillation of the current in the case of large oscillation, but the flux of high-energy ions has no change. The ion energy distribution in one oscillation period is measured as shown in Fig. 5. In the case of a large current, the voltage is low, and the amount of high energy ions generated is relatively small, which is generated when the current is low and the voltage is high. The flux of high-energy ions is large, but it is not as large as the deviation of the measurement results when the RPA measures ion energy. This is mainly related to the flux, because in the case of a large current, the plasma density is relatively high, and the total amount of ions is large.

The appearance of the plume area captured by a high-speed camera is shown in Fig. 7. The picture taken is the bright spot area from the keeper hole. The value can be regarded as the cathode plasma density. The strong light means the intensity is high, and the smaller area means the plasma is more concentrated. In the point mode, there is no obvious change in the plume area. In the plume mode, the plume area is obviously divergent, and there is a clear change in brightness over time. The frequency of the period and current oscillation is basically the same. The plasma concentration region also changes with oscillations. In the case where the plasma density is high and concentrated, closer to the orifice may be caused by a change in gas density.

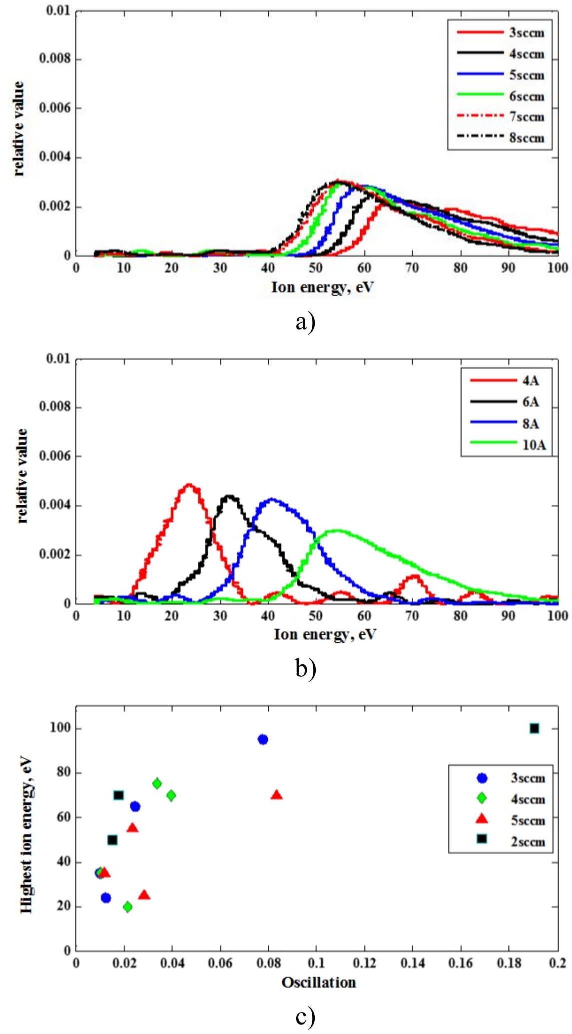

Figure4. The Ion energy distribution of point mode and plume mode (a, b). The highest ion energy of different

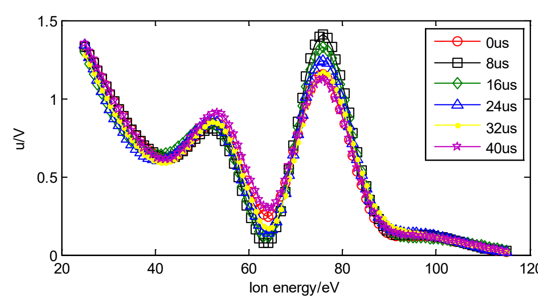

Figure5. The Ion energy distribution in an oscillation period.

D. Mechanism analysis of the influence of oscillation on Ion energy

It can be seen from the previous experimental results that the current oscillation and the voltage oscillation are opposite, the current oscillation is consistent with the oscillation frequency and phase of the electron density, and the voltage oscillation is consistent with the spatial potential oscillation. When the current oscillation reaches a peak value, the plasma density of the cathode reaches a maximum value at this time, and the ion flux near the cathode keeper reaches the maximum, but at this time, the anode voltage of the cathode is the lowest, and the space potential near the keeper is the lowest too. At this time, the high-energy ions are not entangled; when the current oscillation of the cathode reaches the minimum value, the ion flux measured at this time is small, but at this time, the voltage of the anode is the highest, and the space potential near the keeper is also high, the acceleration of the electric field results in the highest ion energy produced. For the discharge circuit of the cathode, the plasma in the cathode plume can be regarded as the resistance constant change resistance. When the plasma density of the cathode plume is high, the electron temperature is low, the divalent ions in the flow zone can be neglected, the ion density and the plasma density can be regarded as equal, so the ion flux is also high at this time. At this time, electron conduction is easy, the equivalent resistance is small, and the voltage across the plasma in the loading plume region is also low. The potential of the space in the corresponding plasma is low, and the acceleration effect on ions is small, so the energy of the ions is low. When the plasma density is low, on the contrary, the energy is rather high.

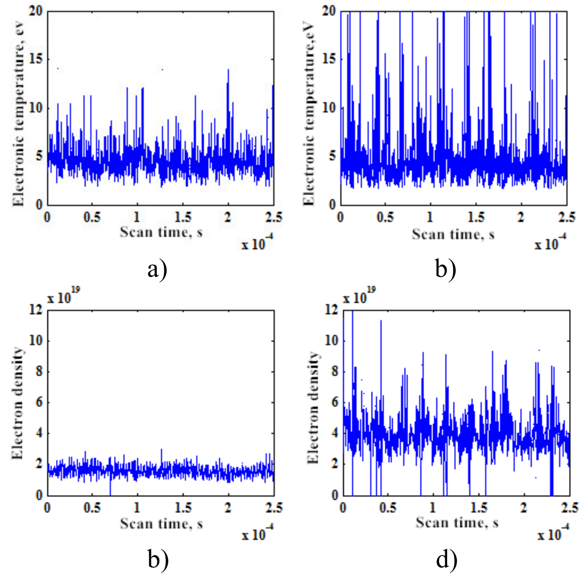

Figure6. The plasma characteristic parameter detected by three-probe. Electronic temperature and oscillation (a, b) Electron density and oscillation (c, d).

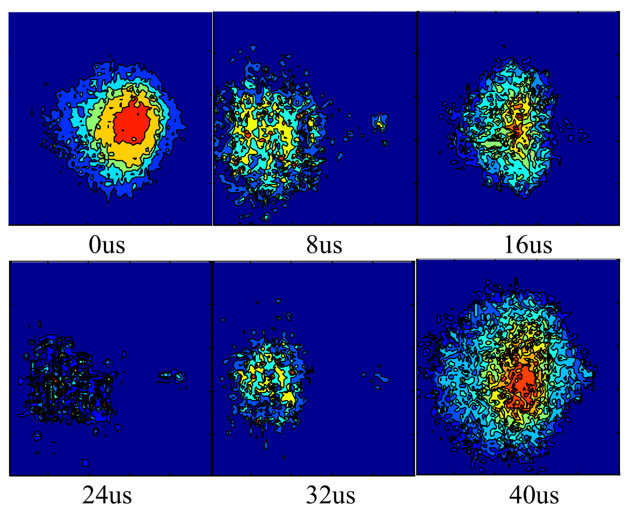

Figure7. The photo of plume in an oscillation period taken by high speed camera.

The reason for the cathode has such oscillation is related to the throttling effect of the cathode hole. During the experiment, we used a constant current power supply. Under normal circumstances, in the case of large extraction current, the electrons generated by the emitter increase, resulting in the electrons accumulation near the orifice region, which generates a large negative electric field, rejects the electrons generated subsequently, cause the plasma density decreases in the plume, and the equivalent resistance increases. Due to the regulation of the constant current source, in order to maintain the current, the supply automatically Increase the voltage to pull the electrons out, so in the case of a small current, the voltage is high. When the accumulated electrons enter the plume region, the plasma density in the plume region increases, the resistance decreases, and the anode voltage also decreases. The electrons in the cathode orifice region are again piled up, eventually forming a periodic change, and a reverse oscillation of the cathode discharge voltage and current occurs.

Therefore, the generation of high-energy ions caused by the change of the spatial potential formed by the voltage oscillation causes the erosion of the keeper, and the flux change caused by the oscillation of the plasma density caused by the current oscillation has less influence on the erosion of the keeper.

IV.Conclusion

According to the experimental results, the cathode is more biased to the plume mode at low flow and high current. The discharge of the cathode, the plasma density and the spatial potential are more oscillating. The plasma density oscillation caused by the oscillation of the current affects the ion flux. The oscillation of the spatial potential caused by the oscillation of the voltage affects the change of the ion energy, and the high energy ion is the main cause of the sputtering erosion of the cathode material, so the voltage oscillation is the main factor for accelerating the cathode erosion. Increasing the cathode magnetic field, increasing the flow rate, and changing the external circuit of the cathode discharge can effectively reduce the oscillation of the loop and generate small energetic ions.

Acknowledgments

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