# Numerical Study on Energy Loss in Discharge Channel of Hall Thruster

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**Abstract: In order to clarify the energy loss in discharge channel of LHT-100 thruster, providing accurate boundary parameter for thermal analysis and performance optimization research, the energy loss of discharge channel in LHT-100 thruster is analyzed and discussed based on numerical simulations. The energy loss expressions as a function of microscopic particles parameters is established based on the energy balance relationship in discharge channel. The discharge process is simulated by particles with the Particle-In-Cell-Monte Carlo Collision (PIC-MCC) method, and then the energy loss are calculated directly by statistics of the plasma parameters, at last the verification experiment is performed. The results show that excitation energy loss is 51.1W, the ionization energy loss is 66.2W, the anode energy loss is 55.4W, the beam energy loss is 815.4W, the inner wall energy loss is 144.7W, the outer wall energy loss is 170.5W; the effective energy loss ratio is 61.7%, the remaining energy loss is mainly due to the energy deposition of charge particles on the wall , the cost of plasma reaction is the second, and the energy deposition of electron on the anode is relatively minimum;There is a good agreement between the numerical calculation and test with a maximum error less than 4.5%.**

## I. Introduction

Hall thruster has notable features of high reliability, high specific impulse etc. Therefore, it has been widely applied in spacecraft, in particular for orbit correction and station keeping of geo-stationary satellites[1~3]. A precise calculation of energy loss in discharge channel is critical to evaluate performance and optimize the design for this thruster, offering at the same time energy loading boundary for thruster thermal analysis.

The energy losses are mainly produced in the process of plasma generation and the interaction between the plasma and discharge channel wall. The non-elastic collisions between electrons and atoms need be continuous happened to maintain the discharge process in channel, which the excitation losses and ionization losses will be produced. The charge particles in plasma hit the channel wall and then the energy loss will be produced. Additional loss terms , including anode energy loss, etc.

Several models and methods have been developed for predicting energy loss in discharge channel of Hall thruster. A parametric model of energy loss was developed by researchers at Fakel[] that predicts the proportions of heat flows distribution in discharge channel of SPT thruster. Brophy[]、Goebel[] built a 0-D performance model of Hall thruster, which the energy losses expression is derived from energy balance relationship of discharge channel. Kim et al[] developed a quasi-neutral one-dimensional hybrid model of a Hall thruster for calculating the energy loss. Long et al[] developed a thermal model which the energy loss functions are established based on the operation parameters and structural parameters, the energy loss in discharge channel of LHT100 thruster are calculated and

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verified. These models can provide a quick estimate of the energy loss in discharge channel. However, it is difficult to improve the accuracy of the calculations.

These theoretical methods and models are the most common ways to obtain the energy loss expression derived with plasma average parameters. Due to the large dispersion of ion density and velocities, the plasma parameters are difficult to be obtained accurately, which leads to errors in these empirical model.

In order to calculate truly the energy losses in discharge channel, the plasma in the discharge channel will be simulation by Particle in cell (PIC) methods, the ions and electrons are all be treated as particles, every energy loss is calculated by static the microscopic particle parameters. The thermal analysis and experimental verification are performed to ensure the accuracy of the calculation.

## II. Energy Loss Model

### A. Energy Loss Function Expression

During the operating of Hall thruster, there is a balance relation of power in discharge channel, which the input power equal to the total energy loss. The energy loss in discharge channel is given as:

$$P_d = P_{exc} + P_{ion} + P_a + P_b + P_w + P_{oth} \tag{1}$$

Where $P_d$ is the discharge power given by $I_d V_d$, $P_{exc}$ is the excitation energy loss in the process of excitation collision between electron and atom, $P_{ion}$ is the ionization energy loss, $P_a$ is the energy loss in the anode due to the electron collection, the $P_b$ is the energy loss to accelerate the ions and become the beam, $P_w$ is the energy loss to the channel wall due to charge particles loss, $P_{oth}$ is the ignored energy loss.

（1）Excitation and ionization energy loss

During the operating of Hall thruster, electron and atoms happen inelastic collisions including excitation and ionization collisions to create plasma in the discharge channel. Globally, the average energy loss in excitation collision is about 8.31eV, and the average energy loss in ionization collision is about 12.1eV. Therefore, the number of excitation collisions and ionization collisions per time in discharge channel are counted based on the numerical simulation of Hall thruster, and then the excitation energy loss and the ionization energy loss is given as:

$$\begin{aligned} P_{exc} &= (8.31eV)\, n_{exc} \\ P_{ion} &= (12.1eV)\, n_{ion} \end{aligned} \tag{2}$$

Where $n_{exc}$ is the statistical number of excitation collision, $n_{ion}$ is statistical the number of ionization collision.

（2）Anode energy loss

The anode is a stainless steel structure and has a high potential in discharge channel. There is a low density of ion close to the anode, and ions is repelled due to the anode high potential. therefore the energy loss due to ions flowing to the anode is ignored. The charge particle collection in anode is electrons. There are three kinds of energy loss in the process of each electron hitting to the anode, including the kinetic energy, $\varepsilon_e$, the thermal energy, （3/2） $kT_e$, and the work function of the surface, $eUs$. Us is about 4.5eV for the stainless steel. The electron flux to the anode is calculated by numerical simulation, and then the anode energy loss is written as:

$$P_a = \sum_{j=1}^{n_{e-a}} \left(\frac{3}{2} kT_e + \varepsilon_e + eU_s\right)_j \tag{3}$$

（3）Channel wall energy loss

The channel wall energy loss mainly come from the interaction between the charge particles and the wall, which represents the heating of the discharge channel for Hall thruster. The energy loss from the neutral particles is neglected due to the relatively low energy. The presence of sheath close to the wall will act on the charged particles, which the electrons are decelerated and the ions are accelerated since the sheath potential is positive, meanwhile each charge particle will loss thermal energy,（3/2）$kT_e$, and the kinetic energy,$\varepsilon_{e-w}$ in the process of loss to wall. The channel wall energy loss is given as:

$$P_a = \sum_{j=1}^{n_{e-w}} \left(q_{e,kinetic} + \frac{3}{2} kT_e - e\phi\right)_j + \sum_{j=1}^{n_{i-w}} \left(q_{i,kinetic} + \frac{3}{2} kT_i + e\phi\right)_j \tag{4}$$

Where $N_{e-w}$ is the number of electrons incident to the wall, $\varepsilon_{e-w}$ is the kinetic energy of electron, k is Boltzmann constant, $T_e$ is the electron temperature, e is the electronic charge, q is the sheath potential, $N_{i-w}$ is the number of ion incident to the wall, $\varepsilon i_{-w}$ is the kinetic energy of ions, $T_i$ is the ion temperature.

（4）Beam energy loss

In the discharge channel, the ions are accelerated by the electrical filed to high velocity, and then become beam exhausted. The beam energy loss is defined as the total kinetic energy of ions exhausted from thruster. Each ion has difference velocity exhausted from the thruster due to difference creating position of ions, so the beam energy loss is given as

$$P_b = \sum_{j=1}^{n_i} (\frac{1}{2} m v^2{}_i)_j \qquad (5)$$

Where Ni is the number of ions exhausted from thruster, M is the mass of ion, vi is the velocity of ion.

（5）Other energy loss

The other energy loss are mainly derived form the model simplification and the numerical calculation. Some energy loss terms in modeling is ignored, such as the ions energy loss to anode, the energy loss that neutral atoms unionization in discharge channel take into the beams, etc. at the same time, there is a calculation error in the numerical simulation of plasma in discharge channel of Hall thruster.

**B. PIC/MCC Simulation**

A Fully Kinetic Particle-in-Cell code with Monte Carlo Collisions (PIC-MCC) is developed to simulate the steady-state operating regime of a Hall thruster, which is a laboratory modification of the SPT100 thruster designed at Lanzhou Institute of physics, China.

Figure 1 shows the calculation area of the numerical simulation. A 2-D axial symmetry simulation model is developed, which the space is two dimensions, (z, r), and the velocity is three dimensions,($v_z$， $v_r$， $v_\theta$). The left of the calculation area is the anode, the upper and the lower are the channel walls, and the right side is the channel exit. During the simulation, the particles will be destroyed, re-emitted or collected when they hit to the boundaries. The electrons that encounter all boundaries are deleted, ions that encounter the channel walls are re-emitted into the calculation area as neutral atoms, and has the same temperature as the channel wall. When ions encounter the other boundaries, they are deleted.

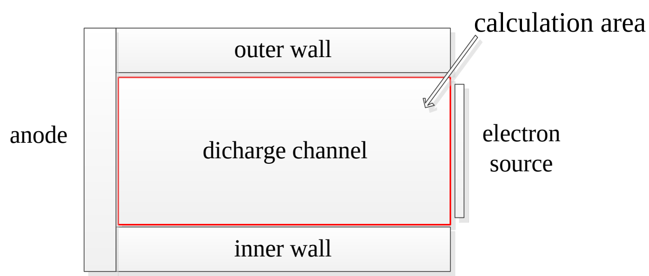



Fig.1 Schematic calculation area

Figure 2 shows the flow chart of numerical simulation. The plasma flow in the discharge channel of Hall thruster is simulated by PIC/MCC method. The basis steps in the modeling process are described as following: first, the conditions of simulation are initialized, which calculation area is meshing by the orthogonal isometric method, boundary conditions are determined combine the operating parameters, and the magnetic field in the discharge channel is introduced by finite analysis. Second, PIC module mainly include primary electrons incidence, electrical field solving, charge particles movement, etc., the primary electrons emitted from the cathode are treat as a simplistic model which a ring-shaped electron source at the channel exit, the initial energy of primary electrons are supposed to be 20eV, and incident into the channel following the Half-Maxwell distribution model. the potential is computed with the Poisson equation, an equidistant square grid is assumed and a centered five-point scheme is applied to solve the equation, and then the electrical field is given by $E = -\nabla\phi$. Charge particle motion follows Newton's second law, which the charge particles forces include the electric filed force and the Lorentz force. The motion equations of charge particles for an discrete time is solved by the leap-frog/Boris algorithm. Third, the collisions process between particles are modeled by Monte Carlo method, the collision cross section is from reference[]. The collision types in the simulation include electron-neutral collision, charge-exchange collision between ions and atoms. The above process is cycled until the convergence condition is satisfied.

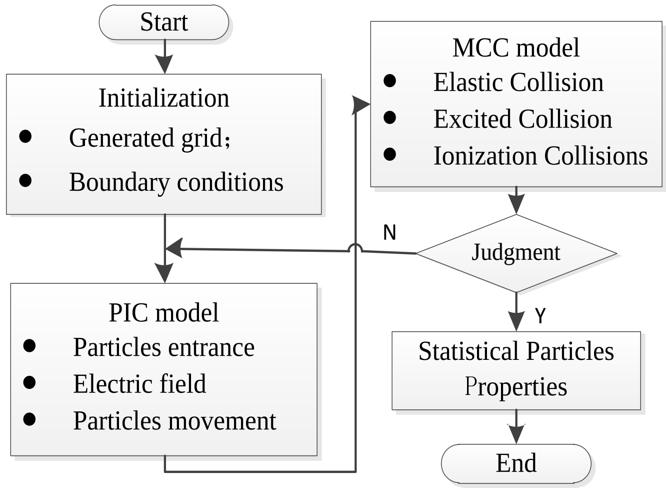



Fig.2 Flow chart of the simulation

Figure 3 shows the simulated radial magnetic filed along the axial direction in the discharge channel of Hall thruster. The magnetic field is implemented into the simulation software in a reprocessing. We calculate the magnetic field using the Ansys software. In order to achieve the ideal magnetic field topology [21], the currents of the magnetic coils and the magnetic screen geometry are iteratively adjusted. The magnetic field is interpolated by a bilinear function from the magnetic calculated grid to the plasma computational grid.

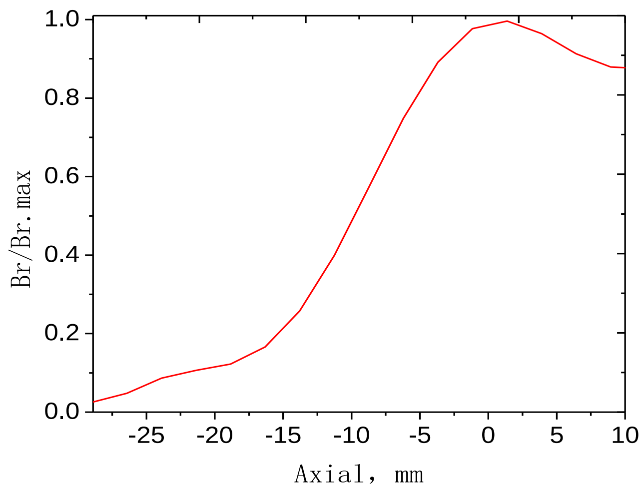



Fig.3 Magnetic field along the center of the channel

In a PIC/MCC simulation model, each simulation particles presents millions of real particles in discharge channel of thruster. The time step and grid size in the simulation need to meet the plasma oscillation frequency and debye length and other plasma characteristic. In order to avoid the instability of simulation, there must be more than 10 macro particles per calculation cell. The debye length of plasma in the discharge channel of Hall thruster is about several to several ten microns and the plasma frequency is about several hundred GHz. Therefore, the number of simulation particles will be about several millions. This is difficulty to achieve at the present computer technology. An integrated approach combines artificial increasing permittivity constant and light weighed heavy particles are used to achieve quicker steady state result[]. This approach is also taken in our simulation model.

The full kinetic PIC/MCC model has been successfully applied in the research on the numerical simulation of performance of Hall thruster[8]. The plasma parameters such as plasma density, potential, charge particles energy, etc.in the discharge channel could be obtained through simulation of the model. The more detail describe about the PIC/MCC model of Hall thruster is introduced in reference[9], we will not repeat them.

Table 1 shows the parameters of LHT100 thruster.

Table 1 The parameters of LHT-100 Hall thruster

| discharge voltage $V_d$/V | discharge current $I_d$ /A | cathode current /A | cathode voltage/V | inner radius /mm | outer radius /mm | discharge channel length /mm |
|---|---|---|---|---|---|---|
| 300 | 4.4 | 1.2 | 16 | 35 | 50 | 26 |

In order to demonstrate the convergence speed and stability of the numerical model, we have performed a simulation combine with the LHT100 parameters. Figure 4 displays the number of particles varying with the running-steps in simulation. The model reaches convergence at the step size of 7000, and the total number of electrons, single charge ions, doubly charge ions are $3.4\times10^5$, $3.4\times10^5$, $0.4\times10^5$, respectively.

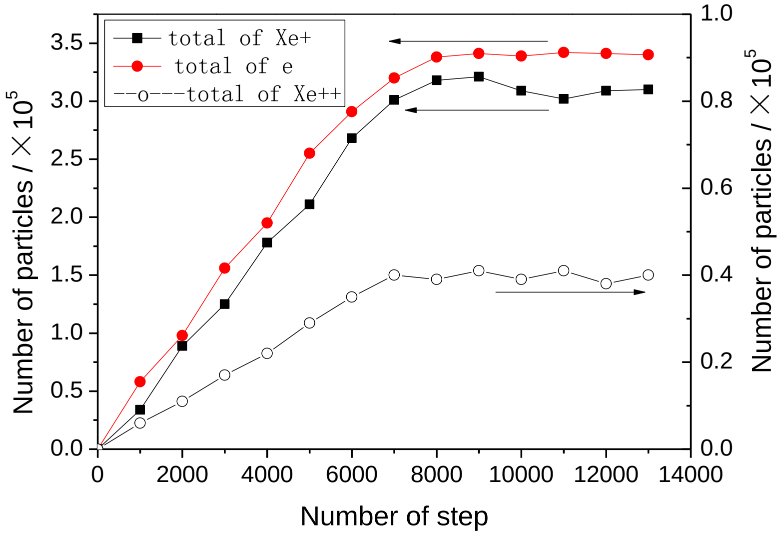



Fig.4 the number of ions and particles varies with the running steps.

## C. Energy Loss Calculation

（1）Excitation and ionization energy loss

The number of excitation collisions and ionization collisions is shown in Fig.5. The number of collisions for 10 time steps is statistics as samples data after the simulation convergence. The result shows that the number excitation collision and ionization collision in the discharge channel is about $3.84\times10^{19}$ /s and $3.35\times10^{19}$ /s, respectively. The volume of discharge channel for LHT100 thruster is about $1.0\times10^{-4}$m$^3$, then the average ionization rate is estimated as $3.35\times10^{23}$/m$^3$s.

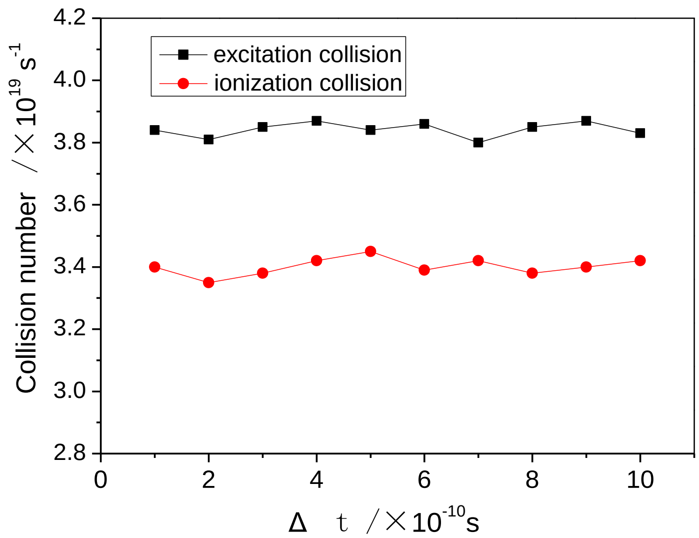



Fig.5 the number of excitation collisions and ionization collisions

Based on the statistics results from Fig.5, the excitation energy loss and the ionization energy loss is calculated by equation (2). The results show that the excitation energy loss and the ionization energy loss in the discharge channel is 51.1W and 66.2W, respectively. The total energy loss of plasma generation is about 117.3W for LHT100 thruster.

（2）Anode energy loss

The collection number of electron in anode for 15 time steps is averaged after the simulation convergence and the results is shown in Fig.6. The average number of electron incidence anode is about $2.9\times10^{19}$ /s for the thruster, and the discharge current could be estimate as 4.62A, which is close to the experimental result 4.5A.

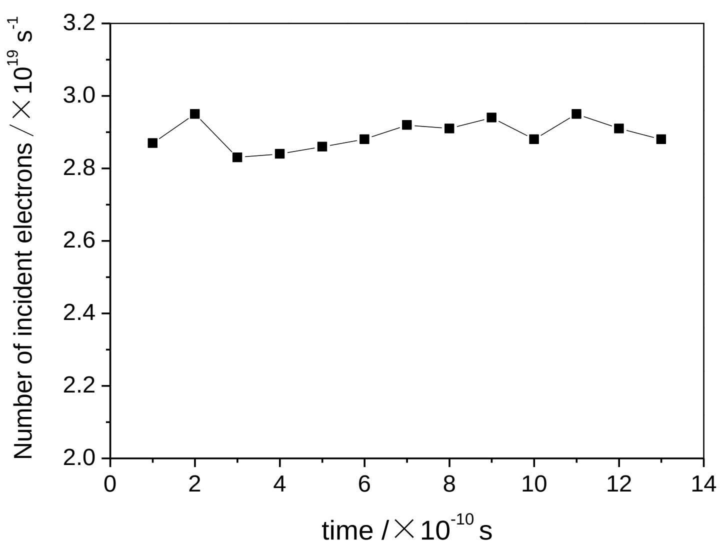
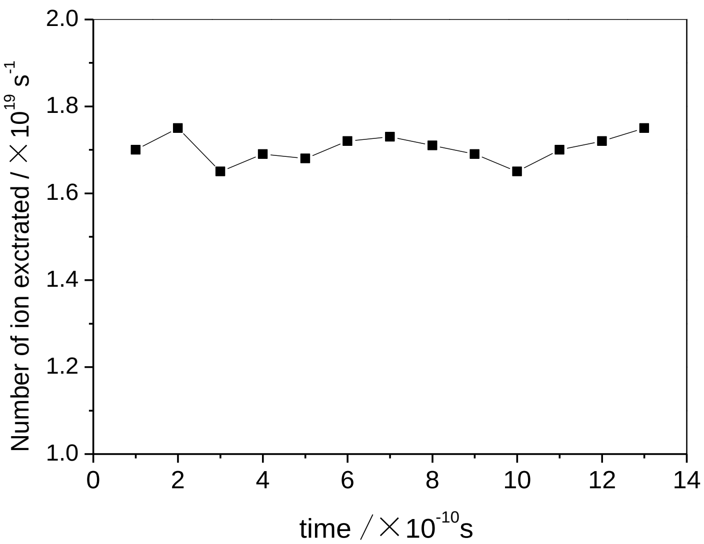



Fig.6 The amount of Electron incidence in anode

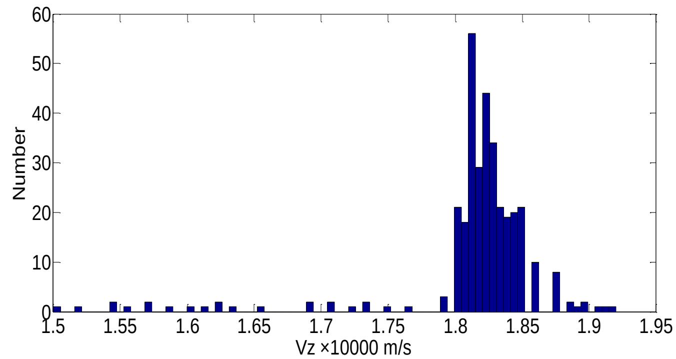
The electron temperature is about 4.2eV[] near the anode, and the work functions of the anode is about 4.8V, combine with the number of electron incidence, the anode energy loss is calculated as 55.4W, the anode area of LHT100 thruster is about $4.0\times10^{-3}$m$^2$, and then heat flows of anode is about $1.3\times10^4$ W/m$^2$.

（3）Beam energy loss

The statistics result of ion exhausted number and velocity is shown in Fig.7. The result in Fig.7(a) show that The number of ejected ions is mainly concentrated in the range of $1.65\times10^{19}$ ~$1.73\times10^{19}$/s, and then the beam current calculated is about 3.1A, which is slightly lower than the beam test value of 3.2A. The Fig.7(b) shows the probability distribution of axial exhaust velocity for ions at the exit plane, which the statistic samples are about 2000. the maximum and minimum values of ion velocities are about $1.9\times10^4$ m/s and$1.5\times10^4$ m/s, respectively, and more than 95% of the ion velocity is concentrated between $1.8\times10^4$ ~$1.85\times10^4$ m/s. The ion velocity is mainly related to the initial position of ion generation and the potential distribution in the channel. Because the ions are mostly produced in the ionization zones, these ions have almost the same velocity.when the initial position of ion generation is close to the acceleration zone, the velocity of ion exhausted at the exit of channel is lower due to the less acceleration energy obtained. Meanwhile, the other factor for reducing the velocity of ion exhausted is charge exchange collisions (CEX) between fast ions and slow atoms, which the slow atom become a new slow ion (CEX ion) due to obtaining an electron from the fast ion. Because the CEX ion has less energy from re-accelerating in the discharge channel, and the CEX ions velocity is much lower than the average velocity.




（a）number of ions exhausted




（b）velocity of ions exhausted

Fig.5 the statistics number of ion exhausted amount and velocity

The beam energy loss is calculated by integrating all the kinetic energy of ions exhausted from the thruster. The result shows that the beam energy loss is about 815.4W. There is about 1320W of input power in the LHT100 thruster, the calculated electrical efficiency is about 61.7%, and then the anode efficiency is calculated as 55.5% assuming the doubly charge rate is 0.1.

（4）Channel wall energy loss

The channel wall energy loss is related to the sheath potential and the electron temperature. Therefore, the sheath potential distribution and the electron temperature distribution need to be simulation calculated firstly. The result is shown in Fig.6. There is the minimum value of electron temperature near the anode, and then electron temperature gradually increase to the maximum value from the anode(z=0) to the z=21mm, after which the electron temperature begins to drop rapidly.

The interaction between electrons and channel wall could be describe by Space Charge Limited model. The relations between sheath potential and electron temperature is reference literature[], and the sheath potential distribution is calculated combine the electron temperature distribution in the discharge channel of LHT100 thruster.

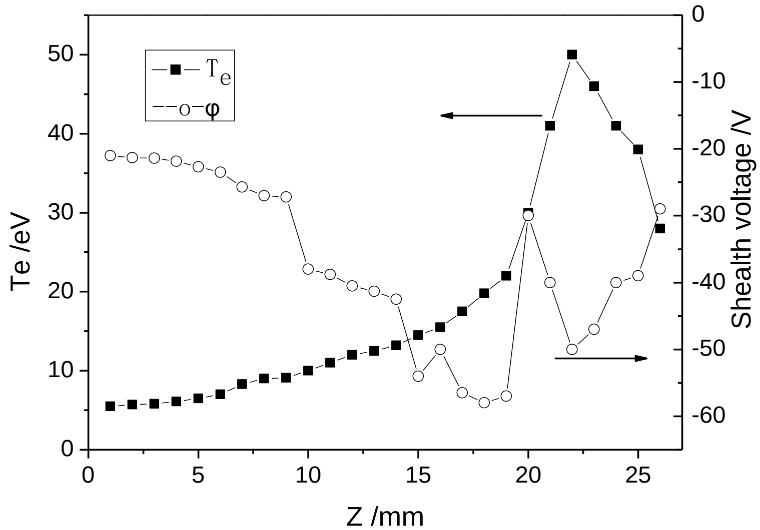



Fig.6 Electric temperature and sheath voltage distribution

The statistic number of charge particle incidence the channel wall is shown in Fig,.7. The result shows that the number of electron incidence the inner wall and outer wall are about $6.7\times10^{18}$ /s and $9.6\times10^{18}$ /s, respectively; the number of ion incidence the inner wall and outer wall are about $0.8\times10^{18}$ /s and $1.2\times10^{18}$ /s, respectively. The electron incidence number is about 8 times of the ions incidence number. Because of the secondary electron emission of the wall, the incidence number of electron is larger than ion number to meet the charge quasi-neutral condition

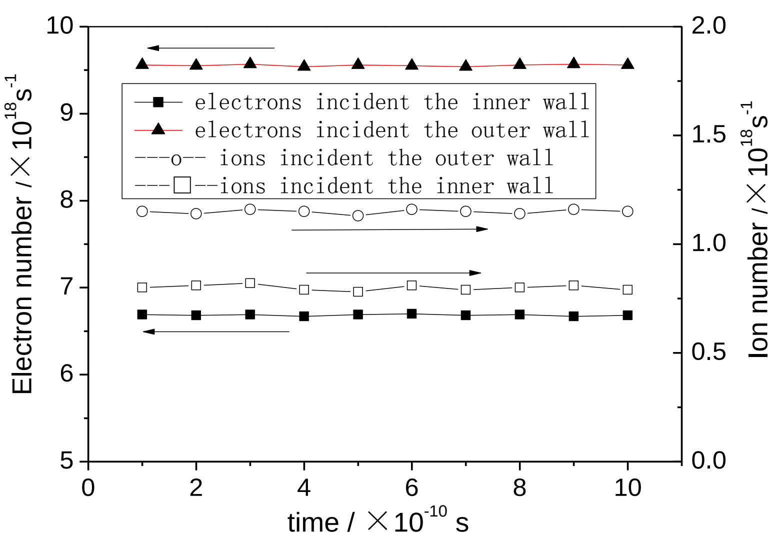



Fig.7 statistics number of charged particles incident in wall

The wall energy loss is calculated by the statistic number combine the equations (3). The result show that the inner wall energy loss is about 144.7W, the outer wall energy loss is about 170.5W. In contrast, the out wall energy loss is greater than the inner wall energy loss. The reasons is that the area of outer wall is bigger than the inner wall based on the similar condition of the plasma density radial distribution and potential radial distribution.

(5) Analysis of energy loss radio

The comparison of energy loss in discharge channel between the numerical calculation and empirical model is shown in table 2. The result show that the values are similar from the two methods. In contrast, the beam energy loss of numerical calculation is slightly lower than the value of empirical model, while the other energy losses are higher than the empirical model. The empirical model is established based on the estimation of plasma density, sheath potential, and average kinetic energy of charge particles, etc., resulting some errors in the empirical model. The difference in micro particles parameters is accurately described and the CEX collision is considered, and therefore there is a good accuracy in the numerical model. The specific impulse calculated is about 1577s, with the test result 1600s more similar.

Table 2 Energy loss list in LHT-100 thruster

| no | components | literature[8]/W | calculation/W |
|---|---|---|---|
| 1 | Discharge （$P_d$） | 1320 | 1320 |
| 2 | Excitation （$P_{exc}$） | 33.6 | 51.1 |
| 3 | Ionization ($P_{ion}$) | 42.9 | 66.2 |
| 4 | Anode ($P_a$) | 44 | 55.4 |
| 5 | Beam current ($P_b$) | 889.2 | 815.4 |
| 6 | Wall ($P_w$) | 297.9 | 315.2* |
| 7 | Other heat ($P_{oth}$) | 12.4 | 16.7 |

*Outer wall energy loss is 170.5W， inner wall energy loss is 144.7W。

The energy loss radio in the discharge channel is further obtained. The result show that the radio of the excitation energy loss, ionization energy loss, anode energy loss, beam energy loss, inner wall energy loss, and outer wall energy loss are 3.8%, 4.9%, 4.1%, 61.7%, 10.7%, 12.7%, respectively. Because the beam energy loss is the efficiency energy loss, and Increasing the beam energy loss ratio is the optimization target of Hall thruster.

### D. Thermal Analysis and Experimental

In order to verify the energy loss calculation, the temperature distribution of LHT100 thruster is calculated, which the anode energy loss and channel wall energy loss are used as heat flows conditions. Meanwhile, an experimental has been performed to test the temperatures of thruster. The detail describe of equipment is in the literature[],When the thruster reaches the heat stabilized in vacuum, the temperature of thurter are measured by T type of thermocouples. The temperature experiment of LHT100 thruster is shown in Fig.8.

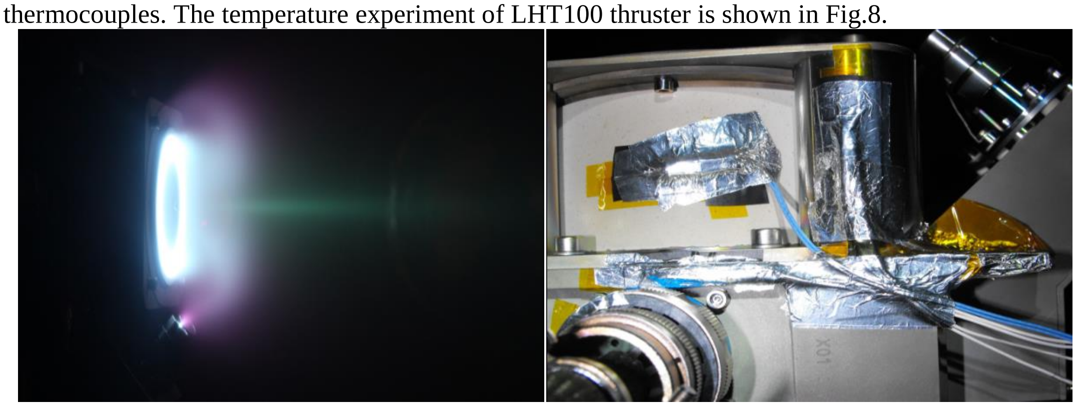


Fig.8 Temperature test of LHT-100 thruster

The temperature distribution of thruster calculated by ANSYS is shown in Fig.9. The result show that the temperature range of thruster is between 374℃~478℃, the maximum temperature is on the exit of discharge channel and the minimum value is on the magnetic base. The temperature of channel inner wall and outer wall gradually increases along the axial direction.

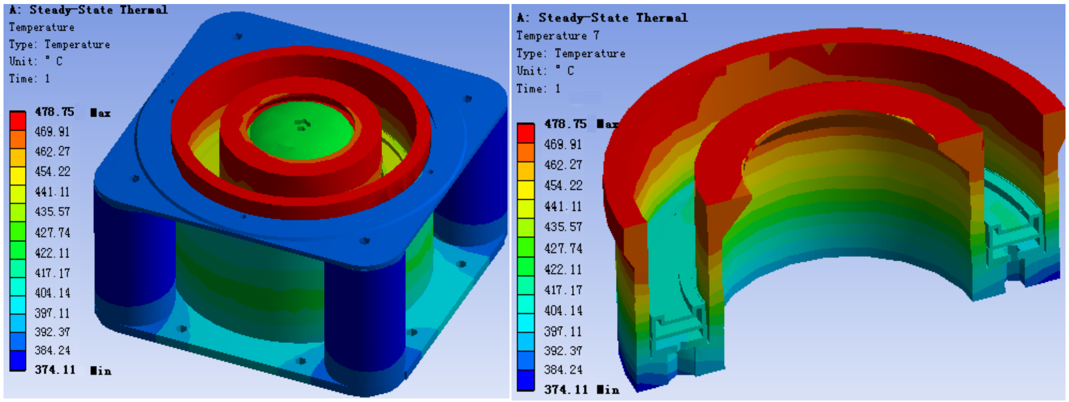



Fig.9 Temperature distribution of LHT-100 thruster

The table 3 shows the comparison between calculation results and temperature measurements. On the condition of steady-state temperature for the thruster, the two results have a good agreement with a maximum error less than 4.5%. It is indicated that the heat flow condition of temperature calculation is reasonably, and then the accuracy of the energy loss calculation is indirectly verified.

Table 3 Simulation results and experimental results (unit：℃)

| components | numerical | experimental | error/% |
|---|---|---|---|
| magnetizer | 206 | 200.8 | 2.5% |
| near connector | 125 | 119.5 | 4.6% |
| outer coil | 161 | 154 | 4.5% |
| upstream Inner coil | 372~379 | 377~397 | 4.5% |
| insulation | 150 | 156 | 3.9% |
| discharge chamber | 374~478 | - | - |
| anode | 401~416 | - | - |

## III. Conclusion

（1）the energy loss in the discharge channel of LHT100 is calculated. The result show that excitation energy loss is , ionization energy loss, anode energy loss, beam energy loss, inner wall energy loss, and outer wall energy loss are 51.1W, 66.2W, 55.4W, 815.4W, 144.7W, 70.5W, respectively.

（2）the radio of energy loss in the discharge channel indicated that the maximum energy loss is used to accelerate ions. The remaining energy loss is mainly due to the energy deposition of charge particles on the wall, the cost of plasma reaction is the second, and the energy deposition of electron on the anode is relatively minimum.There is a good agreement between the numerical calculation and test with a maximum error less than 4.5%

（3）A new energy loss model is established based on the PIC/MCC simulation, which the energy losses are calculated by statistic micro particles parameters. This approach is verified by experiment, and provides a new idea for the calculation of energy loss of Hall thruster

## References

The following pages are intended to provide examples of the different reference types. You are not required to indicate the type of reference; different types are shown here for illustrative purposes only.

*Periodicals*

[1]LONG Jian-fei，ZHANG Tian-ping，SUN Ming-ming, et al.Studies on Key Parameters of Magnetic Engineering Design in LHT-100 Thruster[J].Journal of Propulsion Technology,2015，36(9):1432-1438

[2]SUN Ming-ming，GU Zuo，MA Yong-bin，et al. Thermal Analysis of a LHT-100 Hall Thruster[J]. Journal of Propulsion Technology, 2014，35（12）：1715-1720

[3]TIAN Li-cheng，GUO Ning，LONG Jian-fei, et al. Experimental Study of LHT-100 Hall Thruster Operation in the Wide Power Range[J].Journal of Propulsion Technology, 2014，35（9）:1283-1288)

[4]Archipov B, Krochak L Z, Maslennikov N .Thermal Design of the Electric Propulsion System Components[R]. AIAA 98-3489

[5]Brophy J R, Barnett J W, Sankovic J M, et al. Performance of the Stationary Plasma Thruster: SPT-100[R], AIAA-92-3155

[6]Goebel D M, Katz I. Fundamentals of Electric Propulsion: Ion and Hall Thrusters [M], California: California Institute of Technology 2008, 340-351

[7]Kim V. Main Physical Features and Processes Determining the Performance of Stationary Plasma Thrusters[J].Journal of Propulsion and Power, 1998,14(5):736-740

[8]LONG Jianfei, SUN Mingming, ZHANG Tianping. Thermal model of Hall thruster[J]. High Power Laser and Particles Beams, 2014，26(12): 124002

[9]YAN Li, WANG Ping-yang, OUYANG Hua. Thermal Analysis of the Hall Thruster in vacuum[J].Vacuum, 2014, 108: 49~55

[10]Kim V, Kozlov V, Popov G, et al. Investigation of the Stationary Plasma Thruster Outgassing and Its Thermal Station Impact on Thruster Performance Variation in Time[R]. IEPC 1999-084

[11]Szabo JJ. Full Kinetic Numerical Modeling of a Plasma Thruster[D]. Massachusetts: Massachusetts Institute of Technology，2001

[12]Hobbs G D, Wesson J A. Heat Flow Through a Langmuir Sheath in the Presence of Electron Emission[J] Plasma Physics,1967, 12(9):.85-87

[13]LONG Jianfei, ZHANG Tianping, SUN Mingming. Numerical simulation of performance in Hall thruster[J]. Journal of Solid Rocket Technology, 2015,38(4):514~518

[14]Ahedo E, Gallardo J M, Martinez-Sanchez M. Effects of the Radial Plasma-Wall Interaction on the Hall thruster Discharge[J].Physics of Plashmas, 2003, 10(8):3379-3409

[15]Operating model investigation of a laboratory stationary plasma thruster[R], AIAA 99-2567

[16]TIAN Li-cheng, GU Ning LONG Jian-fei.et al. Experimental Study of LHT-100 Hall Thruster Operation in the Wide Power Range[J].Journal of Propulsion Technology,2014,35 (9):1283-1289.