The Neutral Gas Properties in Orifice Hollow Cathode before Its Ignition

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Abstract: The neutral gas pressure between orifice tip and keeper is a key factor that affects the ignition of orifice hollow cathode. A 2D axial symmetry numerical model was developed to study the neutral gas distribution in the orifice hollow cathode. The model included high Mach number gas and heat transfer process. The neutral gas pressure at the inlet boundary of simulation region was obtained by experiment. The simulated results indicated that the gas pressure between the orifice tip and keeper increased along with the inlet gas flow rate and heat power, the gas temperature correspondingly decreased as the gas flow rate increases.

I.Introduction

THE application of electric propulsion effectively improves the load ratio and on-orbit life of the satellite platform. Due to its high specific impulse and long life, it also becomes the preferred power source for deep space exploration. The all-electric propulsion platform cost is reduced about 50%. Hollow cathodes are the key components of ion thruster and Hall thruster, and also be utilized as the hollow cathode in micro thrusters and the plasma contactors [1-5]. At present, the long life and reliable ignition of the hollow cathode is the key to affect the long life of the space electric propulsion satellite platform. According to the specific mission, the hollow cathode needs tens of thousands of reliable switching ignition capabilities, and the cathode thermal failure is one of the most important failure modes that limits the long life of the hollow cathode. The hollow cathode ignition trigger occurs between the tip and keeper electrode, while the electric field distortion occurs at the tip of the round orifice corner. Under the action of small orifice throttling during the ignition process, the Xenon gas is in the process according to the Laval effect of propellant. After the cathode tip orifice is ejected, the adiabatic expansion becomes a high Mach number flow field, which will affect the distribution of a small amount of the original electrons and the free electrons in the Xenon under preheating. Because of the distorted electric field and the high-speed flow field, the Paschen's law will not be applicable.

In Colorado State University, Williams verified the migration theory of Ba during preheating in a hollow cathode vacuum electron emission test and found that propellant supply at preheating process and before trigger would influence on the hollow cathode ignition. Based on special tests results that proved that Ba atoms which from the Ba evaporating gas in insert would migrate to the orifice tip plate of the cathode, the L-3 communication electronic technology company and JPL established a hollow cathode ignition mathematical analysis model of the XIPS-25 Ba-W hollow cathode to simulate the ignition process [6] and obtained the time-domain migration equation of Ba atom and the original electron current with ignition condition. The model could predict the influence of emitter lifetime. Stephen W Patterson et al. [7] experimentally studied the relationship between the ignition voltage of the orifice hollow cathode of T6 and T5 ion thruster and the gas flow rate of the propellant, and the preheating temperature of the cathode top and cathode. A numerical analysis model is established by R. Niedrist et al. [8] of the

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University of Innsbruck in Austria to study the effects of the Paschen's law and its corrections due to the influence of the inhomogeneous electric field configuration and micro-gap between the hollow cathode electrodes. M.Favre that in Pontificia University [9] who studied on hollow cathode discharge evolution phenomena, and collected spatial potential variation characteristics and plasma density distribution characteristics during the electrical breakdown. The authors found that the gas breakdown process can be divided into three steps: (1) the gas ionization rate increased near the prototype after the ignition pulse was applied to form a virtual anode; (2) the virtual anode expanded toward the cathode; (3) the virtual anode maked it The field strength increases near the cathode, which aggravated the gas ionization in the hollow cathode region and achieved gas breakdown between the cathode and the anode. Hoyoung Pak [10] of the University of Illinois in the United States developed the MC program to study the gas-breakdown characteristics of flat plate's cathode. It was found that when the parallel plate spacing was small, the anode potential was easier to penetrate the cathode pores, which would affect pd value. At the same time, it was found that ion bombardment dominated during gas breakdown and ionization, and the maximum value of the energy of the ion bombardment cathode was approximated to the anode potential. The Steve B Gabriel at the University of Southampton [11] studied the hollow cathode ignition sensitivity factor using a T6 ion thruster hollow cathode. The team believed that the parameters affecting the ignition breakdown characteristics of the hollow cathode mainly included flow rate, orifice tip temperature, keeper voltage, cathode tip orifice diameter, the distance between the tip and keeper, et al.

It is generally believed that when the hollow cathode is ignited, firstly, the propellant gas is ionized and discharged between the contact pole and the top of the cathode, and then the discharge extended to the emitter region through the cathode aperture, finally the discharge is established by the glow transition to the arc. The cathode will being in the stable low voltage and high current discharge mode [12]. The breakdown process of the gas has an important influence on the hollow cathode ignition. In the case where the electrode material and shape are determined, the main factors affecting the discharge breakdown voltage of the gas are the pole pitch and the inter-electrode pressure distribution.

In this paper, the Finite Element Method (FEA) combined with fluid heat transfer and high Mach number fluid model is used to study the flow field distribution of neutral Xe between the cathode tip and keeper before the trigger the hollow cathode.

II.Simulation Model

A. Simulation Region

Since the hollow cathode is axisymmetric, the three-dimensional problem can be studied by a 2D axisymmetric model. The simulated region is shown in Fig.1, which mainly includes the cathode tube, the cathode orifice tip and the keeper electrode. The diameters of the cathode insert, the cathode orifice of the tip and the keeper electrode are 2.0 mm, 0.5 mm and 1.5 mm, respectively.

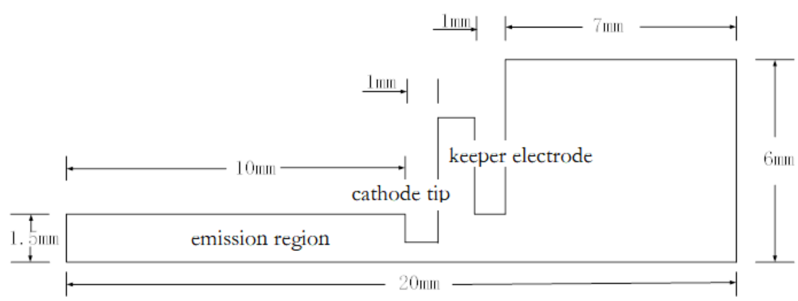


Fig.1 Schematic diagram of the simulation region

B. Simulation Process

When the neutral gas flows through the small orifice of the cathode tip, the neutral gas flow rate becomes larger that leads to the decrease of the gas pressure and the temperature due to the throttling effect of the small diameter orifice, what is called the Laval effect. The fluid velocity in the inner and downstream areas of the small orifice usually exceeds one Mach number. Therefore, this paper uses the COMSOL multi-physics combines the fluid heat transfer and the high Mach number fluid model to study the dynamic behavior of the neutral gas.

Firstly, the Knudsen number of the neutral gas in the cathode tube is experimentally obtained. Assumed the flow rate is 1 sccm and gas obeys the ideal gas equation, the number density of the propellant atom is calculated to be 3.8e23m^(-3) according to p=nKT.

The molecular free path formula is described as

$$\lambda = \frac{1}{\sqrt{2}n\pi d^2} \tag{1}$$

λ is $6.7e-17$m.

The Knudsen Number，$Kn = \lambda / L$，is $2.5e-16$。

Kn≪1, therefore, the gas flow follows the law of continuous flow motion and can be computed by fluid method.

In the orifice hollow cathode, the pressure in the cathode tube is in the order of 100 Pascal, and keeper outside is vacuum (the pressure is about 10^{-3}Pa). Therefore, breakdown occurs in the region between orifice tip and keeper, where the gas is throttling expansion. The pressure and temperature is lowered, and the flow rate is increased.

Based on the above analysis, the flow rate simulation model of the orifice hollow cathode was constructed by COMSOL multi-physics simulation software. In the model, the following assumptions are made: (1) The fluid is assumed to be Newtonian fluid that is descripted by Navier-Stokes (N-S) equation, and obey continuity and energy conservation equations; (2) The fluid is a stable, axisymmetric, and isotropic adiabatic laminar flow; (3) The residual gas in the vacuum chamber is subject to the ideal gas state; (4) the wall of vacuum chamber is thermally insulated and has no slip; (5) The thermal flow of the propellant gas is guided by Fourier's Law, $q = -k\nabla T$.

Based on the above assumptions, the physical process of the fluid is described by the Momentum equation, the continuity equation, and the energy equation. The N-S equation is expressed as follows,

$$\rho \frac{\partial \vec{u}}{\partial t} + \rho(\vec{u} \cdot \nabla)\vec{u} = \vec{F} - \nabla P + \mu \nabla^2 \vec{u} + \frac{\mu}{3}\nabla(\nabla \cdot \vec{u}) \tag{2}$$

The density and velocity of the fluid are subject to the continuity equation，

$$\nabla \cdot (\rho \vec{u}) = 0 \tag{3}$$

The energy conservation equation is,

$$\rho c_v (\vec{u} \cdot \nabla) T = K \nabla^2 T - \rho(\nabla \cdot \vec{u}) T \tag{4}$$

The first order approximation of energy conservation equation is,

$$P = \rho R_s T \tag{5}$$

By solving the above equations, we can obtain the velocity field, pressure and temperature distribution of the system.

The Mach number of the velocity field of the propellant gas can be expressed as,

$$Ma = \frac{\vec{u}}{c},\ c = \sqrt{\gamma R T} \tag{6}$$

where ρ is the fluid mass density, $\vec{u}$ is the velocity field, $\vec{F}$ is the external volume force, μ is the annual coefficient, C_v is the isovolumetric specific heat coefficient, T is the temperature, K is the thermal conductivity, c is the sound velocity, Rs is the specific gas constant, R is the gas constant, and γ is the normal pressure heat capacity ratio.

The gas flow of the gas fluid at the time of the hollow cathode ignition is a steady state problem, therefore, $(\partial \vec{u})/\partial t = 0$. The N-S equation is expressed as,

$$(\vec{u} \cdot \nabla)\vec{u} = \frac{1}{\rho}\vec{F} - \frac{1}{\rho}\nabla P + \frac{1}{\rho}\mu \nabla^2 \vec{u} + \frac{1}{\rho}\frac{\mu}{3}\nabla(\nabla \cdot \vec{u}) \tag{7}$$

where $(\vec{u} \cdot \nabla)\vec{u}$ is called the convection acceleration caused by the imbalance of the velocity field distribution, $\frac{1}{\rho}\nabla P$ is the force caused by the pressure gradient, $\frac{1}{\rho}\mu\nabla^2\vec{u}$ and $\frac{1}{\rho}\frac{\mu}{3}\nabla(\nabla \cdot \vec{u})$ refers to the force caused by viscosity.

Model includes a multi-physical coupling method of high Mach number fluid and fluid heat transfer modules. In the model, the keeper, cathode tube and cathode tip material are defined as Ta, the emitter is LaB6, and the working gas is Xe. In Fig.1, in the simulation the upstream of the cathode tube is the gas inlet and the outer region of the keeper is the gas outlet

III.Examples and Results Analysis

A. Xe Gas Pressure Measurement Inside Hollow Cathode

As the basis of the flow field simulation model input or model verification, the internal gas pressure test of the hollow cathode was designed. The test was carried out in the TS-5A hollow cathode ground test vacuum chamber.

The backpressure of vacuum chamber was 10^(-5)Pa. The test equipment and diagram were shown in Fig.2 and Fig.3.

Fig.2 Hollow cathode test vacuum device

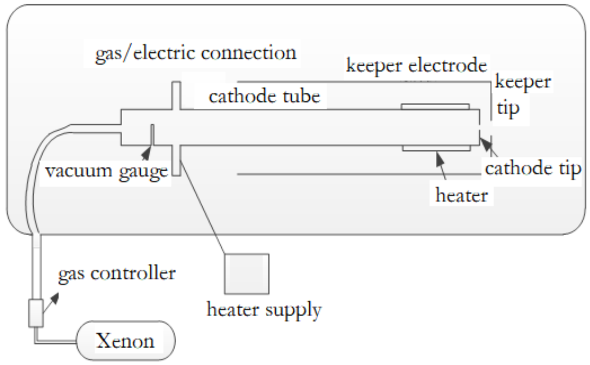


Fig.3 Schematic diagram of the gas pressure test device in the hollow cathode

The temperature and gas pressure at the upstream inlet end of the cathode were measured at 1-5 sccm propellant flow rate with 0A, 4 A, 6 A, and 7.5 A of the heater current. The pressure measurements at the inlet at flow rate of 1-5 sccm are listed in Table 1. The pressure and temperature measurements at the cathode inlet of different heating powers are listed in Table 2, the flow rate is 1.0 sccm.

Table.1 Pressure and temperature measure result at the inlet in different propellant flow rates without heating

No.	Flow rate		Flow rate /sccm/N_2	Vacuum /Pa	The temperature of keeper flange/℃
	sccm	mg/s			
1	0.00	0	0.00	0.0	19.0
2	0.50	0.068	0.46	78.5	19.0
3	1.00	0.136	0.96	157.0	19.0
4	1.50	0.204	1.46	224.0	19.0
5	2.00	0.272	1.96	287.5	19.0
6	2.50	0.34	2.46	348.5	19.0
7	3.00	0.408	2.96	408.0	19.0
8	3.50	0.476	3.47	467.0	19.0
9	4.00	0.544	3.96	524.0	19.0
10	4.50	0.612	4.46	581.0	19.0
11	5.00	0.68	4.96	638.5	19.0

Table.2 Pressure and temperature measurements at the inlet in different heating power

No.	Flow rate		Flow rate measurement /sccm-N_2	Heating current	vacuum test value/Pa	Keeper flange temperature /℃
	sccm	mg/s				
1	1.00	0.136	0.96	0	157.0	19.0
2				4	372.0	165.0
3				6	459.5	261.0
4				7.5	500	312.0

B. Verify of the Simulation Model

Taking the T6 hollow cathode as an example, the calculation results of this model are compared with the results reported in the literature. Fig.4 shows the pressure distribution near the small hole, and Fig.5 shows the velocity distribution on the axis. From the comparison of the simulation results, the trend of the pressure and velocity is the same, but the calculation results of this model are slightly higher than those reported in the literature. The same trend of change can explain the rationality of the calculation model.

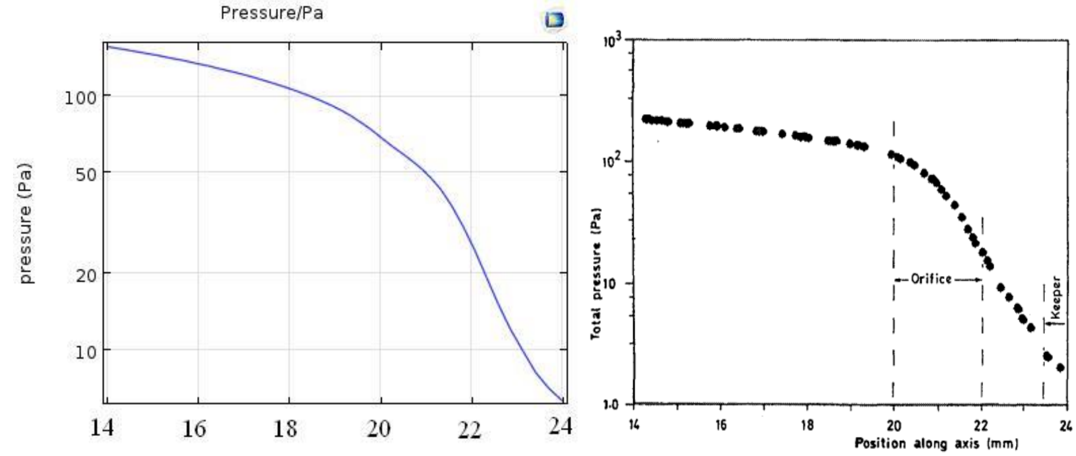


Fig.4 Pressure distribution on the axis comparison of the simulation results of this model and literature[12]

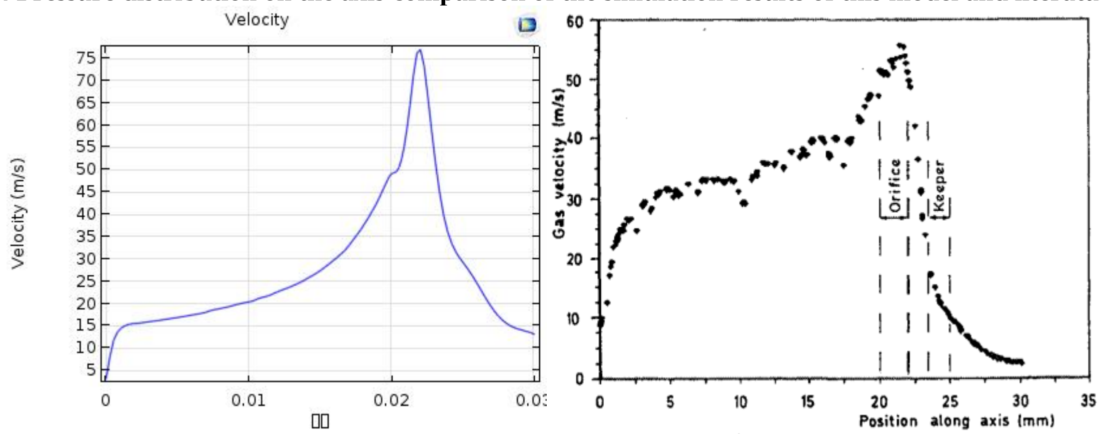
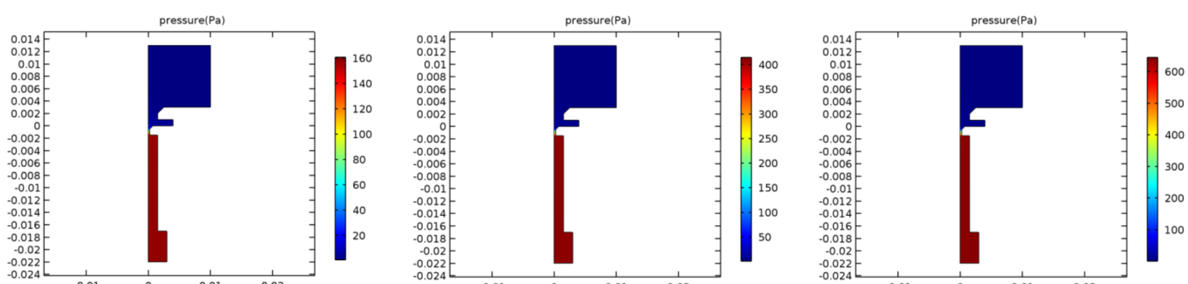


Fig.5 Simulation results of fluid velocity distribution on the axis and comparison of literature report results[12]

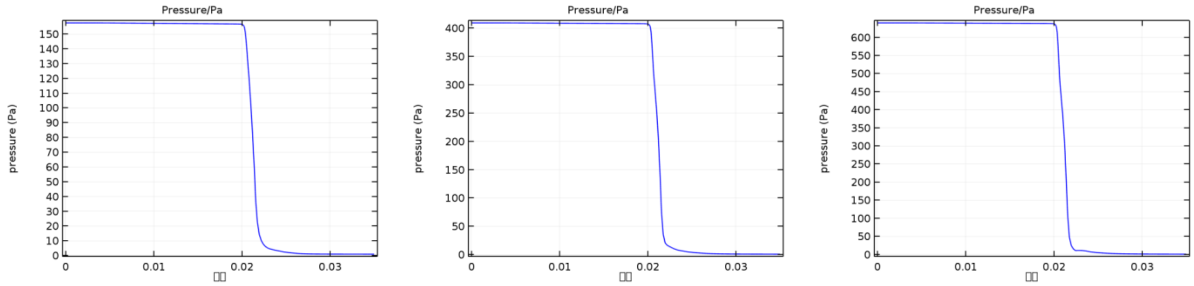
C. The Simulation Result Zero Ampere Heating Current the Flow Field at Different Propellant Flow Rate

The simulation results of the pressure distribution of different propellant flow rates are shown in Fig.6 and Fig.7. Fig.6 shows that as the flow rate increases, the gas pressure in the cathode tube and the emitter cavity increases. Fig.7 shows the variation trend of the values. It can be seen that the pressure distribution in the cathode tube and the emitter cavity area is basically unchanged. The pressure in the cathode tip orifice area (22mm-23mm) is rapidly reduced, which is mainly caused by the equal enthalpy effect of the throttling expansion of the cathode orifice. According to the theory of throttling expansion, the pressure lowers and the temperature also lowers. As shown in Fig.8, the temperature near the calculated small hole drops rapidly.



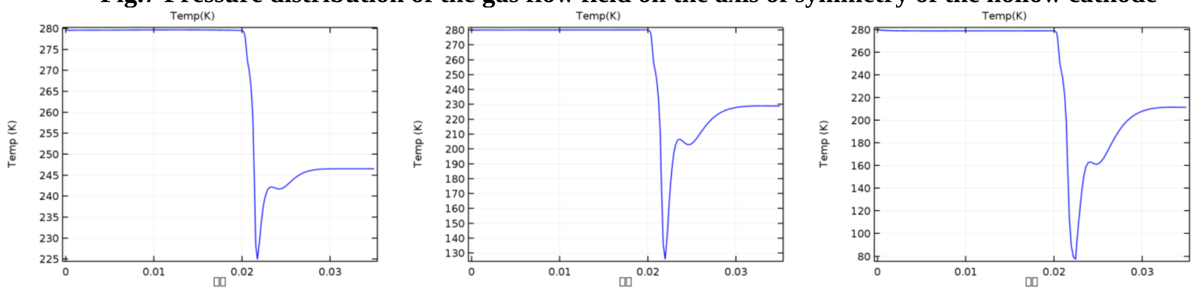
1sscm 3sccm 5sccm

Fig.6 Pressure distribution of the gas flow field inside the hollow cathode



1sccm 3sccm 5sccm

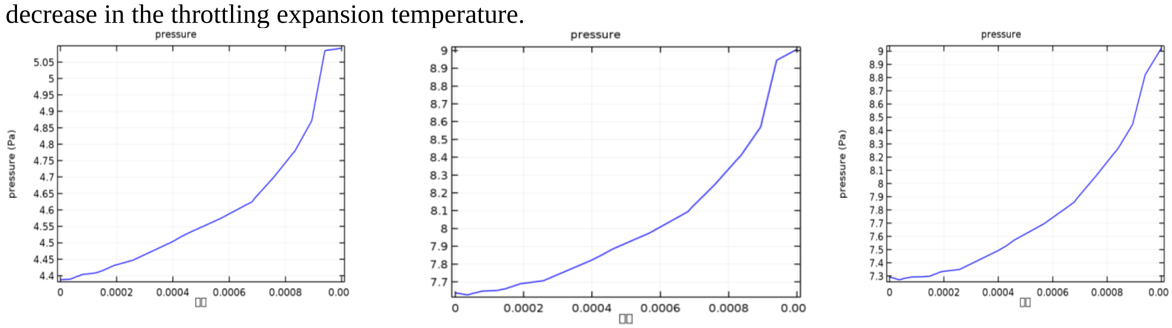
Fig.7 Pressure distribution of the gas flow field on the axis of symmetry of the hollow cathode



1sccm 3sccm 5sccm

Fig.8 Calculation results of temperature change on the axis

Fig.9 shows the pressure distribution at the space of breakdown occurs. It can be seen that the pressure in this region increases as the flow rate increases. Fig.10 shows the maximum and minimum pressures between the orifice tip and keeper at different fluid flow rates. Fig.10 shows that the pressure drops at 5 sccm, which may be due to a decrease in the throttling expansion temperature.



1sccm 3sccm 5sccm

Fig.9 Pressure distribution at the region that between orifice tip and keeper

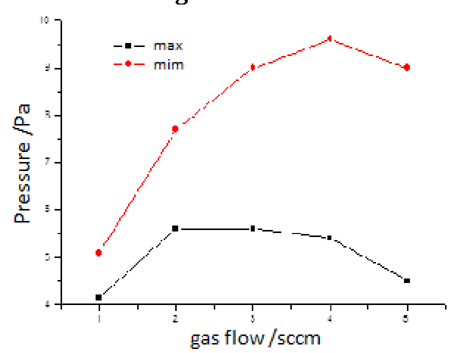


Fig.10 Pressure distribution within the vertical distance between the orifice tip and the keeper

Fig.11 shows the pressure distribution between the orifice tip walls between the electrodes, which has the same tendency to the pressure between the tip and the keeper, as shown in Fig.12.

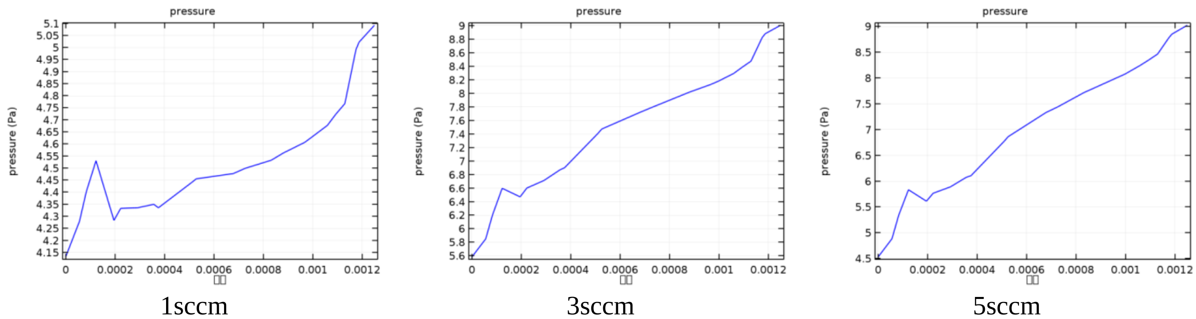


Fig.11 Pressure distribution at the space between the cathode tip and the keeper

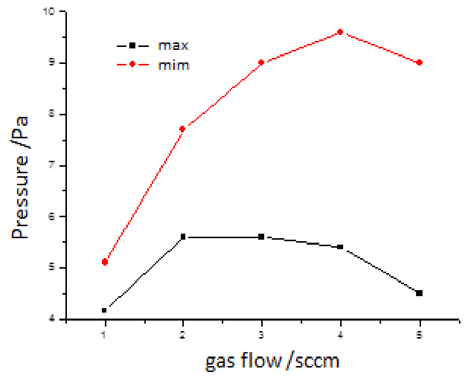


Fig.12 Pressure distribution between the tip and the keeper

D. Simulation of Fluid Flow Field in Preheating Condition with Different Heating Currents at the Same Flow Rate

The flow field distribution of the propellant in the orifice hollow cathode is simulated for different heating powers of the heater. The model is calculated 1 sccm Xenon, 0A, 4A, 6A and 7.5A current heating. The gas pressure distribution results are shown in Fig.13. Fig.13 shows that the gas pressure in the cavity of the cathode tube and the emitter region increases, while the temperature increases for the same working fluid flow rate supply.

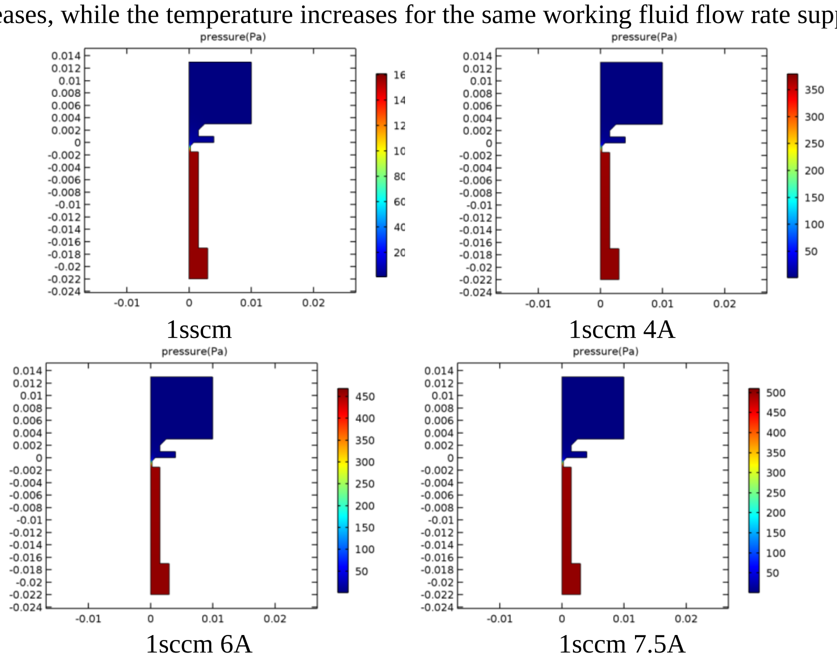
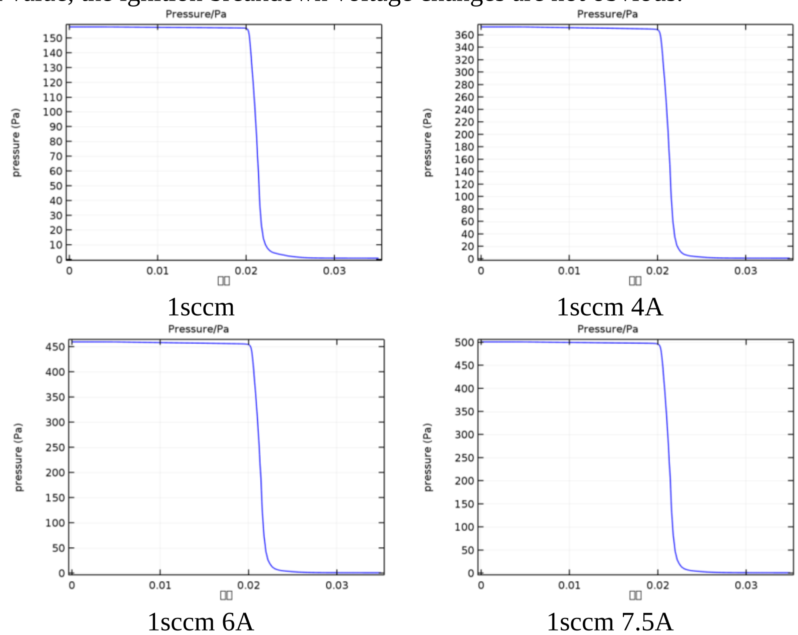


Fig. 13 Flow field distribution of working gas flow at different heating powers at 1sccm flow rate

Fig.14-16 show the relationship between pressure distribution and position on the calculated area axis, the cathode tip and the keeper vertical distance (as shown in Fig.9) and the tip distance on cutting edge (shown in

Fig.11). Fig.14 shows that the pressure in the hollow cathode tube and the emitter cavity increases with temperature, and the relationship between the pressure and the heater current (power) is shown in Fig.17.

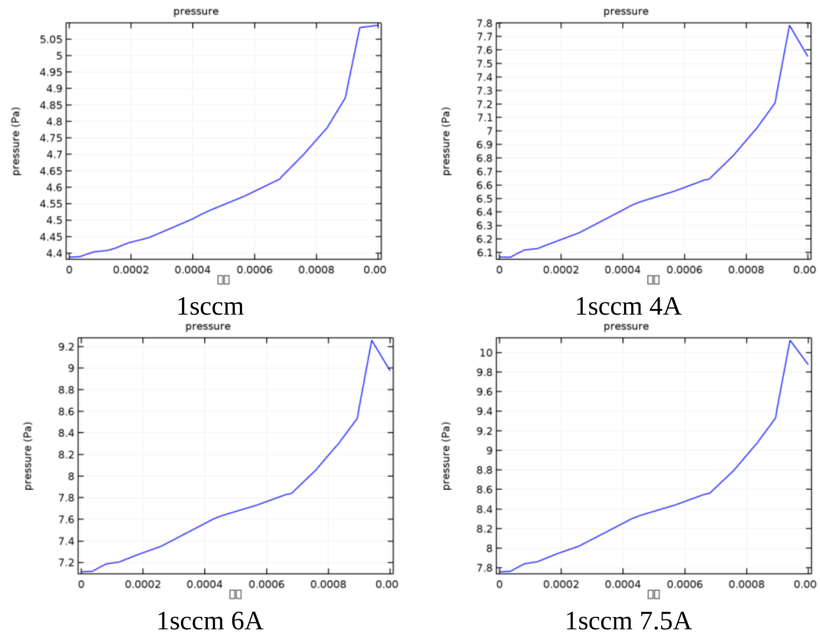
The gas pressure between the cathode tip and the keeper where ignition breakdown occurs monotonously increases, and as the heating current increases, the increasing trend slows down, which is also reflected in the increase in the hollow cathode breakdown voltage as the heating power increases. When the cathode tip temperature increases to a certain value, the ignition breakdown voltage changes are not obvious.



1sccm　1sccm 4A

1sccm 6A　1sccm 7.5A

Fig.14 Pressure distribution on the central axis of the hollow cathode calculation region



1sccm　1sccm 4A

1sccm 6A　1sccm 7.5A

Fig.15 Pressure distribution between the cathode tip and the keeper

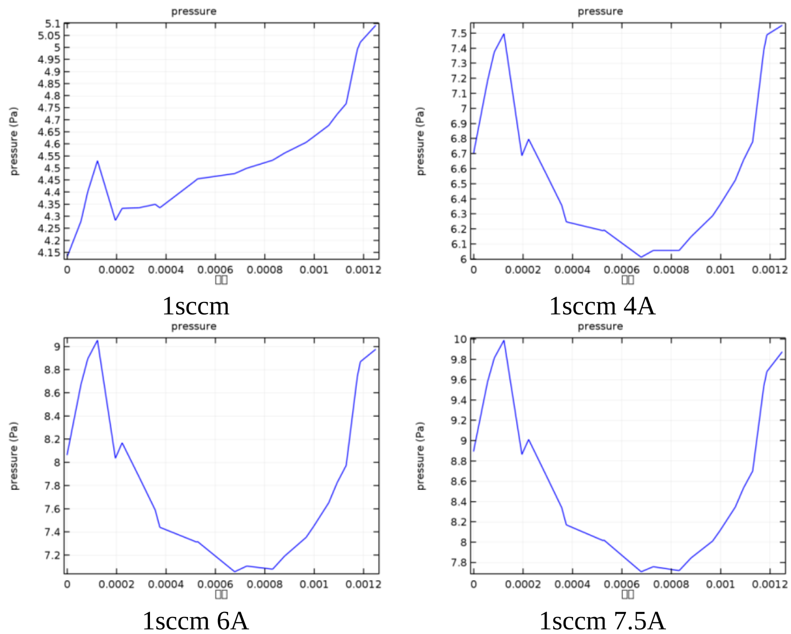


Fig.16 Pressure distribution between the orifice tip and keeper along the sharp corner

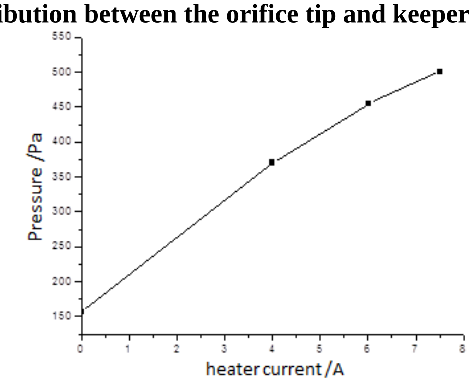
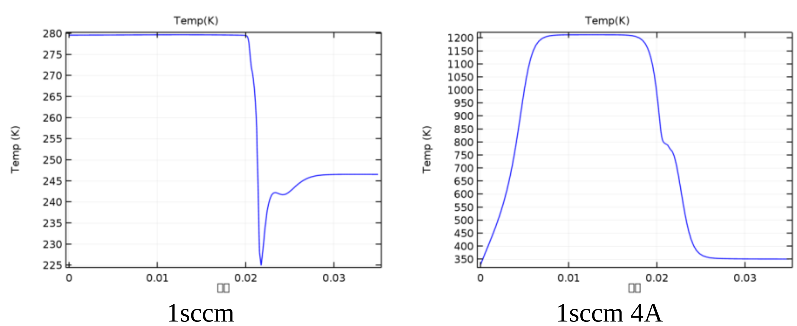
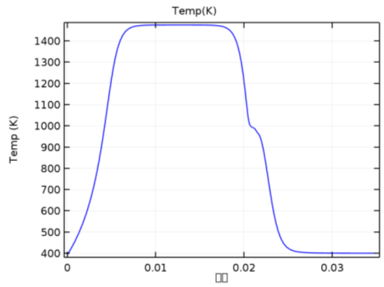
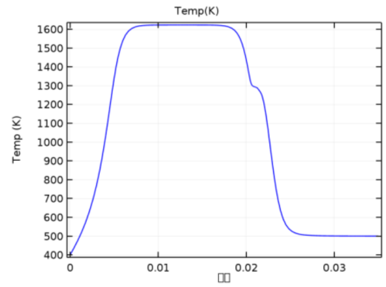


Fig.17 Gas pressure in the cathode tube and emitter cavity as a function of heating current (power)

The effect of heater heating current on fluid temperature is shown in Fig.18. As the heating power increases, the temperature of the gas in the hollow cathode cavity also increases, so that the throttle expansion and cooling effect of the gas in the cathode tip orifice is no longer obvious.





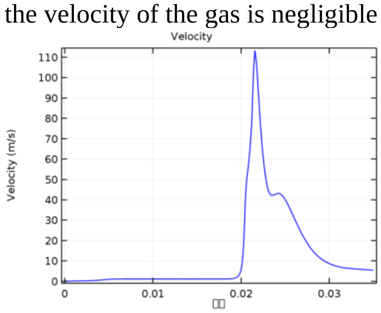


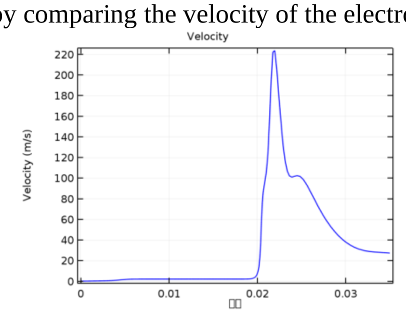
1sccm 6A 1sccm 7.5A

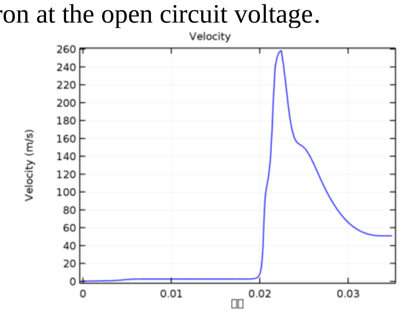
Fig.18 Effect of heating current on the temperature of the gas flow field in a hollow cathode

The following section discusses the gas flow field velocity in the cathode orifice region. Fig.19 shows that the gas flow rate between the cathode tip and the keeper is relatively fast, because the effect of the throttling expansion of the cathode tip orifice. For example, 5sccm, the highest velocity has reached 2.8Ma. Fig.20 shows that the heating power has essentially no effect on the flow rate of the Xenon gas.

Taking the LHC-5 LaB_6 hollow cathode as an example, the open circuit voltage between the cathode tip and keeper before ignition is 60V. According to the energy conservation, the emitter is in the preheating stage (before the hollow cathode ignition breakdown trigger), and the first electronic velocity of the emission reaches up to $2.6 \times 10^6 \mathrm{m/s}$. The electronic velocity is much larger than the highest velocity of the atom in the propellant, so that the velocity of the gas is negligible by comparing the velocity of the electron at the open circuit voltage.

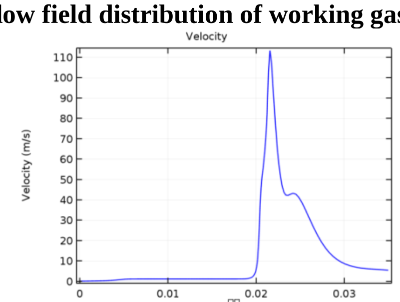


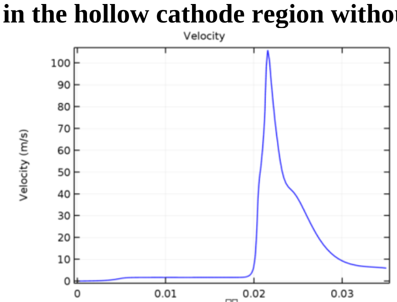




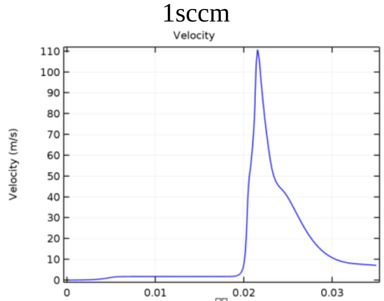
1sccm 3sccm 5sccm

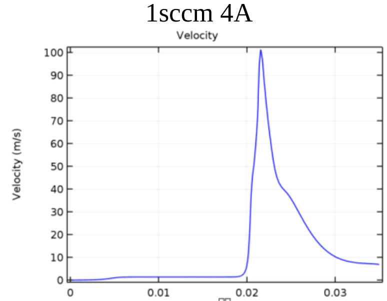
Fig.19 Flow field distribution of working gas in the hollow cathode region without heating





1sccm 1sccm 4A





1sccm 6A 1sccm 7.5A

Fig.20 Effect of temperature on flow rate at 1 sccm Xenon flow rate

IV.Conclusion

By analyzed the characteristics of the hollow cathode preheating ignition breakdown and combining with literatures investigation results, a multi-physics simulation model was established based on fluid flow and fluid heat transfer. The model can simulate the flow rate, hollow cathode preheating power and cathode structure parameters. The influence of parameters on the gas flow field between the orifice tip and the keeper (ignition breakdown electrodes);

a. The model simulation results of the flow field are in good agreement with the data reported in literature;

b. The simulation results show that the gas pressure on upstream of the orifice tip increases with the gas flow rate from inlet, but the gas flow rate has no obvious change;

c. The simulation results show that under the effect of the throttling expansion of the cathode tip orifice, the pressure of the gas in the cathode tip orifice will decrease rapidly, and the effect is continued between the cathode tip and the keeper. The velocity of the gas is increased rapidly, even forming a high Mach fluid;

d. We know the Paschen's law, when the material determined, the parameter that effect the breakdown voltage are pressure Pa and electrode spacing Pd. The calculation results show that under the current structural parameters, with the supply of propellant flow rate, When the flow rate increased, the gas pressure between the tip and the keeper increased gradually, but after the flow rate is larger than a certain value, the pressure decreased, and this phenomenon needs further analysis and simulation verification;

e. Simulation results show that as the hollow cathode preheat current (power) increases, the gas pressure between the tip and the keeper gradually increases, and the pressure in the cathode tube and the emitter cavity also increases accordingly;

f. According to the calculation result, the velocity of the first electrons of the LHC-5 LaB_6 hollow cathode in the ignition preheating stage is much higher than the flow rate of the propellant gas (about 4 orders), so the influence of the gas flow rate on the ignition breakdown can be ignored in the future research;

g. The construction of the simulation model of the hollow cathode propellant gas flow field under multi-physics coupling follows the foundation for further modeling of the hollow cathode ignition breakdown transient process.

Acknowledgments

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