The Ignition Erosion Mechanism of Heatless Hollow Cathode

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Abstract: Hollow cathode is an electron source, which can neutralize the plume of ion thruster and hall thruster. Heater is used to heat the emitter (electron emit materials, LaB_6 or BaO-W) for the ignition. It may encounter the partially short or even open circuit problems after several tens of thousands cycles, the electric propulsion system will fail. Heatless hollow cathode can be started up by plasma breakdown and improve the system reliability. Energetic ions will be produced during the breakdown, which may erode the hollow cathode components. While the influence of the breakdown on the hollow cathode is not clear, a heatless hollow cathode is completed a ten thousand of ignition cycles in this work. The posttest destructive analysis shows that the downstream of orifice and emitter are chamfered, there are some spherical bulges near the orifice entrance. In order to study the ignition erosion mechanism, a hollow cathode erosion model is built based on fluid mode.

I. Introduction

AS an electron source, the hollow cathode is used for ion plume neutralization in the ion and hall thrusters[1]. Which are widely used in geostationary satellite position keeping, satellite orbit lifting, and

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space exploration missions. In addition, hollow cathode is used in many other devices, such as gaseous lasers and plasma processing sources[2-4]. The hollow cathode uses LaB_6 or BaO-W as electron emitter, which is fixed in the refectory tube. The emitter emits a large amount of electrons above 1250 K. By using the xenon or krypton discharge, plasma is produced inside the hollow cathode. A heater is wired outside the gas tube and provide the initial heating energy for the ignition. After tens of thousands of ignitions, there will be local short circuit or even open circuit problems[5]. The electric propulsion system fails without the heater.

By using the plasma breakdown, the hollow cathode can be started without a heater. Heatless hollow cathode has quick start capability, lower energy consumption, and high reliability. Koshelev developes a low-current (0.2-0.5 A, 0.05 mg/c) heatless hollow cathode for the low power hall thruster. This cathode is carried out a 10,000 hours wear and ignition test[6]. The electric thruster research center of zhukovsky national aeronautics and astronautics astronauts accumulates a wealth of experience in the rapid start-up heatless hollow cathode with a discharge current of 0.3 amps to 300 amps. Israel institute of technology analysis start-up process of the heatless hollow cathode, provides the V-I characteristics and the plume image during the start-up process[7]. Israel advanced defense systems Co.Ltd. develops a 0.1-1A low current hollow cathode, and simulates its temperature characteristics. At 0.8A, the high temperature leads to the blocking due to material deposition[8]. Italy Pisa University develops a 0.5-3A LaB_6 heatless hollow cathode for low-power hall thruster. The effect of two aspect ratio of the orifice on the performance of the hollow cathode is verified at 0.08 mg/s and 1 mg/s xenon gas flow rates. On the other hand, LaB_6 heatless hollow cathode is developed for high power hall thrusters.

In order to reduce the starting erosion, graphite electrode is used. The cathode is carried out 100 cold starts, 340 hours (18 A) test with xenon and krypton respectively combined with a 5-kilowatt hall thruster[9-10]. The University of Southampton conducts a study on the effect of the keeper and orifice shape on the start-up characteristics of the heatless hollow cathode. It is found that the keeper can affect the ignition voltage. In order to review the ignition erosion on the ignition and steady-state characteristics[11], a LaB_6 heatless hollow cathode is accumulated one million cycles of ignitions. The steady-state I-V characteristics are measured at different stages of the experiment. Finally, the hollow cathode is conducted a destructive analysis.

II. Experiment Setups

A. Heatless hollow cathode

The schematic diagram and the photo of the heatless hollow cathode are shown in Fig. 1. The LaB_6 emitter is 10 mm long. The orifice plate is made of tungsten. The keeper is 2.5 mm long with a thickness of 2 mm. The vacuum chamber (diameter, 30 cm, length 80 cm) is equipped with a molecular pump with a pumping speed of 1600 L/s. The base pressure is 10^{-5} Pa.

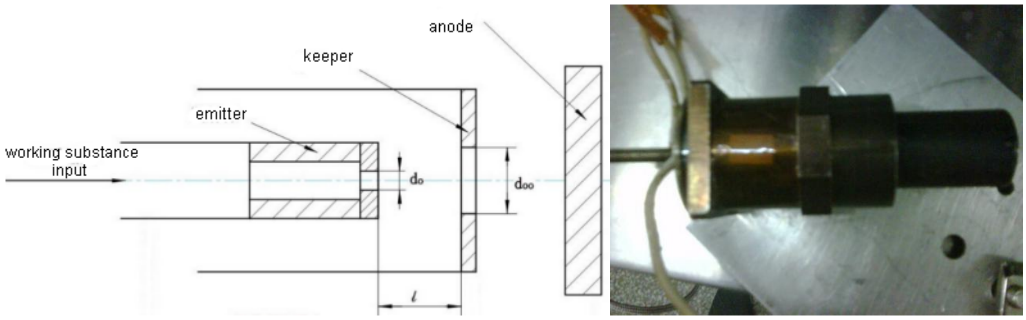


Figure 1. Schematic diagram and photograph of the heatless hollow cathode

B. Ignition start circuit

The ignition circuit is shown in Fig. 2(a). The keeper is connected to the positive pole of the ignition power supply (1000 V, 1 A). The cathode tube is connected to the negative pole. The ignition power supply voltage is used for plasma breakdown. The keeper supply (50 V, 30 A) is used to maintain the plasma discharge. The current limiting resistor R is used to protect the keeper power supply. The ignition voltage is set to 350 V, the preset ignition current is 800 mA, the anode power supply is 50 V, the preset current is 5.00 A, the xenon gas flow rate is 4 sccm. After the cathode is ignited, the anode supply is turned off for 60 s cooling process. Fig. 2(b) is a measuring circuit used to obtain the I-V characteristics.

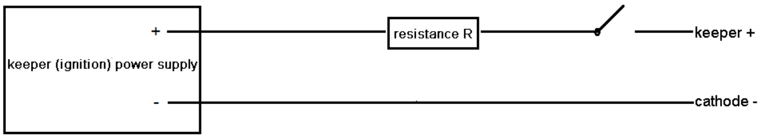


Figure 2(a) Ignition circuit

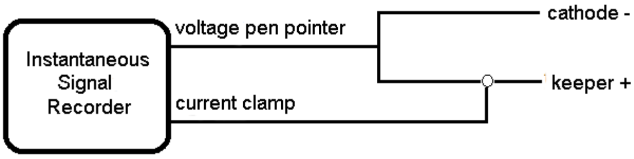


Figure 2(b) Measuring circuit

In order to study the effect of ignition erosion on the steady-state operating characteristics, the I-V characteristics are measured at the first, 1462, 4579, 7000, and 10,000 cycles. The current clamp is used to measure the ignition current and the voltmeter is used to detect the voltage during the ignition. The data is recorded in a recorder. The experiment is conducted with 10,000 cycles of ignition. After the ignition test, the cathode is carried out a destructive analysis.

III. Results and discussion

A. The orifice erosion

The pre and post-test appearance of exterior surface of orifice plate is shown in Fig. 3. It can be seen that the downstream surface of the orifice plate is textured, the orifice diameter increases by 0.2 mm after 10000 ignitions. The orifice is chamfered smoothly, local melting occurs near the entrance of the orifice. The ignition voltage is applied between the keeper and the orifice, the xenon is ionized here and are accelerated to the orifice during the ignition. The energetic ions can sputter and bombard the orifice plate. The electric field is more concentrated at the chamfer, the ion bombardment is more serious. The melting of the entrance of the orifice reveals the overheating problem.

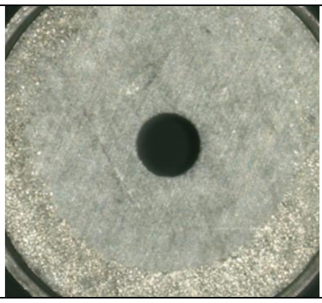
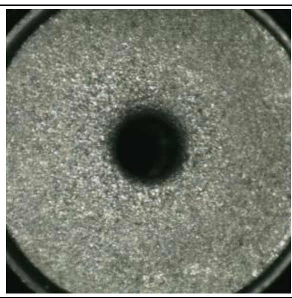
		
(a) Cathode orifice plate pre-test condition	(b) Cathode orifice plate post-test condition	(c) Metallograph of post-test orifice cross-section

Figure 3. Micrograph of orifice plate

B. The emitter erosion

Figure 4 shows the cross-sectional micrograph of the emitter after ignition 10,000 cycles. It can be seen that the emitter erosion is similar to the orifice. The downstream emitter is 0.3 mm enlarged, and the upstream emitter changes slightly. The plasma breakdown inside the emitter region forms high energy ion and erode the emitter.

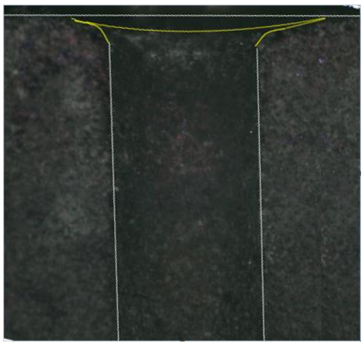


Figure 4. Metallograph of emitter cross-section after 10000 cycles of ignitions

C. The I-V characteristic

Figure 5 compares the I-V characteristics at different ignitions (1462, 4579, 7000, and 10000), the gas flow rate changes from 2 sccm to 4 sccm, the discharge current changes from 2 to 10 A. It can be seen that the anode voltage decrease ~ 3V with the increase of the gas flow rate. The variation of the I-V curves under the different ignition cycles is almost the same. The anode voltage deviation is within 5V, which indicates that the ignition erosion does not affect the steady state working significantly.

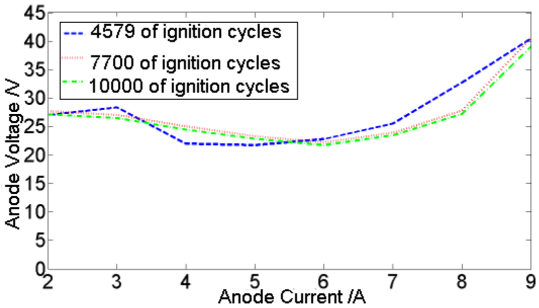


Figure 5 (a) The I-V curves at 2 sccm (4579 ignitions, 7700 ignitions, and 10000 ignitions)

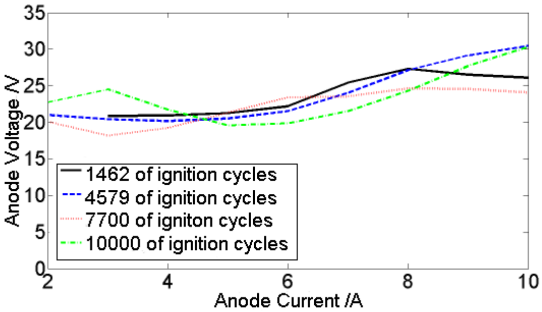


Figure 5 (b) The I-V curves at 3 sccm (1462 ignitions, 4579 ignitions, 7700 ignitions, and 10000 ignitions)

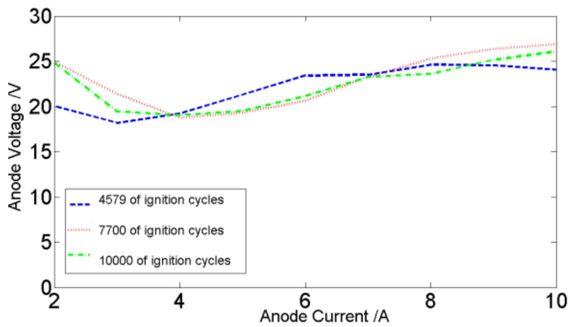


Figure 5 (c) The I-V curves at 4 sccm (4579 ignitions, 7700 ignitions, and 10000 ignitions)

IV. Model

A. Ignition discharge and bombardment simulations

Hollow cathode has a 2-D axisymmetric structure, a two-dimensional axisymmetric plasma fluid model is chosen. The cathode size is shown in Fig. 6. The pressure in the emitter region is several kPa, the size of the emitter and orifice are in the order of millimeters. The plasma model includes: electron number density conservation equation, energy conservation equation, mass particle (ions and atoms) mass conservation equation, Poisson equation, emitter heat transfer equation. The ionization model includes: collision between electrons and atoms, which cause the excitation, de-excitation, ionization, recombination, and the transition between excited states[12]. Electron emission models include: thermal emission, field enhanced emission, secondary electron emission. The relationship between ion energy and secondary electron emission is shown in Ref.13. Heat transfer between plasma and cathode includes ion bombardment heating, electron bombardment heating and electron emission cooling. The gas pressure distribution from the fluid model is shown in Fig. 7.

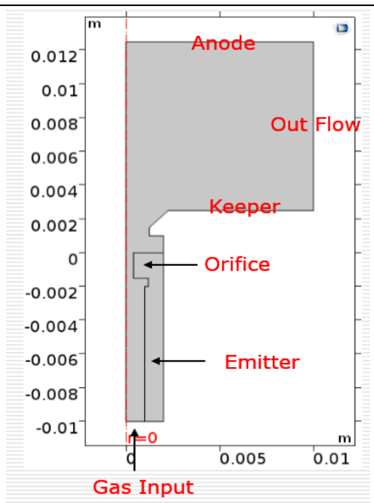


Figure 6. Hollow cathode Geometry

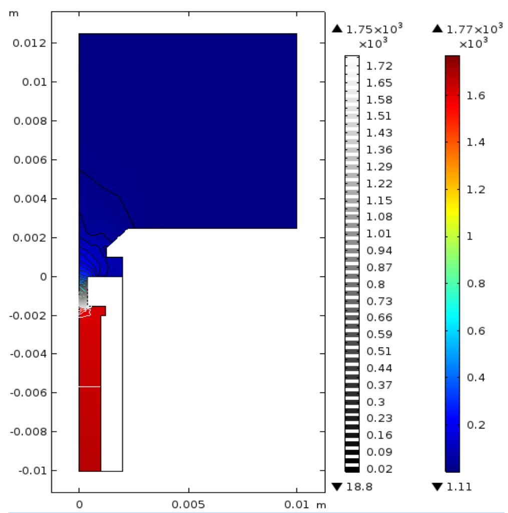
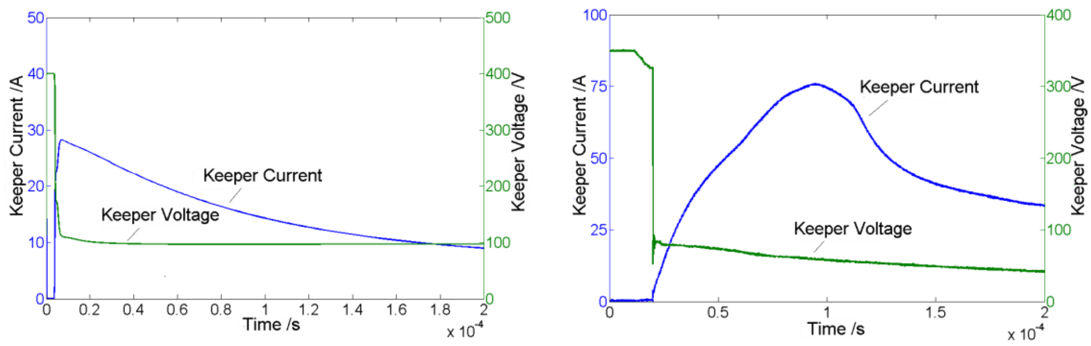


Figure 7. Gas pressure distribution

The tungsten orifice and emitter erosion are caused by the ion sputtering, the yield according to the ion energy is form Ref.14. The yield is multiplied by a factor of 10000, and a single discharge equivalents to 10,000 cycles of ignition. The model is built by COMSOL Multiphysics. The simulation shows that the discharge voltage drops rapidly, while the discharge current rises to several times the normal value quickly and then decrease later. Figure 8 shows a good agreement between the simulation and the experiment.

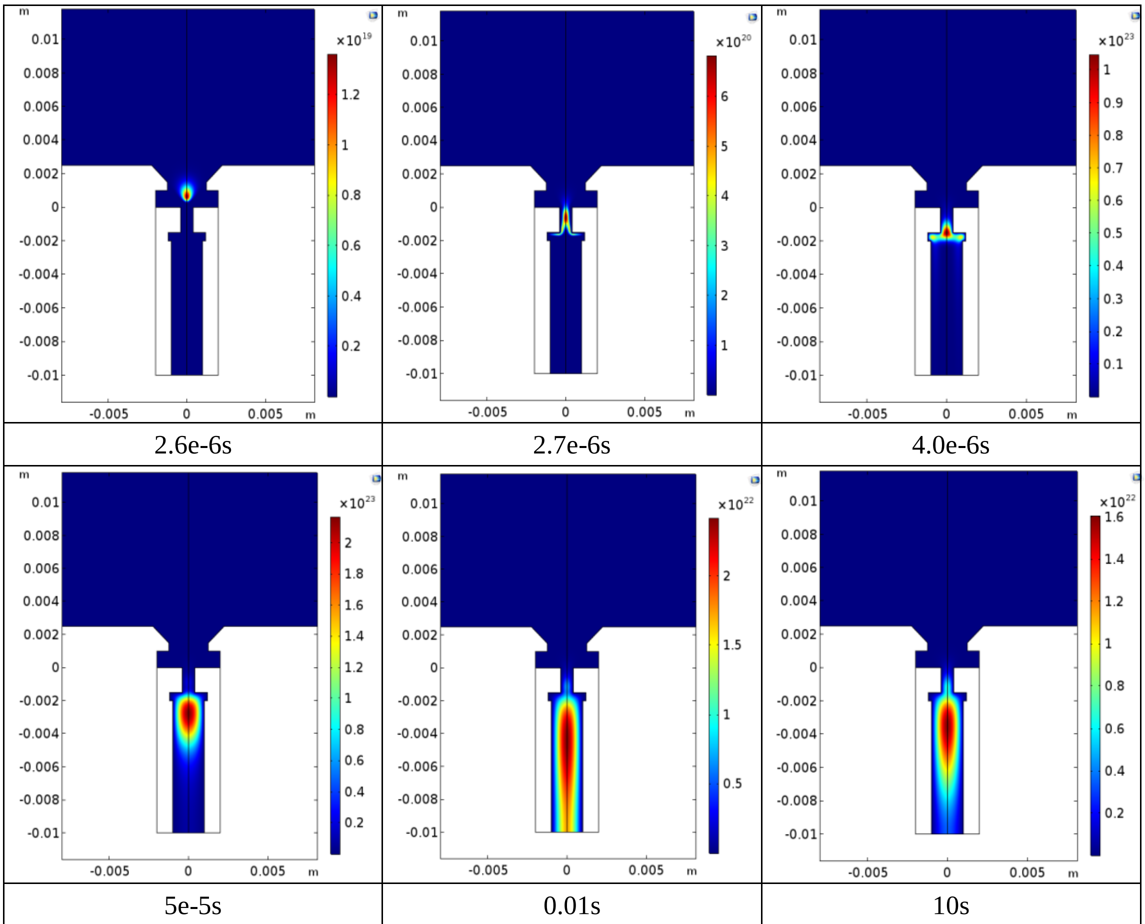


a) Keeper voltage and current (simulation) b) Keeper voltage and current (experiment)

Figure 8. Ignition characteristics of heatless hollow cathode

B. The ignition progress

The typical start-up progress of heatless hollow cathode includes three stages, which is shown in Fig. 9. On the first stage, large amount of plasma accumulate between the keeper and the orifice. Then the discharge region moves to the orifice region when the plasma density reaches 10^{18} m^{-3}. And the high potential moves together. On the third stage, the high density plasma is formed in the orifice region, heat energy is transferred from the orifice to the emitter. After the plasma is formed in the entire emitter region, the emitter achieves the thermal emission. Secondary electron emission and the thermal diffusion are important factors to the initiation of heatless hollow cathode.



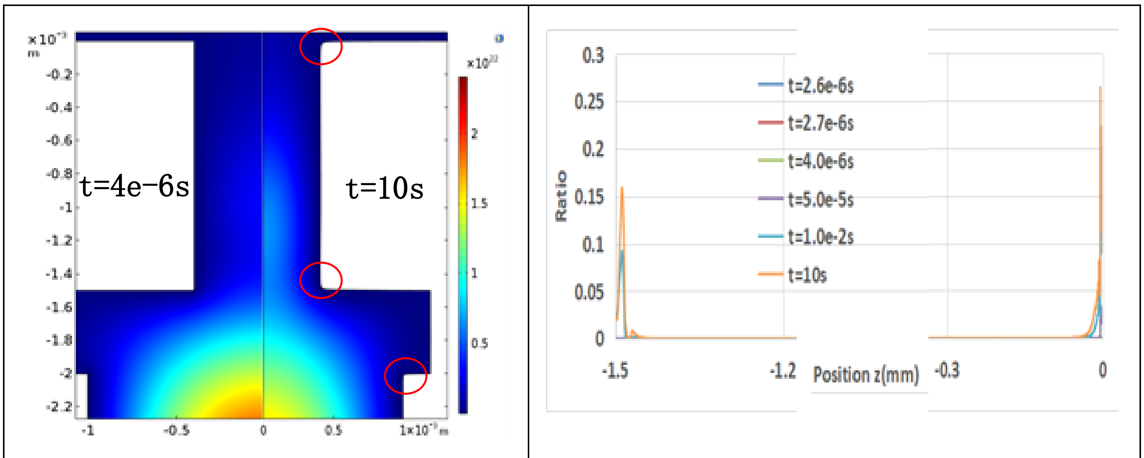
2.6e-6s | 2.7e-6s | 4.0e-6s

5e-5s | 0.01s | 10s

Figure 9. The ignition progress of heatless hollow cathode

C. Model of the orifice and emitter erosion

The microseconds ignition process can be divided into gas breakdown, plasma heating and arc discharge stage[15]. Figure 10(a) shows the erosion rate of the orifice and the emitter after the ignition. Figure 10(b) shows the erosion rate of the orifice in different periods. Consistent with the experiment, it can be seen that the erosion at the edge of the orifice is the most obvious, especially at the downstream export. Figure 11 shows that the emitter erosion take place at the downstream export, the other part of the emitter is almost free of erosion, which is consistent with the experiment.



a) the erosion morphology (t=4e^{-6}s and t=10s) | b) The cumulative erosion rate of the orifice

Figure 10. The orifice erosion during the ignition

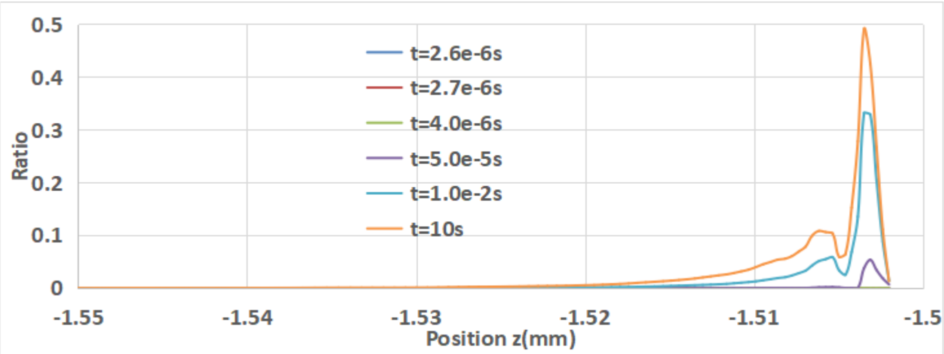


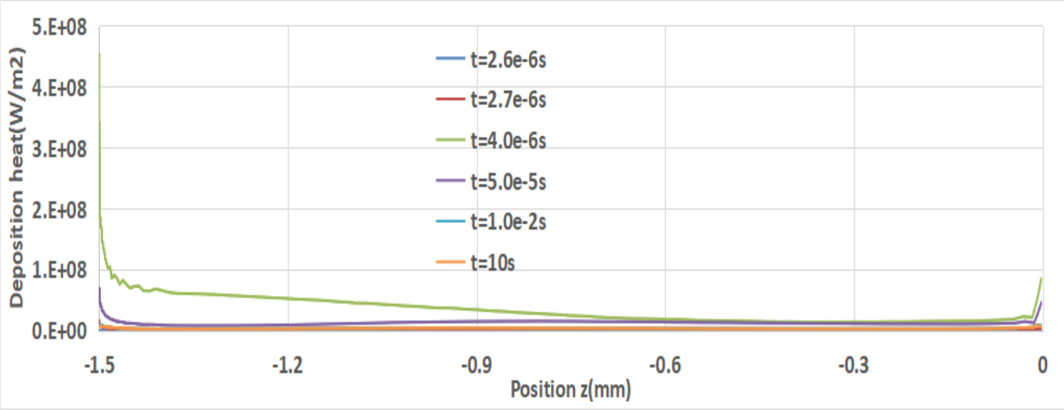
Figure 11. The emitter erosion during the ignition

D. Orifice and emitter heat deposition

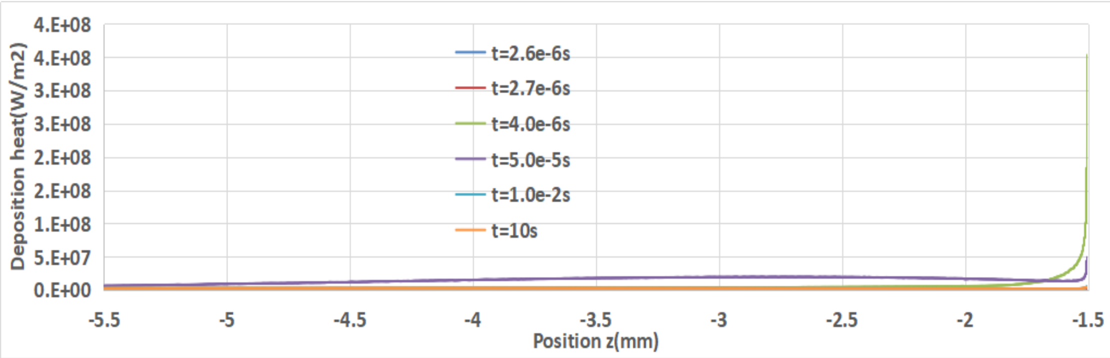
Figure 12 shows the heat deposition on the orifice and emitter during the ignition. It can be seen that most heat energy is deposit on the orifice during the breakdown. The upstream orifice obtain much more energy than the downstream end. Which relate to the melting in Fig. 12(a). Heat energy is also concentrated at the downstream end of the emitter at first and then transmits along the emitter.

V. Conclusion

The heatless LaB_6 hollow cathode is carried out a 10000 cycles of ignition. The orifice is bombard and melt by energetic ions, and the emitter is eroded slightly. It has little effect on the V-I characteristics and ignition characteristics. A model is built to simulate the start-up process and erosion of the heatless cathode. Which shows that the ion bombardment causes the chamfering of the orifice and the emitter, and the heat deposition on the orifice cause the overheating and orifice melting.



a) Heat deposition on the orifice



b) Heat deposition on the emitter

Figure 12. Heat deposition on the heatless hollow

Acknowledgments

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