Progress on New Scandate Hollow Cathode for Electric Propulsion

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Abstract: Lanzhou Institute of Physics recently developed a type of LHC-3 scandate hollow cathode used in LIPS-100 ion thrusters. It was successfully started in 4 minutes with 7.5A heating current. Its operating temperatures in triode mode are comparing to LHC-3 type lanthanum hexaboride (LaB6) hollow cathodes. LHC-3 scandate hollow cathode’s discharge performance in triode mode is well improved in the same time. Additionally, the new type of hollow cathode is tested in the LIPS-100 ion thrusters as discharge cathode. The anode voltage decrease by about 8V when the scandate hollow cathode is used. In the end, two scandate cathodes were placed in 90% Rh moisture environment for 240 hours, the discharge performance keep almost exactly the same after the test.

I. Introduction

Hollow cathodes for Electric propulsion devices usually divided into two types depend on its emitter material. The series of hollow cathodes developed by Lanzhou Institute of Physics, such as LHC-3, LHC-5, LHC-20, traditionally used the lanthanum hexaboride as emitter. LaB6 hollow cathode is featured by its well durance to oxygen and water vapor, which is harmful for emitter's work function. LHC-5 LaB6 type hollow cathodes has already completed flight mission twice based on LIPS-200 ion thruster and LHT-100 hall thruster between 2010 and 2017. Hollow cathodes used in these thrusters, its discharge current usually rage from 1.0A to 6.0A. But, as the development of large radius thruster, higher discharge current cathodes were needed. The work function of the lanthanum hexaboride is near 2.7 eV1, while the work function of the scandate-BaO-W is ony 2.01 eV. Thus, in the same discharge geometry, scandate cathodes generally need lower operating temperature, which means lower anode voltage and longer lifetime2.

This paper is comprised of three sections. The first section will describe the performance of scandate cathode tested in triode configuration3. The second section will describe the performance of scandate cathode4 used as the discharge cathode of LIPS-100 ion thruster. Finally, the cathode test results in moisture environment will be discussed.

II. Experimental Setup

A. Hollow Cathode

A cross-section of the LHC-3 hollow cathode is shown in figure 1. The heater is coiled around the cathode tube in which the hollow cathode insert is located.

The tube ends with an orifice plate which is used to increase the internal pressure in order to lower the ion energy due to a high plasma density region and to maintain relatively low values of propellant consumption. The emitter is usually heated to thermionic emission temperatures with the aid of an external source, typically a resistive element in direct contact with the exterior of the tube. The heater is turned off as soon as the cathode runs in a self-heating mode. A coaxial electrode, called keeper, is used to initiate the discharge, to keep the cathode hot5, and to protect the orifice

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plate and the heater from ion bombardment. The heater is normally surrounded by heat shields to reduce the power dissipation toward the keeper.

Figure 1. Schematic of LHC-3 hollow cathode

The hollow cathodes used in the experiment is LHC-3 type hollow cathode, the key parameters of the LHC-3 type hollow cathode are shown in table 1.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas species</td>
<td>Xe ≥(99.9995%)</td>
</tr>
<tr>
<td>Propellant flow rate</td>
<td>0.136 × (1 ± 5%) mg/s</td>
</tr>
<tr>
<td>Heater current</td>
<td>7.5 ± 0.1A</td>
</tr>
<tr>
<td>Heating power</td>
<td>≤80W</td>
</tr>
<tr>
<td>Keeper current</td>
<td>1.6 × (1 ± 5%) A</td>
</tr>
<tr>
<td>Anode current</td>
<td>0.8 × (1 ± 2%) A</td>
</tr>
</tbody>
</table>

B. Test Configuration

The experiment was carried out at Lanzhou Institute of Physics in the TS-5A vacuum system. Schematic diagram of hollow cathode test equipment is shown in Figure 2. The vacuum device is 50cm dia.×100cm long, a molecular pump kept the pressure in the 10⁻⁴ range. The cathode keeper and main discharge supplies were regulated d.c. supplies with constant voltage-constant current control characteristics. A separate ignitor supply was used for starting the cathode discharge. In the setup, a triode arrangement was used to simulate the LIPS-100 ion thruster. The anode consisted of a 0.4 mm Mo disk mounted 7.0 cm from the keeper tip.

Figure 2. Schematic diagram of hollow cathode test equipment.
III. Results and Discussion

A. Electrical characteristics in triode mode

A comparison between electrical characteristics of the LHC-3 type scandate cathode and LaB₆ cathode in triode mode is shown in figure 3(a). The experiment is carried out in triode mode, which the heater current is set as 7.5A, keeper current set as 0.6A, anode current set as 2.7A, flow rate set as 1.0sccm. The experiment procedure follows these steps: first, turn on the heater power supply, the keeper voltage, anode voltage was applied in 3 minutes. Then, turn off the heater power supply when the discharge process is established. The procedure is carried out 50 times in total for both kinds of cathode. Figure 3(b) shows the electrical characteristics of the LHC-3 cathode operated in triode mode.

![Figure 3. (a) Anode voltage as a function of number of cycles, (b) LHC-3 LaB₆ cathode in operation.](image)

The anode voltage of scandate cathode ranges from 12 to 14V in the triode mode, while the anode voltage of LaB₆ cathode is between 18 to 22V in the same mode. This result reflects the scandate cathode can emit the equal value of current with much lower power consumption. At the same time, the cathode temperature profile was measured using an optical pyrometer, figure 4 shows the temperature as a function of time. It is obvious that scandate cathode working in lower temperature than the LaB₆ cathode.

![Figure 4. Cathode tip temperature as function of time](image)

In the test, cathode tip instead of the emitter temperature was measured using optical pyrometer, since the emitter is placed inside the cathode tube and cannot be directly measured. Typical LaB₆ cathode working temperature is...
1300°C while the scandate temperature is 1050°C. The electrons are introduced into the system by thermionic emission from the insert surface and this process is described by the Richardson-Dushman equation:

\[ J = A T^2 \exp \left( \frac{-W}{kT} \right) \]  

where \( J \) is the emission current, \( T \) is the surface temperature in kelvins, \( e \) is the charge, \( k \) is Boltzmann's constant, and \( W \) is the work function. The work function of scandate is lower than \( \text{LaB}_6 \) cathode, according to Richardson-Dushman equation, scandate cathode can provide the required emission current with lower temperature. Therefore, the consumed power used to sustain the plasma discharge is lower, and the discharge voltage is also lower due to the emission current is set to a constant. In addition, the improvement of lifetime is expected because the insert life is limited by evaporation.

At last, the heating power of two kinds of LHC-3 type hollow cathode is shown in table 2. It is obvious that scandate cathode require much lower power than \( \text{LaB}_6 \) cathode at the same current.

<table>
<thead>
<tr>
<th>Tab.2. Heating power of cathode in triode mode</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cathode</strong></td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
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<tr>
<td>3</td>
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<td>4</td>
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B. Electrical characteristics as discharge cathode

LHC-3 hollow cathode is designed as the discharge cathode used in low power thruster like LIPS-100, which the power is usually lower than 500W, thrust force lower than 15mN.

Figure 5. (a) Discharge cathode keeper voltage as function of number of cycles, (b) Anode voltage under different work conditions.

The discharge cathode keeper voltage as function of number of cycles is shown in figure 5. The voltage of scandate cathode\(^7\) varies from 8.06 to 9.12V in the 10 times of cycles while the \( \text{LaB}_6 \) varies from 13.44 to 14.45V. The experiment shows the same trend when tested in the triode configuration\(^8\). Since the keeper current is a constant for a certain beam current, therefore the power consumption of cathode itself is decreased compared to the case when the \( \text{LaB}_6 \) is used. This is very helpful for the improvement of the performance of LIPS-100 ion thruster.

Fig. 6 shows the variation of thruster anode voltage for the two type cathodes, as the beam current is 0.3A. The anode voltage when the scandate cathode used is lower than \( \text{LaB}_6 \) cathode. In addition, the screen grid life is inversely proportional to anode voltage, thus, the lifetime of LIPS-100 thruster is expected to be longer as scandate cathode be used.

C. Long duration water vapor Exposure Tests

Two LHC-3 scandate cathodes were exposed to water vapor levels of 90% for periods of about 240 hours in total. The environment temperature\(^9\) is kept at 60°C. The scandate cathodes carried out discharge test in diode mode.
separately before and after the duration experiment\textsuperscript{10}. The result of the discharge voltage after test is plotted in fig. 6. The keeper voltage value after test is plotted as dashed line in contrast to the results before test shown as solid line.

![Figure 6. Scandate cathode keeper voltage as function of number of cycles](image)

IV. Conclusion

The results of the discharge experiment demonstrating the performance of scandate hollow cathode have been presented. Scandate cathode discharge voltage is proved to be lower than LaB\textsubscript{6} cathode in triode test. The experiment carried out in LIPS-100 ion thruster as discharge cathode has shown the same trend. The operating temperature of the scandate cathodes needed for emit 5A current is 1050°C, which is lower than LaB\textsubscript{6} cathode for about 250°C. And this is very helpful for the improvement of lifetime of thruster. In addition, the performance of scandate hollow cathode is also proved to be stable after exposure to water vapor for 240 hours. The experiment shows no evidence of poisoning, but the Extended Life Test is still required to assure the possibility of using in thruster.
References


