Research on the 500kW Class Superconducting Strong Magnetic Field High Power Magnetoplasmadynamic Thruster Technology

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Long-distance large scale deep space exploration missions, especially the manned Mars exploration mission, put forward an urgent demand of ultra-high specific impulse, large thrust and long life for space propulsion technology. Based on the test data of MAT-100 100kW Magnetoplasmadynamic thruster (MPDT), a thruster performance prediction model is established. The structural size parameters of anode, cathode and other core components of 500kW MPDT were designed through the prediction model, and the configuration optimization design of "convergence" superconducting strong magnetic field was completed. The designed thruster power was 558kW, specific impulse was 6200s, and thrust was 12.9N. At present, the cathode component of thruster and the t-level superconducting magnetic coil body have been developed, laying a foundation for the subsequent prototype development and ground tests.

I. Introduction

The long-distance medium- and large-scale deep-space exploration mission such as manned Mars have put new and higher requirements on the space propulsion system. It is mainly reflected in three aspects: first, it has a very high specific impulse to significantly reduce propellant consumption, improve the payload ratio of spacecraft, and greatly reduce the launch weight of spacecraft; Second, it has a relatively large thrust, which can greatly shorten the orbital transfer time of spacecraft, especially for manned deep space exploration missions, which can greatly reduce the total radiation dose of astronauts; Third, it has a long life to support large spacecraft in carrying out missions such as large-scale orbital

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maneuvers, multiple round-trip interplanetary flights, and rapid detection of multi-target stars, greatly improving the efficiency of space missions. Therefore, in order to meet the requirements of subsequent major space missions, the space propulsion system must have high specific impulse, large thrust and long life and other technical capabilities. High performance MPDT technology can not only meet the demand of subsequent major space mission, also can drive the significant mission mode innovation, make the represented by Jupiter detection distance deep-space missions by the slow, target detection into less rapid, target detection, make more crew fast manned Mars mission possible, thus realize leap-forward of human space exploration ability promotion.

The additional magnetic field Magnetoplasmadynamic thruster (AF-MPDT) uses the Lorentz force generated by the interaction of the magnetic field and current to accelerate the plasma and generate thrust [1]. In order to greatly improve the performance level of MPDT, the international mainstream practice is to increase the additional magnetic field [2-4], which also makes the thrust generation mechanism very complicated. As shown in Figure 1, AF-MPDT mainly includes four main acceleration mechanisms [5]:

*1.*Self-field acceleration: the self-induced magnetic field produces the axial force of $j_z \times B_\theta$ and the radial force of $j_z \times B_\theta$. The axial force directly generates thrust, and the radial part causes the pressure imbalance at the center electrode to indirectly increase the thrust. ;

2. Swirl acceleration: the force generated by the action of the additional magnetic field and current, $j_r \times B_z$ and $j_z \times B_r$, causes the plasma to vortex angularly. In theory, most of the vortex can be expanded by the physical nozzle (or magnetic nozzle). Kinetic energy is converted into axial energy;

*3.*Hall acceleration: Under the condition of strong additional magnetic field and small propellant flow rate (large Hall parameter), according to Ohm's law, the angular current j_θ is induced, similar to the self-field mechanism, and the force generated by the additional magnetic field is pinched. The component and the outward force component $j_\theta \times B_z$ and $j_\theta \times B_r$, but different from the self field, the direction of the force component cannot be directly judged clearly;

*4.*Aerodynamic acceleration: mainly the ohmic heating and the thermal expansion of the plasma in the nozzle. Under the condition of large propellant flow rate and small current, the aerodynamic thrust plays a leading role.

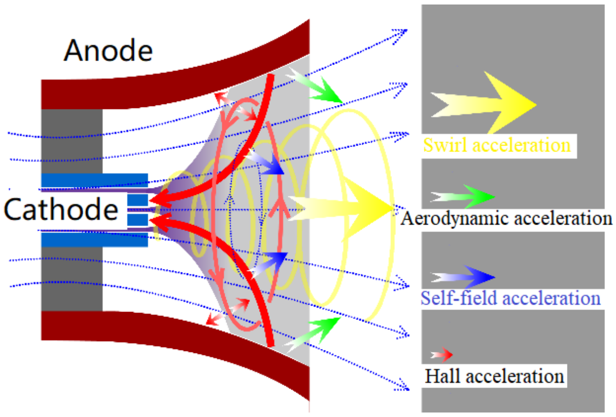

Fig. 1 AF-MPDT working principle and main acceleration mechanism

In 2013, Alta S.P.A. pulse quasi-steady MPDT was developed by Italian Alta company, which referred to the Russian "ageyev-type" high current plasma accelerator. Its specific impulse is around 4000s and its efficiency reaches 50%. [6]

In 2016, 100kW class MPDT SX3 was developed by the University of Stuttgard in Germany. The highest measured power of the thruster is 114kW, with a thrust of 3.4N; The best performance parameters are 65.7kW power, 2.167N thrust, 3710s specific impulse and 59% efficiency.[7]

II. Scheme design

A Overall design

The MAT-500 500kW class super-large power MPDT is mainly composed of expanded anode, multi-hollow cathode, superconducting additional magnetic coil, cathode cooling channel, anode cooling channel, insulator and other components. The overall scheme is shown in figure 2, and the kA class long-life cathode is shown in figure 3.The propellants, anode diameter, cathode diameter, electrode length and additional field configuration of high power MPDT have a complex coupling relationship with the power, specific impulse and efficiency of the electric thruster.

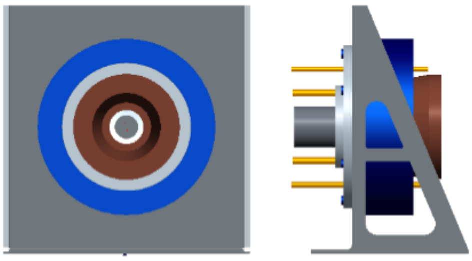

Fig. 2 General scheme of MAT-500 MPDT

Fig. 3 Cathode of MAT-500 MPDT

Relevant research institutions used MACH2 method to conduct numerical simulation of MPDT working process [8], and summarized an analytical model to study the influence of various index parameters on the working process of thruster. This model provides a simple expression for thruster thrust and plasma voltage drop, and the established model holds that the thrust is proportional to the square root of the product of added magnetic field, discharge current and mass flow. The voltage drop increases linearly with the additional magnetic field and is independent of discharge current and mass flow rate. However, the test data of MAT-100 100kW high-power electromagnetic thruster (MPDT) developed by our research team shows that the propellant flow and power supply current of the thruster have a significant impact on the voltage, and the factors cannot be ignored. Therefore, combined with previous experimental data, the performance prediction model was optimized, and correction factors of current and flow were added. The optimized model is as follows:

$$V_p = \frac{40.3}{\sqrt{A\bar{\varphi}}}\left[\frac{446aB}{R-1}\left(\frac{R^2 In^2 R}{R^2-1} - \frac{R^2-1}{4}\right) - 1\right] * f(I,\ \dot{m}) \tag{1}$$

$$T = \frac{25}{A^{\frac{1}{4}}}\sqrt{\frac{a}{\bar{\varphi}}\frac{R(R+1)\sqrt{R\text{-}1}}{\sqrt{R^{3.8}\text{-}1}}}\sqrt{\dot{m}IB} \tag{2}$$

Where A is the number of protons of the propellant atom, $\bar{\varphi}$ is the ionization factor, a is the ratio of the cathode radius to the electrode length, B is the additional magnetic field strength, m is the propellant mass flow, and I is the discharge current. The error between the digital value of the revised voltage and thrust model and the measured value is within 4%, and the trend consistency is good, which can be used as the performance prediction formula to calculate the performance parameters of the 500kW MPDT.

Based on the design parameters of the thruster, such as expansive anode radius, multi-hollow cathode radius and electrode length, the performance parameters of the thruster were obtained by using the optimized performance prediction model, as shown in table 1.

Table.1 Main design and performance parameters of MAT-500 MPDT(500kW)

R_a(mm)	Le(mm)	B(T)	I(A)	I_{sp}(s)	P(kW)	η	T(N)
148	410	1.2	2500	6200	558	0.72	12.9

B Strong magnetic field design

For the MPDT, the magnetic field is the decisive parameter affecting the performance of the thruster [9]. The magnetic field is mainly measured by three parameters: the magnetic field strength, the shape of the magnetic field, and the position of the magnetic field relative to the thruster. The shape of the magnetic field has a significant influence on the ionization and acceleration of the thruster plasma. The reasonable magnetic field design can greatly increase the thrust, specific impulse and efficiency of the thruster. Therefore, the design of the magnetic field shape is especially important for the magnetic field design.

Based on the electromagnetic field finite element simulation software, according to the basic size and flow density of the electromagnetic coil, the three-dimensional results of the electromagnetic field simulation calculation are shown in Fig. 4, and the two-dimensional magnetic field distribution is shown in Fig. 5. It can be seen that the magnetic field intensity distribution is uniform and has a tendency to slowly diverge downstream of the cathode, that is, a proper "convergence" magnetic field configuration. The maximum magnetic field strength of the superconducting coil can reach 1.6T, and the magnetic field strength at the front end of the cathode is greater than 1T.

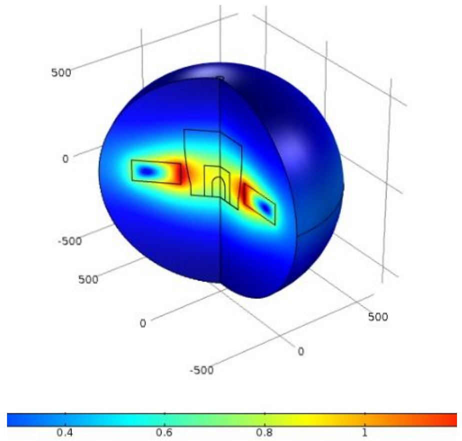

Fig. 4 Three-dimensional magnetic field distribution of the electromagnetic coils

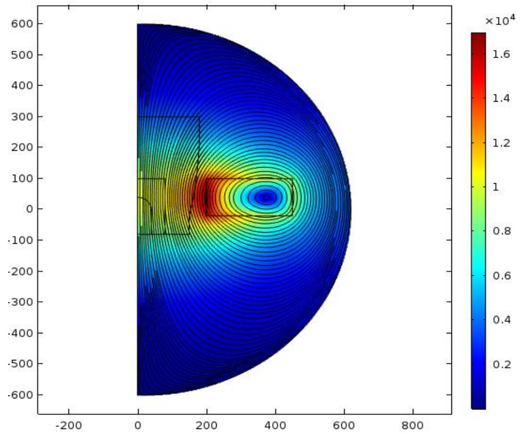

Fig. 5 Two-dimensional magnetic field distribution of the electromagnetic coils

As shown in figure 6, with the increase of throat magnetic induction intensity, the distribution of electron and ion number density is closer to the inner magnetic field line, forming a decreasing radial diffusion trend. At this point, the magnetic field weakens slowly from z=0 at the throat to z=20R_p0, and most charged particles can maintain a relatively high degree of magnetization. Since the magnetic field itself mainly extends in the axial direction, plasma expansion is greatly inhibited along the radial direction. When applied magnetic field expansion Angle decreases, and ϕ form obvious gradient along the radial direction is no longer, plasma after joining magnetic field of the throat, ion is not affected by the radial electric field acceleration and dispersed, so also indirectly inhibit ion radial expansion.

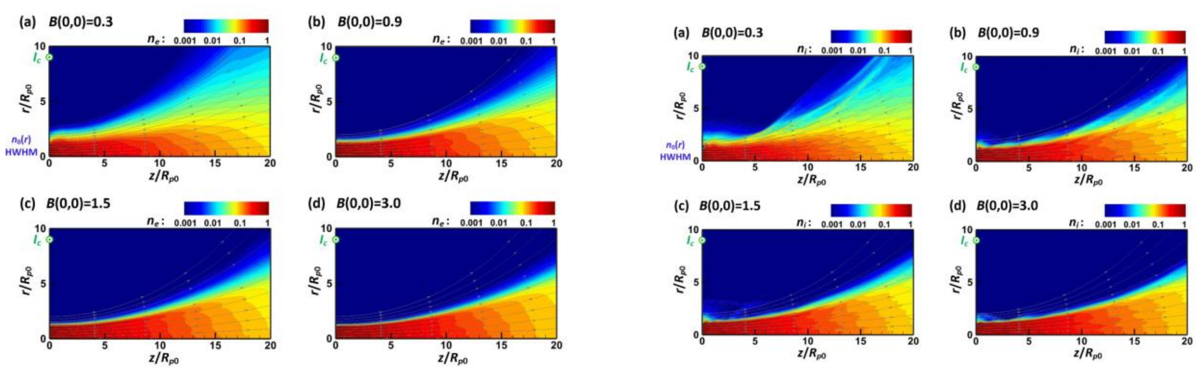

Fig. 6 The electron and ion number density distribution varies with magnetic induction intensity

C Thruster anode design

The structure and size of the thruster anode directly determine the shape and size of the discharge chamber, which is crucial for the performance of the thruster. In addition, MPDT power loss is mainly at the anode, and the anode has a large thermal load. Therefore, in order to ensure the normal operation of the 500kW thruster, it is necessary to focus on the special cooling fluid channel design of the anode assembly.

Combined with previous research experience, the anode is designed as an expanded structure with a "double spiral groove", and it is optimized and iteratively calculated with the magnetic field shape, and finally the inner radius of the anode is 148 mm and the anode length is 410 mm. The vector direction of the cooling fluid flow field of the anode assembly is shown in Fig. 7. The cooling fluid flows stably according to the spiral flow path and is continuously heated uniformly. The fluid does not have a local dead flow vortex phenomenon, and the flow velocity of the fluid in the liquid collection chamber at the outlet is reduced. The two fluids are sufficiently heat exchanged and are stably discharged from the outlet. The temperature of the cooling fluid at the inlet is at least 300K, the temperature of the outlet fluid is up to 348.3K, and the temperature rise is 48.3K. The heat exchange capacity of the cathode assembly is stronger and lower than the boiling point of water, which satisfies the requirements. As can be seen from Figure 8, the maximum anode temperature is 190.4 °C, which is much lower than the high temperature operating temperature of copper, indicating that the coolant can effectively remove the heat generated by the anode in time and can control its temperature within the safe working range.

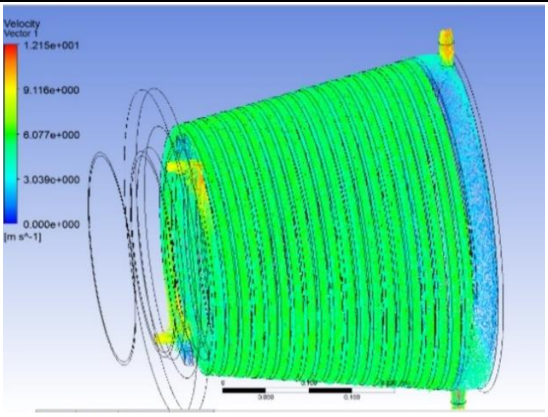

Fig. 7 MAT-500 MPDT anode component flow field vector simulation results

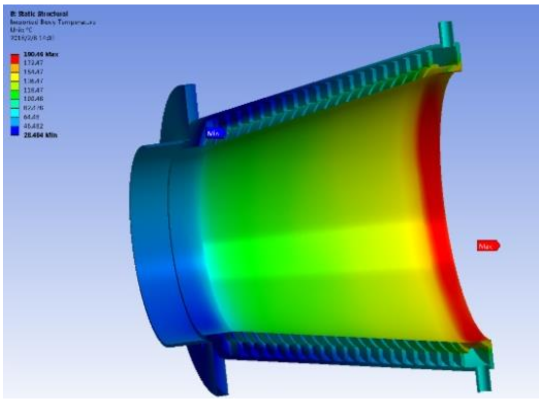

Fig.8 MAT-500 MPDT anode module temperature simulation results

D Thruster cathode design

The thruster cathode is in the center of the discharge zone, and it must directly withstand the bombardment of ions, strong heat radiation and Joule heat caused by the discharge current, and the working environment is the worst. In addition, the cathode surface area is much smaller than the anode and the heat conduction distance is farther, which poses a great challenge to the heat transfer design. Therefore, the life of MPDT is mainly controlled by the life of the cathode. The reasonable cathode design has an extremely important influence on the performance and life of the thruster.

The internal design of 500kW class MPDT hollow cathode structure is 37 variable diameter holes, the hole diameters are from 2mm to 8mm, and the long-life discharge current can reach 13.2kA, which meets the design requirements of 5.0kA. The vector direction of the cooling fluid flow field of the cathode assembly is shown in Fig. 9. The fluid flows back and forth from the inlet to the rear axis. The fluid does not have a local dead-flow vortex phenomenon. The fluid axially passes through the high-temperature cathode front-end region for heat exchange continuously. It is heated to effectively carry away the heat of the cathode. The temperature of the cooling fluid at the inlet is 300K, the temperature of the outlet fluid is up to 324K, the temperature rises to 24K, and the heat exchange capacity meets the requirements. It can be seen from Fig. 10 that the maximum temperature of the cathode assembly cooling sleeve is 236 °C, which is much lower than the high temperature working temperature of copper; the maximum temperature of the cathode rod of the cathode assembly is 2267 °C, which is lower than the high temperature working temperature of the tungsten cathode. The temperature of the components is controlled within a safe working range.

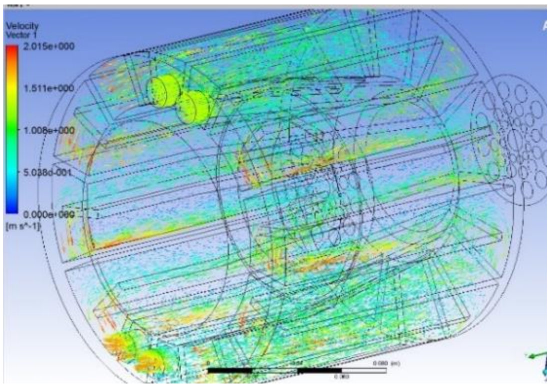

Fig. 9 MPDT cathode component flow field vector simulation results

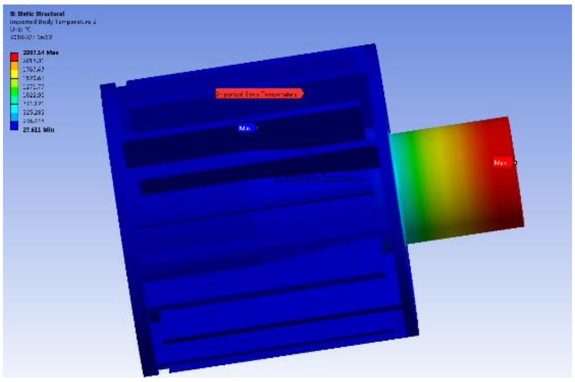

Fig.10 MPDT cathode module temperature simulation results

III. Superconducting magnet design and optimization

A superconducting coil structure design

The T-level superconducting magnet is composed of NbTi low-temperature superconducting material, coil box, G10 insulation material and fastening-aluminum alloy belt. During normal operation, its internal temperature shall not exceed the temperature under the condition of superconducting coil wires. The temperature required for the operation of the superconducting coil is realized through the refrigeration system, which is used to produce the temperature that meets the working conditions of the superconducting magnet, so that the superconducting coil is always in the superconducting state during operation. The design structure of the superconducting coil is shown in Fig. 11, and Fig. 12 shows the winding of the superconducting coil.

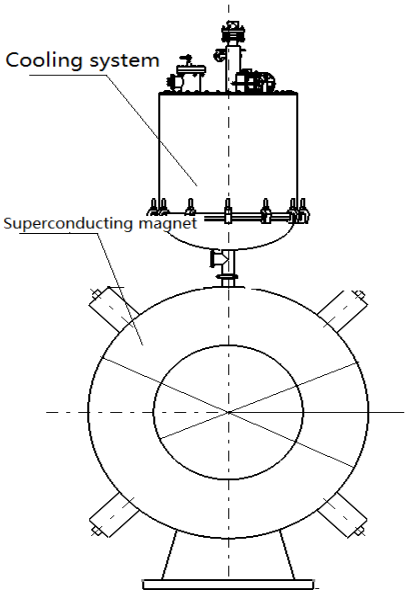

Fig. 11 Schematic diagram of superconducting magnet structure

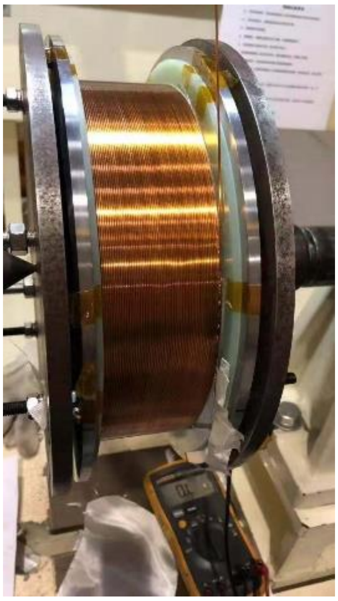

Fig. 12 MAT-500 MPDT superconducting coil production site

B Magnet thermal analysis

The analysis of the temperature of the low temperature and high temperature sections of the superconductor coil shows that the total heat conduction and radiation of the tie rod is 0.10W, the total heat conduction and radiation of the cold screen is 4.8W, and the heat leakage of the cold screen is 2.35W, which meets the design requirements.

C Power supply and quench protection scheme

For the superconducting magnet power supply, the design of over current protection, over voltage protection and EMC electromagnetic compatibility is carried out. Three-phase active PFC+ high-frequency phase-shifting soft switch technology is adopted to achieve power output, active filtering method is adopted to filter the output ripple of high-frequency switching power supply, and high-precision and high-stability control circuit is adopted to achieve the stability and precision requirements of power supply. The main circuit scheme of superconducting power supply has complete protection control logic to realize the safety of magnet and power supply. Considering the length of superconducting magnet strip is very long, it is considered to introduce a tap in the middle of the coil, plus the tap on both ends of the lead wire, and conduct the detection of the out-of-overage signal through three points..

IV. Conclusion

1. Based on the existing test data of 100kW high-power MPDT of our team, the performance prediction model was optimized and applied to the design of high-power MPDT. Its design power is 558kW, specific impulse is 6200s, thrust is 12.9N, and it has high performance technical indicators.

2. The fluid-structure coupling analysis, calculation and optimization of the heat transfer capacity of the cooling passage of the cathode and anode components with the MPDT were carried out, and the parameters such as pressure loss and coolant temperature rise met the design requirements. Therefore, the thruster has the ability of stable heat dissipation for a long time, laying the foundation for long life work.

3. The optimal design of the strong magnetic field configuration of the "convergent" superconductor was completed, and based on this, the design of the miniaturized superconductor coil structure, heat leakage and power loss protection was carried out, which can provide a more suitable magnetic field environment for the work of the MPDT.

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