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Analysis of Numerical Simulation Results of LIPS-200 Lifetime Experiments

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Abstract Accelerator grid structural and electron backstreaming failures are the most important factors affecting the ion thruster's lifetime. During the thruster's operation, Charge Exchange Xenon (CEX) ions are generated from collisions between plasma and neutral atoms. Those CEX ions grid's barrel and wall frequently, which cause the failures of the grid system. In order to validate whether the 20 cm Lanzhou Ion Propulsion System (LIPS-200) satisfies China's communication satellite platform's application requirement for North-South Station Keeping (NSSK), this study analyzed the measured depth of the pit/groove on the accelerator grid's wall and aperture diameter's variation and estimated the operating lifetime of the ion thruster. Different from the previous method, in this paper, the experimental results after the 5500 h of accumulated operation of the LIPS-200 ion thruster are presented firstly. Then, based on these results, theoretical analysis and numerical calculations were firstly performed to predict the on-orbit lifetime of LIPS-200. The results obtained were more accurate to calculate the reliability and analyze the failure modes of the ion thruster. The results indicated that the predicted lifetime of LIPS-200's was about 13218.1 h which could satisfy the required lifetime requirement of 11000 h very well.

Keywords: LIPS-200 ion thruster, accelerator grid structural failure, electron backstreaming failure, lifetime

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(Some figures may appear in colour only in the online journal)

1 Introduction

Ion electric propulsion [1,2] is one kind of advanced space technology, which has the advantages of high specific impulse, high efficiency and long lifetime. By using the ion electric propulsion system on a spacecraft, the satellite's effective payload mass can be reduced, the thruster's lifetime can be extended and the launching costs can be reduced.

The LIPS-200 ion thruster [3,4] was developed by the Lanzhou Institute of Physics which aims at performing NSSK of China's Geostationary Orbit (GEO) satellite. This thruster successfully flew in 2012. After that, aiming at the normal application, the thruster's reliability and safety design have been strengthened, seven aspects such as the structural mechanical design, thermal design and high voltage safety have been optimized, and the optimized thruster will be applied to China's electric propulsion satellite XX. According to the designed parameters, LIPS-200 should be able to operate 12-15 thousand hours and can switch on/off 5500-8000 times. In previous work, we have analyzed and summarized the related datas from the ground lifetime experiments of an ion thruster which was used for a foreign NSSK GEO satellite; following that analysis, the technical scheme of the ground lifetime experiment for LIPS-200 was proposed [3,4]. Considering the present status of the LIPS-200 ion thruster and the experimental constraining conditions, the lifetime validation experiment was carried out for LIPS-200 and 5680 hours' experimental datas have been accumulated to date. The results of the ground [5] and in-orbit [6,7] experimental tests of previous ion thrusters showed that the wear-related failure modes were more than 20 types, of which the most important ones, that determine the lifetime of the thruster and are related to the plasma sputtering erosion, are the accelerator grid structure [8] and electron backstreaming failure [9]. These two failures occur due to the increasing of the diameter and depth of the accelerator grid, because of sputtering of the Charge-Exchange-Xenon (CEX) ions.

Due to the existence of the high electric field around the accelerator grid, the CEX ions impinging on the downstream surface of the accelerator will cause the pit erosion between two apertures and groove erosion among three apertures [10−13]. When the pit and groove completely penetrate the grid, the grid system structure will change [14,15], and then the grid spacing will change because of the change of the rigidity of the accelerator. This will change the electric field near the accelerator grid, therefore the focusing characteristic of the beam ion and hence the thruster's performance will be changed. Thus, understanding the bombarding sputtering of the CEX ions to the accelerator grid is of great importance to predict the thruster's lifetime [10] and analyze the extraction characteristic of the beam ions. On the basis of the failure mechanisms of the accelerator grid, in 1993s, Brophy et al. [10] firstly established a semi-empirical lifetime model and calculated the thruster's lifetime; comparisons with experimental results were also performed. The same model was also used by Jonathan et al. [16] to evaluate the operating lifetime of NASA's Evolutionary Xenon Thruster (NEXT). In 2001, Masakatsu et al. [17] built a three-dimensional lifetime model of an ion thruster optics system; they obtained that the beam current and voltage of the accelerator grid were the main factors determining the performance and lifetime of the thruster. In 2008, Liu et al. [18] applied a three-dimensional model to calculate the depth of the sputtering erosion and predict the lifetime of the grid. Recently, Sun et al. [13] developed a two-dimensional particle model to investigate a three-grid electron cyclotron resonance ion thruster, the rule of a deceleration grid on the performance of the grid system was specified.

In a word, there are many research works investigating the performance and predicting the lifetime of the grid system of the ion thruster. However, most of them only paid a little attention to the effect of actual experimental data on the lifetime of accelerator grid structural and electron backstreaming. In this paper, the experimental results after 5500 h of accumulated operation of the LIPS-200 ion thruster are present firstly. Then, combining those test results, theoretical analysis and numerical calculations are carried out to predict the LIPS-200's lifetime. For the simulation part, a two-dimensional Particle-in-Cell and Monte-Carlo model [19−23] are used.

This paper is organized as follows. In section 2, the experimental results of the erosion depth and variation of the diameter of the accelerator grid are presented. Then, based on those tests, section 3 discusses two typical failure modes and the lifetime of the ion thruster is predicted numerically. Finally, a brief conclusion is given in section 4.

2 Analysis of the experimental results

The schematic of the TS-7 vacuum chamber of the LIPS-200 ion thruster's ground lifetime test is shown in Fig. 1. The diagnostic equipment is outside of the chamber. To reduce the exposure frequency to atmospherics, the erosion morphology of the downstream accelerator grid is measured when the thruster is in the vacuum chamber.

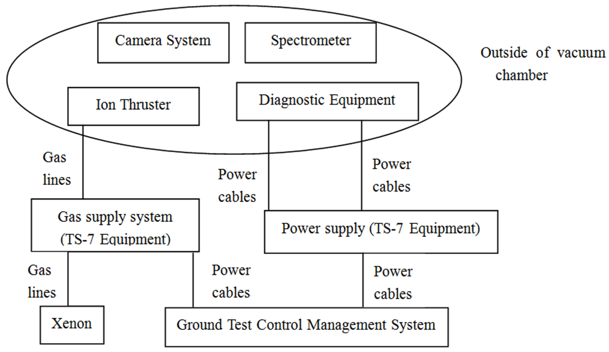


Fig.1 The schematic of the TS-7 vacuum chamber

We use an optical measuring device to measure the erosion and theoretically calculate the accelerator grid's aperture, depth of pits and grooves sputter etching on the accelerator grid.

Fig. 2 shows the measured sputtered erosion of the grid's surface after the thruster's accumulated operation of 5500 h.

The testing results shown in Fig. 2 indicate that, with the increasing of the thruster's accumulated operation time, the erosions act on the accelerator grid surface increase, which are induced by the CEX ions. Compared with other regions, the sputtering erosion on the surface of the accelerator grid's central region is the most severe, and it has the tendency of increasing in an acceleration speed. It can be concluded that the most important factor determining the thruster's lifetime is the sputtering erosion depth at the central surface of the accelerator grid.

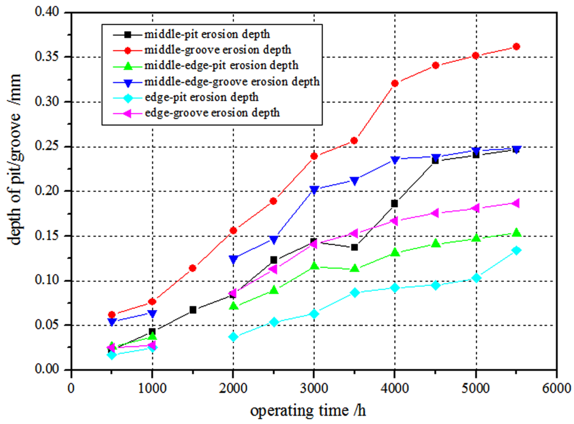
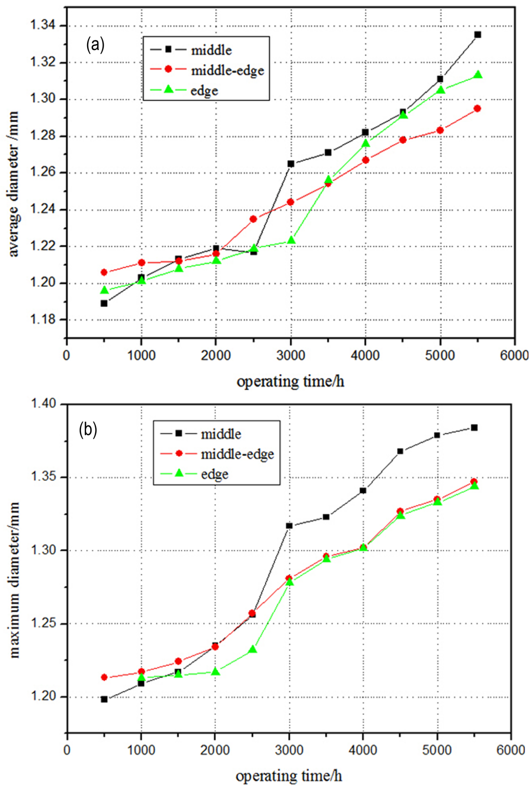


Fig.2 The sputtering erosion on the grid's surface after 5500 hours' operation

It is worth noting that when the thruster operates for over 5500 h, the maximum depth of the pit erosion at the center of the accelerator grid reaches 0.362 mm.

Fig. 3 shows the measured variation of the average and maximum diameter in different regions on the accelerator grid's surface, which varies with the thruster's operation time.



(a) Average diameter versus operation time, (b) Maximum diameter versus operation time

Fig.3 Measured average diameter (a) and maximum diameter (b) as a function of the operation time of the thruster in different regions

Fig. 3 shows that with the increasing of the thruster's accumulated operation time, the average and maximum diameters of the acceleration grid aperture increase in different regions. This enlargement is a result of the CEX ions induced sputtering. Furthermore, this enlargement will decrease the potential barrel, which plays an important role in preventing the electron backstreaming. When the kinetic energy of the electron moving upstream surpasses the electric potential produced by the potential barrel in the aperture center, electron backstreaming occurs. Electron backstreaming will gradually cause some components in the discharge chamber to warm up seriously, do harm to the chamber components and increase electric energy loss decreasing the thruster's efficiency; finally, the thruster will lose its functionality and become obsolete. So the increase of the accelerator grid aperture's diameter, which is caused by the sputtering erosion of CEX ions to the accelerator grid wall, is the key factor causing the grid's single-point failure, i.e. electron backstreaming failure.

From Fig. 3 it can be seen that when the thruster operates for over 4000 h, the largest average diameter locates at the center of the accelerator grid's surface. When the accumulated operation time of the thruster reaches 5500 h, it can be seen that the average diameter of the grid aperture in the rim increases rapidly.

Similarly, in Fig. 3(b), when the accumulated operation time of the thruster reaches 500 h, the maximum diameter of the acceleration grid locates at the center; while from 4000 h to 5000 h and then to 5500 h, the maximum aperture diameter in the accelerator grid's edge firstly increases rapidly.

Note that the range of measurement error is defined as ± 0.1 mm. Given the measurement error, the testing results in Fig. 3 show that the longer the thruster's accumulated operation time is, the faster the diameter of the aperture in the central region of the accelerator grid increases.

Fig. 4 shows the measured electron backstreaming limit voltage as a function of the operating time.

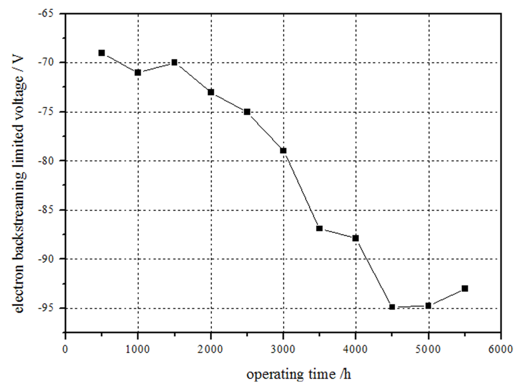


Fig.4 Variation of the electron backstreaming limit voltage with the thruster's accumulated operation time

The testing results in Fig. 4 show that, with the increasing of the accumulated operation time, the absolute value of the electron backflow limit voltage increases gradually.

Figs. 2, 3 and 4 determine the ion thruster's two kinds of key single-point failure modes: accelerator grid failure and electron backstreaming failure respectively.

In the following section, numerical simulation is used in combination with theoretical to predict the LIPS-200's lifetime during the DFH-3B lifetime experiment and analyze the most important failure modes affecting the thruster's failure modes.

In the following section, based on the experimental results presented above, numerical simulation and theoretical analysis are implemented to estimate the LIPS-200's lifetime, the most important failure mode affecting the thruster's failure mode is then predicted.

3 Lifetime prediction

In order to predict the thruster's operation lifetime, by analyzing the testing results shown in Fig. 2 to Fig. 4, one grid aperture in the central region of the accelerator grid is chosen here as the objective of thruster research.

Fig. 5 shows a schematic of the computation domain of a LIPS-200 ion thruster grid used in the simulation.

This computational domain includes the screen and accelerator grid. The left boundary is set at the sheath surface in the discharge chamber where the ion emission starts and the potential is V_s+V_p, where V_s and V_p represent the potential of the screen grid and plasma in the discharge chamber respectively. The potential of the accelerator grid is marked by V_a. The radius and thickness of the screen and accelerator grids are indicated by r_s, r_a and t_s, t_a, respectively. The t_s and t_a are the thickness of them. The boundary condition at the symmetry line of the grid is $\partial\phi/\partial n = 0$. n means the axial and radial position respectively.

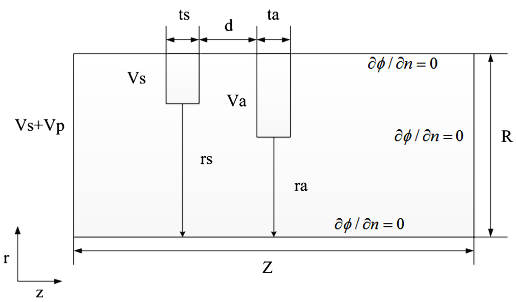


Fig.5 A schematic of the computational domain

Fig. 6 shows the flow of the numerical simulation and Fig. 7 shows the density distribution of the CEX ions.

The numerical simulation results in Fig. 7 show that during the operation of the thruster, the magnitude of the maximum density of the CEX ions is in the order of 2×10^{15} m^{-3}, i.e., the ratio of the CEX ions number to that of the total beam ions is only around 4%.

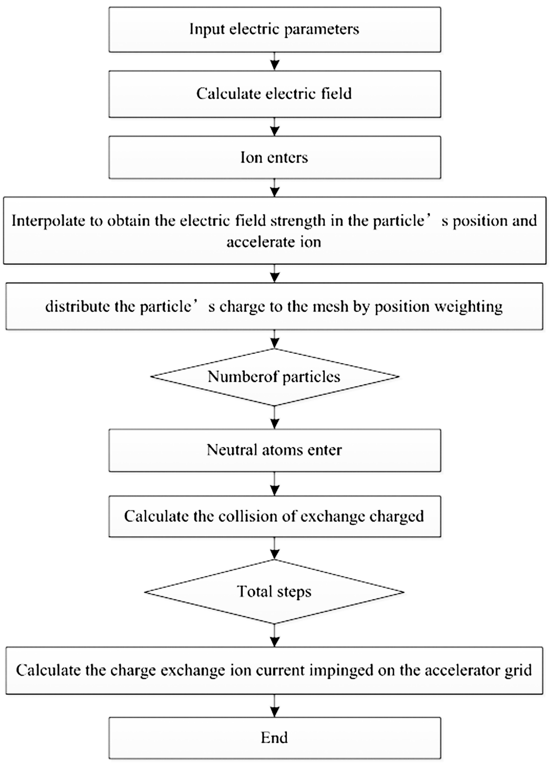


Fig.6 The flow chart of the simulation

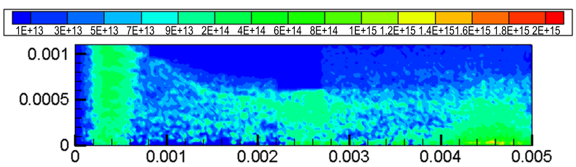


Fig.7 Density distribution of the CEX ions

Table 1 shows the calculated impinged CEX ions current at the accelerator grid's wall during the LIPS-200's steady beam extraction by numerical simulation, and Table 2 shows the sputtering yield and mass sputtering rate of the accelerator aperture's wall. Those data are needed later for the prediction of the potential failure modes.

Table 1. Impinged current on the accelerator grid

Accelerator grid		
Upstream	Downstream	Inner wall
2.356E-008 (A)	3.024E-008 (A)	7.673E-008 (A)

Table 2. Sputtering yield and sputtering rate

Accelerator grid	
Sputtering yield	8.805E-020 (atoms/ion)
Sputtering rate	8.805E-015 (particles/s)

a. Accelerator grid structural failure

When the accelerator grid structural failure occurs to the thruster, the corresponding grid's lifetime can be expressed as:

$$\tau = \frac{\sqrt{3}\lambda_s(2l_{cc}w - w^2)t_a\rho_{Mo}e}{2J_s\lambda_Y Y m_{Mo}}. \quad (1)$$

Where λ_s is the area midification factor, l_{cc} is the distance between adjacent accelerator grid apertures, w is the width of the pit/groove on the downstream surface of the accelerator, which is caused by sputtering erosion, ρ_{Mo} and m_{Mo} are the ion density and mass of Mo respectively, e is the electron charge, J_s is the CEX ions current on the cnetral aperture of the accelerator grid, λ_Y is the modification factor of the sputtering yield [24−28], and Y is the sputtering yield.

The area modification factor is a physical quantity related to the pit/groove's depth.

According to the testing results in Fig. 2, the maximum depth of the accelerator grid aperture's sputtering erosion groove is about 0.362 m. When we substitute this value and numerical simulation results in Tables 1 and 2 into Eq. (1), the thruster can operate 7718.1 h after its 5500 h operation, i.e., when accelerator grid structural failure occurs to the LIPS-200 thruster, the numerical simulation considering the execrable case in the lifetime experiment gives the thruster's lifetime of 13218.1 h.

b. Electron backstreaming failure [29−31]

Electron backstreaming in the ion thruster is caused by beam electrons that flow back into the discharge chamber. This phenomenon happens if the electric potential in the aperture exceeds the potential barrier established by the acceleration grid [13]. If the electron backstreaming failure occurs, the defined ration of the electron backstreaming fraction and beam current is 1% [32].

According to the definition of the electron backstreaming, when the thruster fails, its lifetime can be expressed as:

$$\tau = \Delta d_{\mathrm{a}} / \dot{D}_{\mathrm{a}}, \tag{2}$$

where, Δd_{a} and $\dot{D}_{\mathrm{a}}$ are the variation and variation rate of the accelerator grid aperture diameter, respectively. The variation rate of the accelerator grid aperture diameter is a physical quantity related to the sputtering yield and impinged CEX ion current on the accelerator grid, i.e.,

$$\dot{D}_{\mathrm{a}} = \frac{2m_{\mathrm{Mo}} Y n I \sigma d}{\rho_{\mathrm{Mo}} d_{\mathrm{a}} t_{\mathrm{a}} e}, \tag{3}$$

where m_{Mo} and ρ_{Mo} are the atomic mass and density of Mo respectively. Y is the sputtering yield, n is the plasma density, I is ion current, σ is the collision cross-section of the CEX ions, d is the sum of grid spacing and the thickness of accelerator grid, d_{a}, t_{a} are the accelerator grid's diameter and thickness, respectively, and e is the electron's charge.

Using the geometric structure parameter of LIPS-200 and substituting the parameters in Tables 1 and 2 into Eq. (3), the variation rate of the accelerator grid diameter is calculated in the order of 1.105×10^{-11} mm/s.

Fig. 8 shows the variation of the thruster's accelerator grid aperture diameter versus the accelerator grid electron backstreaming threshold.

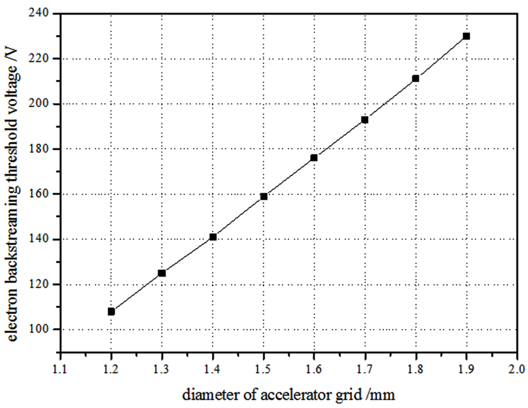


Fig.8 Accelerator grid aperture's diameter as a function of electron backstreaming threshold voltage

With the accelerator grid aperture's diameter being fixed, when the absolute value of the accelerator grid voltage is less than the corresponding electron backstreaming threshold voltage, electron backstreaming occurs. Fig. 8 shows that when the electron backstreaming occurs to the thruster's grid, the absolute value of accelerator grid voltage is 112.81 V. According to the relationship [33] between the voltage and the radius of the accelerator grid, we could calculate that the maximum diameter is about 1.8496 mm, while the accelerator grid voltage is set as -185 V during the thruster's operation, in other words, the increment of the accelerator grid's diameter can reach 0.65 mm at the moment when the electron backstreaming starts to occur.

The analysis is performed according to the worst case of the variation of the accelerator grid's diameter in the center region shown in Figs. 2 and 3. When the thruster operates for over 5500 h, the maximum variation of the accelerator grid's diameter is 0.215 mm.

Comparing test results and the numerical simulation results, it can be concluded that there is still some margin in the diameter, when the electron backstreaming occurs to the accelerator grid aperture.

Combining Eqs. (2) and (3), the thruster's remaining lifetime is calculated as 7718.1 h when the electron backstreaming occurs after the thruster's 5500 h operation, in other words, the predicted total lifetime is about 13218.1 h, for the thruster studied in the paper.

4 Conclusions

To evaluate the on-orbit lifetime of the designed LIPS-200 ion thruster, this paper firstly combines the ground experimental tests, numerical simulations and theoretical analysis to investigate the possibilities of two potential failure modes: accelerator grid failure and electron backstreaming failure. The predicted lifetime of the thruster is around 13218.1 h, which fits the required demand of the design. The results show that the most important failure mode of the ion thruster optics is the accelerator structure failure, which relates to the voltage, diameter and thickness of the accelerator grid's voltage, plasma density and so on. By analyzing further the impact of these parameters on the convergence characteristic of the beam current and the density of the CEX ions, the operating lifetime and performance of the ion thruster could be improved. Therefore, this investigation provides a reference for the performance optimization and lifetime enhancement for the next generation of ion thrusters.

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