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Thermal Deformation Analysis and Measurement of the Triple Grid for a 30cm Diameter Ion Thruster

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Abstract—Critical ion thruster component that affects operation and service life is the grids assembly, and the hot gap variation of the grids directly determines the erosion process of the grids. In order to obtain the hot gap variation of the triple grid for a 30cm diameter ion thruster under 5kW work condition, finite element analysis is used to calculate the distribution of temperature and thermal deformation, then a deflection measurement experiment is carried out to verify the simulations. The results show that the temperature change of the screen grid is the fastest for the lowest heat capacity and the highest deposition energy among the three grids. The hot gap between the center area of the screen grid and the accelerator grid is decreased from 0.95 mm to 0.45 mm in the first 5 minutes. Meanwhile, the central gap is decreased from 0.85 mm to 0.42 mm between the accelerator grid and the decelerator grid after the thruster works about 2000s. The thermal deformation of the decelerator grid presents a “trapezoid” shape. On the contrary, that of the accelerator grid presents a “parabolic” shape. The results of simulation and measurement of temperature in the edge of the screen grid are 338 °C and 321 °C, respectively. The thermal displacement test results show that the hot gap in the center area between the screen grid and the accelerator grid, the accelerator grid and the decelerator grid are decreased from 0.95 mm to 0.48 mm, and 0.85 mm to 0.46 mm, respectively. The simulation results are consistent with test results, and the errors are considered mainly come from the structural equivalent model and which is calculated to be less than 10%.

Index Terms—Ion thruster; The triple grid; thermal deformation; temperature distribution;

I. Introduction

A 30cm diameter Lanzhou Ion Propulsion System, LIPS-300, is a high power (full power status is 5kW), high thrust ion thruster which was designed for the new generation large-scale truss-type satellite platform in China [1-3]. A triple grid assembly consists of the screen grid, the accelerator grid and the decelerator grid of thruster has been designed for ion extraction and ion acceleration. During the operation of the ion thruster, the temperature of the grids increases gradually due to the heat transfer, heat radiation and charged particle energy deposition. As the edge of the grids are fixed to the main structure of the thruster, thermal deformation caused by temperature change can lead to the hot gap variation of the grids [3-6]. Meanwhile, the hot gap change will increase the frequency of breakdown (figure 1(a) shows the breakdown mark of 30cm grids assembly and indicates that the breakdown mainly happens in the central

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area). Frequent breakdown will probable influence the reliability of the PPU (Power Process Units) for the impact on power components by large current and the duration of breakdown. In addition, the hot gap change of the grids will increase the risk of contact short-circuit between different grid (figure 1(b) shows the edge buckling of the triple grid), ion beam focus performance degrades and the grids erosion process accelerates [7-9].

In the performance test process of NASA Solar Electric Propulsion Technology Application Readiness (NSTAR) ion thruster [9-10], the thruster work power was set to 2.3 kW (full power status) and the breakdown occurred frequently at center area of the screen grid and the accelerator grid in the first 5 minutes due to the hot gap narrows rapidly. The hot gap change curve showed that thermal deformation of the screen grid is much bigger than that of the accelerator grid during the start-up process of the ion thruster. After the rapid variation of the grid gap in the start-up process, the hot gap between the screen grid and the accelerator grid gradually increases and which is maintained at about 0.3mm after thermal equilibrium. Meanwhile, the breakdown phenomenon is almost eliminated. According to the research conclusions of the thermal deformation on radio frequency ion thruster electrodes by numerical calculation and finite element analysis [11], respectively, which indicates that the temperature gradient along the grid perforated part radius are considered in the range of 30°C~50°C with the temperature in the center area of the grid is 330°C. By treating the electrodes as thin-walled dished grids, the largest thermal deformation is in the center of the grid, with a value of about 1.5mm. Accordingly, the thermal deformation in the edge of the grid is 0.2mm. Error between the calculation results of numerical method and the results of finite element analysis by ANSYS do not exceed 10%.

Due to the thruster produces the highest heat at full power status, then the temperature and thermal deformation of the triple grid are simulated by ANSYS under 5kW work condition. The equivalent model of the triple grid and thermal boundary conditions are based on the our previous research results. In addition, temperature and thermal deformation measurement of the triple grid are carried out to verify the simulation results.

II. Temperature and thermal deformation simulation results

Temperature distribution is the precondition to obtain the thermal deformation of the triple grid. ANSYS is used to simulate temperature distribution and thermal deformation of the triple grid, and the simulation process include FEM model construction, material properties equivalence and boundary conditions setting, etc.

2.1 FEM model

The grids has thin wall, multi-holes and shell structure features, and it is hard to model as a real structure [12]. Therefore, the model needs to be simplified to complete mesh generation. According to our previous research results [13], a non-aperture equivalent structure of the triple grid is established to replaces the original multi-holes structure by using the homogenization method. The equivalent process is shown as figure 2.
The original arch structure feature is maintained, and the equivalent elastic modulus in y direction of the grids can be expressed as:

$$E_y = \sigma_y / \varepsilon_y = 8E(l - r) / \pi(l + r)$$  \hspace{1cm} (1)

where $E$ is the actual elastic modulus (the grids material is molybdenum with an elastic modulus of 320 GPa), $l$ and $r$ are the outer radius and the inner radius of the aperture, respectively, and $t$ is the thickness of the grids. With the assumption that the material properties of the equivalent structure are isotropic [15], the equivalent elastic modulus $E_{eff}$ of the grids can be expressed as equation (2), and the equivalent material properties of three grids are shown in Table 1.

$$E_{eff} = E_x = E_y$$  \hspace{1cm} (2)

<table>
<thead>
<tr>
<th>Components</th>
<th>Material</th>
<th>Transparency</th>
<th>Equivalent density / kg · m$^{-3}$</th>
<th>Equivalent Young’s modulus / Gpa</th>
</tr>
</thead>
<tbody>
<tr>
<td>screen grid</td>
<td>Mo-01</td>
<td>0.69</td>
<td>2973.00</td>
<td>20.79</td>
</tr>
<tr>
<td>accelerator grid</td>
<td>Mo-01</td>
<td>0.27</td>
<td>7001.00</td>
<td>89.43</td>
</tr>
<tr>
<td>decelerator grid</td>
<td>Mo-01</td>
<td>0.48</td>
<td>4684.75</td>
<td>45.32</td>
</tr>
</tbody>
</table>

After material properties are equivalent, the irregular holes and gaps in the model that effect meshing are repaired to ensure successful grid meshing. All the standard components (such as bolt, joint ring, etc.) are simplified without changing the constraint surface, and simplification need to keep same constraint condition to real structure. Figure 3 shows the simplified process of the bolts.

In addition to that, the structural feature of the rest parts of the triple grid are preserved. The thermal conductivity, radiation coefficient and thermal expansion coefficient of the grids are set according to references. The material of all the standard components are set as TC-4, and the original model and simplified FEM model of the triple grid are shown as figure 4(a) and figure 4(b), respectively.
2.2 Boundary conditions setting

Boundary conditions setting include thermal boundaries and constraint boundaries, and the mainly settings include:

1) Heat flux

According to the thermal model of the ring-cusp ion thruster by previous research results [16], the energy deposition in the screen grid and the accelerator grid of 30cm diameter ion thruster can be given in the form of heat flux. The decelerator grid is the outermost part of the triple grid, and the potential of the decelerator grid is 0V. Therefore, The ions impact on the decelerator grid can be ignored, and the deposition energy of the decelerator grid is mainly from excitation of atom and ions, which are expressed as equation (3)~equation (5)

\[ P_{Xe}^* = 8.3I_{pe}[1 - \exp(-\sigma_{Xe}^* n_0 L_{pe})] \]  
\[ P_{ion}^* = 11.27I_{pe}[1 - \exp(-\sigma_{ion}^* n_i L_{pe})] \]  
\[ P_{del}^* = A_{sg} (1 - \Phi_{acc})(P_{Xe}^* + P_{ion}^*) / A_{del} \]

where \( P_{Xe}^* \) and \( P_{ion}^* \) are excitation energy of xenon atom and xenon ions respectively, \( I_{pe} \) is emission current of the hollow cathode, \( \sigma_{Xe}^* \) and \( \sigma_{ion}^* \) are excitation cross section of atoms and ions respectively [17], \( n_0 \) and \( n_i \) are neutral density and ion density respectively, \( L_{pe} \) is mean free path of primary electrons. The excitation radiation energy affects the screen grid first, then the accelerator grid and finally the decelerator grid. Therefore, the radiation area of the screen grid and the transparency of the accelerator grid should be considered in the deposition energy of the decelerator grid. \( A_{sg} \) and \( A_{del} \) in equation (5) are the area of the radiating surface of the screen grid and the decelerator grid respectively, and \( \Phi_{acc} \) is the transparency of the accelerator grid. The heat flux densities of the screen grid, the accelerator and the decelerator grid are calculated to be 2116 Wm\(^{-2}\), 312.9 Wm\(^{-2}\) and 275.4 Wm\(^{-2}\), respectively.

2) Reference temperature

Temperature in ion beam extraction area on the grid surface can not be measured when the thruster is working because of the ion sputtering effect to the sensors. In order to ensure that the analysis results are consistent with real temperature, the temperature of the mounting rack (the mounting rack is shown in figure 6(b)) is set to be 125°C by thermal test. Environment temperature is set to 22°C to simulate the working condition in the ground.

3) Radiation surface

According to the actual radiation of the triple grid, radiation relationships between three grids are outer surface of the screen grid to inner surface of the accelerator, outer surface of the accelerator grid to inner surface of the decelerator grid, and outer surface of the decelerator grid to space environment. Respectively. Figure 5 shows the radiation relationship between the screen grid and the accelerator grid,
and the surface radiation coefficient of three grids are both set as 0.45 according to the test results.

![A pair of radiation surfaces of the screen grid and the accelerator grid](image)

**Fig.5 A pair of radiation surfaces of the screen grid and the accelerator grid**

4) Simulation time setting

According to the actual single working time of the 30cm ion thruster, thermal simulation time is set as in the range of 0.1s~14400s, and iteration step length increases as the iteration times to reduce the total time of simulation.

5) fixed support

The triple grid is assembled with the mounting rack of the ion thruster by standard components, and all the screws on the installing ring are set as fixed support.

### 2.3 Temperature simulation results

Temperature variation curves of different three grids are shown in figure 6(a), and figure 6(b) shows the temperature distribution of the triple grid and the mounting rack.

![Temperature variation curves](image)

**Fig.6(a) Temperature variation curves**  
**Fig.6(b) Temperature distribution**

According to figure 6(a), temperature variation of different grid is significant, and the temperature of the screen grid, the accelerator grid and the decelerator are increased from 22℃ to 280℃, 183℃ and 107℃ in 5 minutes, respectively. The main reason caused large temperature different is that the opening area of the screen grid is 69%, which is much bigger than 27% opening area of the accelerator grid and 45% opening area of the decelerator grid. Secondly, the screen grid is directly affected by the thermal radiation of the excitation plasma in the discharge chamber. In addition, heat capacity of the screen grid is the lowest and the deposition energy is the highest among three grids, which caused the temperature variation of the screen grid is the most rapid among three grids [10]. The effect of excitation plasma on the accelerator grid recedes a lot than the screen grid for the accelerator grid is in the middle of the triple grid, and the temperature variation of the decelerator grid is the slowest among the three grids for the decelerator grid is the outermost and energy loss by space radiation.

The temperature of three grids are increased gradually with the extension of working time, and the equilibrium temperature of different grid is different. As shown in figure 6(a), The equilibrium temperature of the screen grid is the highest which is reach up to about 400℃, and the equilibrium temperature of the accelerator grid and the decelerator grid are 330℃ and 210℃, respectively. The temperature equilibrium condition is that the temperature variation is less than 1℃ in 10 minutes.
Therefore, the temperature equilibrium time of the triple grid is in the range of 4 to 4.5 hours, which is in accordance with the test results.

2.4 Thermal deformation simulation results

The equilibrium temperature different of three grids are inevitable, and which lead to different thermal deformation. The deformation direction of three grids are both toward to z direction (ion beam extraction direction), which is perpendicular to the grid surface. Figure 7(a) shows the z directional thermal deformation in the center area of three grids, and figure 7(b) and figure 8(a) shows the relative displacement in the center area between the screen grid and the accelerator grid, the accelerator grid and the decelerator grid, respectively. As shown in figure 7(a), the maximum thermal deformation of the screen grid, the accelerator grid and the decelerator grid are 2.1 mm, 2.1 mm and 1.7 mm, respectively.

Figure 8(a) shows that the thermal deformations of three grids are reach to stable status after 2000s, and the gap between the center area of the screen grid and the accelerator grid is decreased from 0.95 mm to 0.45 mm in the first 5 minutes. Accordingly, the central gap is decreased from 0.85 mm to 0.42 mm between the accelerator grid and the decelerator grid.

Figure 8(b) shows the overall shape changes of the decelerator grid and the accelerator grid when the deformation reaches a stable state. It can be indicate that the thermal deformation of the decelerator grid present a “trapezoid” shape. On the contrary, the thermal deformation of the accelerator grid is convex in the central area, which present a “parabolic” shape. The simulation results indicate the hot gap in the edge area between the accelerator grid and the decelerator grid tend to increase. Meanwhile, the hot gap in the central area tend to decrease, and the maximum relative displacement in the center is calculated to be 0.6 mm-0.65 mm.

The main reason for the results shown in figure 8(b) is the different temperature distribution of two grids. Figure 9(a) and figure 9(b) show the equilibrium temperature distribution of the accelerator grid and
the decelerator grid, respectively. The heat radiation energy from discharge chamber is greatly reduced after passing through the different grid, which caused the energy deposition of the decelerator grid is much less than other two grids. Temperature change of the decelerator grid caused by thermal conduction is higher than that caused by heat radiation. Therefore, the thermal deformation in the edge area of the decelerator grid is larger than that in the central area, and which present a “trapezoid” shape, while the thermal deformation of the screen grid is the opposite, and which present a “parabolic” shape.

III. Test results and discussion

In order to verify the simulation results, temperature test and thermal deformation test of the triple grid are carried out in the vacuum facility. As shown in figure 10, the common method of temperature measurement is to use silica gel to fix the sensor on the surface of the thruster. However, in order to avoid silica gel contamination of the thruster surface and the influence on the measurement accuracy. Ceramic screws and nuts are designed to fix the thermocouple and ensure the insulation between the sensors and the thruster, and a thin copper plate is used as the heat conduction plate, and the copper plate is fixed on the screen grid mounting ring. After that, the sensors are installed on the copper plate to complete the measurement. The results show that the temperature in the edge of the screen grid is reach up to 321 °C, which is close to the 338 °C obtained from simulation results showed in figure 6(b). Therefore, the simulation results for the other regions shown in figure 6(b) are also considered accurate.

Fig.10 Temperature test of the grids

Thermal deformation is measured by photography and image analysis. An alumina pin is made to measure the hot gap variation, which is divided into two parts. The diameter of the bottom part is 2 mm at a height of 2 mm, and the diameter of the upper part is 0.8 mm at a height of 4 mm. The alumina pin is fixed to the screen grid by ceramics, and the pin is designed to keep a small thermal mass to reduce their impact on thermal behaviors of the ion optics. A camera is used to capture the image of the hot grid gap changes. The camera is covered with aluminum foil to prevent heat radiation from the thruster and keep...
the camera operating properly under the plasma environment. In the test, the 30cm diameter ion thruster is operated at 5kW with beam extraction. Two photographs are taken by the camera in the initial status and the stable operating status respectively after 2 hours. By comparing the location change of the pin, the thermal deformation displacement of the grids can be obtained. Figure 11(a) shows the alumina pin installed on the grids and the pin head is protruded out of the decelerator grid, while figure 11(b) shows the location of the alumina pin after 2 hours of operations with ion beam extraction.

![Fig.11 (a) Pinhead protruded out of the surface](image1)
![Fig.11 (b) Image of pinhead taken by camera](image2)

The test results show that the hot gap in the center area between the screen grid and the accelerator grid is decreased from 0.95mm to 0.48mm. Accordingly, the central gap is decreased from 0.85mm to 0.46 mm between the accelerator grid and the decelerator grid. The test results are accordance with the simulation results, and the errors is calculated to be less than 10%. The hot gap change in the edge region is not tested for the camera is obscured by the arched shape of the grids. Errors between simulation results and test results are considered mainly from the structural equivalent model [12]. Non-aperture equivalent structure by homogenization method can approximately reflect the real structural characteristics, especially for elastic modulus of the triple grids. However, the rigidity of the non-aperture equivalent structure is different from that of real structure.

The hot gap variation has obvious influence on the erosion of the grids. Therefore, the trend of the grid gap can be supported by the results of the life test of the 30cm diameter ion thruster. According to the simulation results of the hot gap, figure 12(a) shows the thermal deformation trend of the three grids after reaching temperature equilibrium. As shown in the figure, the grid holes in the edge region are misaligned, while the grid holes in the center region are basically aligned. The misalignment will lead to rapid erosion of the grid holes in the early stage of the life test, and the erosion direction is toward the center of the grids due to the direct ion bombardment. Therefore, the grid holes in the edge region present elliptical shape. However, the grid holes in the center region is less affected by the grid gap variation, so the grid holes gradually expands (similar to linear change). Figure 12(b) shows the erosion of the holes in the edge of the decelerator grid after 5700 hours measured by the three-dimension profilometer. The edge holes show obvious elliptical erosion, and the erosion toward the center area is more obvious, which can further support the simulation results of the grid gap variation.
IV. Conclusion

The grid gap is the critical factor affecting the life of ion thrusters. The simulation results show that temperature change of the screen grid is much faster than that of the accelerator grid and the decelerator grid due to the larger opening area, the lowest heat capacity and the highest deposition energy among three grids. After 2000s, the thermal deformation of three grids are reach to stable, and the stable hot gap is obviously reduced compared with the initial value. The hot gap in the center area between the screen grid and the accelerator grid, the accelerator grid and the decelerator grid are decreased from 0.95mm to 0.45 mm, and 0.85mm to 0.42 mm, respectively. Due to the energy deposition of the decelerator grid is much less than that of the other two grids, and the heat conduction in the edge area of the decelerator grid is higher than that radiated, the overall shape change of the decelerator grid presents “trapezoid”. On the contrary, the accelerator grid presents a “parabolic” deformation due to the heat is highest in the central area. Since the hot gap in the central area of the triple grid decreases rapidly when the ion thruster is in operation, the probability of breakdown occurring in the center area is highest. The results of simulation and measurement of temperature in the edge of the screen grid are 338 ℃ and 321 ℃, respectively. The low comparison error indicates that the simulation results have better accuracy. The thermal displacement test results show that the hot gap in the center area between the screen grid and the accelerator grid is decreased from 0.95mm to 0.48mm. According, the hot gap is decreased from 0.85mm to 0.46 mm between the accelerator grid and the decelerator grid. The test results are accordance with the simulation results, and the comparison error is less than 10%, and the errors are considered mainly come from the structural equivalent model, in other words, the equivalent of elastic modulus cause the errors.

Authors’ contributions

All authors contributed equally to this work.

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Data Availability statement

The datasets used and analyzed during the current study available from the corresponding author on reasonable request;

References


