Development Status of a 5 kW Multi-mode High Specific Impulse Hall Thruster HEP-140MF

IEPC-2017-327

Presented at the 35th International Electric Propulsion Conference
Georgia Institute of Technology • Atlanta, Georgia • USA
October 8 – 12, 2017

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Abstract: HEP-140MF is a nominally 5kW magnetic focus type hall thruster with advantages of high specific impulse and low plume divergence angle developed by Beijing Institute of Control Engineering (BICE) recently, the thruster has been planned to used on full electric propulsion geosynchronous satellites for both north south station keeping and orbit transferring. The development status of that effort including details on the flightweight design, test results and qualification test plans has been described in this paper. The flightweight design of HEP-140MF is based on the successful 1.35 kW hall thruster HEP-100MF flight model and adopted some important improvements unlike previous hall thrusters. The thruster adopted high discharge voltage about 600V to accelerate ions to achieve higher specific impulse, new magnetic circuit structure and discharge channel geometry to achieve high total efficiencies at multi-mode and cold ignition hollow cathode to eliminate the risk of heater defaults. The thruster provided a new kind of combination of three power levels and high specific impulse to achieve significant mass and cost-savings for full electric propulsion satellites. The thrusters can operated at three power levels of 5 kW, 4kW, 3 kW and at 500~600 V discharge voltage. The thruster delivered high performance with total efficiency exceeding 59% and the specific impulse exceeding 2450 s at 5 kW, as well as total efficiency exceeding 54% and the specific impulse exceeding 2400 s at 3 kW. The thruster has successfully passed all performance requirements and qualification-level environmental testing. The full life test will be conducted in 2017.

I.Introduction

Hall thrusters have been widely used for north-south station keeping of geostationary orbit satellites. In recent years, with the improvement of the power level of the satellite platform, the power level of hall thrusters applied in satellites increased from 1.35 kW to 4.5 kW, this made the hall thruster thrust level from the previous 80 mN increased to 200~300 mN, a sharp rise of the thrust of the hall thruster makes GTO to GEO orbit transfer time significantly shortened, hall thrusters will be not only used for north-south station keeping, but also for orbital transfer.

The advanced extremely high frequency satellite AEHF-1 developed by Lockheed Martin was forced to use BPT -4000 hall thrusters to complete orbit transfer from GTO to GEO because of the default of the apogee chemical engine, which fully proved the feasibility of hall thrusters used for orbit transfer. Since then, all the satellite

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manufacturers have carried out the development of the full electric propulsion geostationary orbit satellite, which has become the technological development trend of the geostationary orbit satellite. Lockheed Martin developed a full electric propulsion geostationary satellite platform equipped with BPT-4000 hall thrusters in cooperation with Aerojet[1], Space system/Loral developed a full electric propulsion geostationary satellite platform equipped with SPT-140 hall thrusters in cooperation with Fakel EDB[2], French SNECMA developed the PPS-5000 hall thruster to meet future European full electric propulsion satellite missions[3].

This paper introduces the development status of 5 kW multi-mode high specific impulse hall thruster HEP-140MF developed by Beijing Institute of Control Engineering(BICE), including flight product design, performance testing, environment testing, the subsequent flight validation plan and life test, etc.

II.Flight Design Overview

In order to meet the requirements including orbit transfer, station keeping, the momentum wheel unloading and de-orbit of Chinese full electric propulsion geostationary satellite platform, and take into account of the different power supply ability at different life stages of the satellite, BICE is responsible for the development of the electric propulsion system. The optimization target of the electric propulsion system developed by BICE is to minimize the total weight of the electric propulsion system, shorten the orbital transfer time as far as possible, reduce the thruster life demand, reduce the technical difficulty and improve reliability of electric propulsion system. Based on the above considerations, the performance requirements of the hall thruster applied to Chinese full electric propulsion geostationary satellite platform are listed in Table 1. The thruster is named HEP-140MF.

Table 1. HEP-140MF thruster performance specification requirements

Input Power	3kW、4kW、5kW
Thrust	⩾240mN，5kW ⩾192mN，4kW ⩾130mN，3kW
Specific Impulse	⩾2450s，5kW ⩾2400s，4kW ⩾2400s，3kW
Accumulated Operational Time	⩾10000 hr
Cycles	⩾10000 starts

HEP-140MF thruster must be able to work in three different power level including 5kW，4kW and 3 kW. 5 kW mode is corresponding to orbit transfer work mode, 4 kW mode is corresponding to orbit transfer work mode in the case of reduced power, 3 kW mode is corresponding to position keeping, momentum wheel unloading and de-orbit at the end of life. The main difference between the HEP-140MF thruster and other products such as BPT-4000, SPT-140 and PPS-5000 is that the discharge voltage of HEP-140MF thruster is of little change in different power modes and the discharge voltage is much higher than before. Compared to traditional multi-mode hall thrusters, the range of anode flow variation is lower because of nearly constant anode voltage, it is good for the ionization of propellant xenon and the technical difficulty of the thruster reduced. High specific impulse (2450 s) orbit transfer woke mode resulted in lower thrust relative to traditional medium specific impulse high thrust orbit transfer woke mode, accordingly orbit transfer takes one more month, but much more propellant is saved. HEP-140MF is a better solution.

A. Accelerator Design

In order to achieve the design goal of 2450 s specific impulse, the discharge voltage of HEP-140MF thruster is determined to 500~600 V in the phase of design preliminarily, then the discharge voltage is set as 540V in 5 kW and 4 kW power mode and 600 V in 3 kW power mode by thruster vacuum fire performance test eventually. The high discharge voltage design can meet the thruster of over 2400 s specific impulse requirements.

The magnetic circuit design of HEP-140MF thruster inherited design experiences of 1.35 kW magnetic focusing hall thruster HEP-100MF with successful flight test on SJ-17 satellite[4], include an inner coil, an outer coil and an additional trim coil (shown in figure 1), rather than an inner coil and four outer coil, magnetic field in discharge channel in the circumferential is more uniformity and symmetry. In order to avoid to occupy the inner coil winding space, the position of the additional trim coil moves from the upstream of the inner coil to the upstream of the outer coil, and the additional trim coil can adjust the discharge current oscillation of the thruster. The maximum radial magnetic field strength B_{rmax} in discharge channel centerline can be moved to downstream of the channel exit by adjusting relative position and size of magnetic screen and magnetic pole. We found that B_{rmax} moved downstream of channel exit resulted in a narrower erosion belt width and better efficiency. The vacuum fire performance test found that HEP-140MF thruster can get an excellent performance when B_{rmax} moved 6mm downstream to the channel exit (as shown in figure 2).

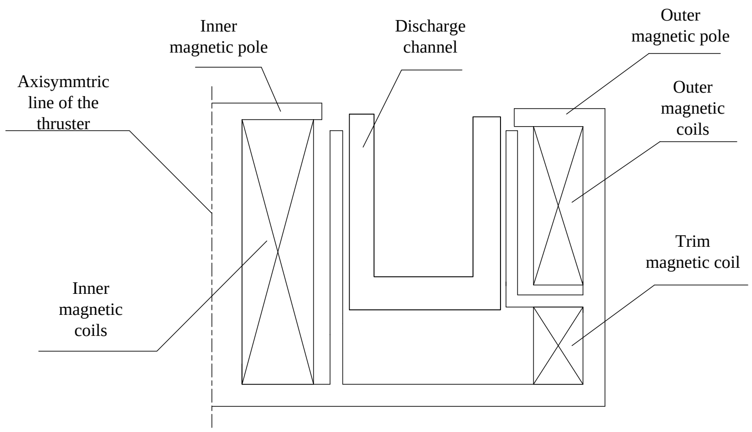

Figure 1. the Schematic diagram of HEP-140MF thruster magnetic circuit

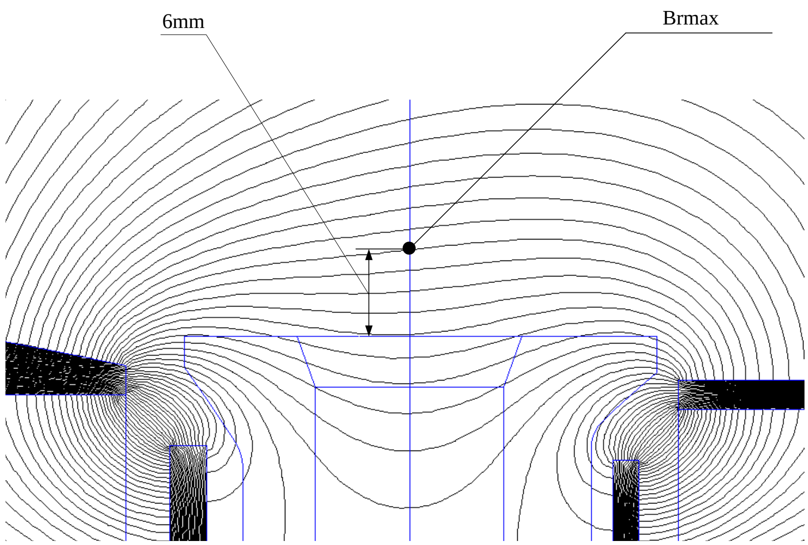

Figure 2. B_{rmax} of the discharge channel centerline moving downstream 6mm

The mean diameter of the discharge channel of HEP-140MF thruster is Φ120 mm. The width of the discharge channel respectively chooses 13 mm, 15 mm, 18 mm and 20 mm so as to compare the effects of different widths on performances under the condition of the same magnetic field and the cathode by the vacuum fire performance test. The performance test results shown that different widths had different effects on performance and had less effects on performance than B_{rmax} moving to the downstream of discharge channel. The thruster with the width of 18 mm or 20 mm working under 5 kW is more efficient, however the thruster with the width of 13 mm or 15 mm working under 3 kW is more efficient, thus eventually the thruster's discharge channel adopted a variable cross-section profile and the channel width is with a transition from 13 mm to 18 mm.

The design of HEP-140MF thruster must ensure that there is a reliable electrical insulation between the anode and cathode and gas supply pipeline, so both the anode and cathode gas supply pipeline are required to series connect gas insulators. The gas insulator of HEP-140MF thruster cathode inherited HEP-100MF thruster technology state because the cathode pipeline is at a low potential, however the gas insulator of anode could not inherited HEP-100 thruster simply with no changes, the gas insulator in the series of two-stage solution was used to meet the needs of increasing discharge voltage.

The HEP-140MF thruster fully used domestic materials and components, including high grade pure iron, anti-sputtering BN ceramic， high-temperature excitation coil and so on. In addition, the machining difficulty and assembly difficulty of the thruster were drastically reduced by simplification of design structures.

In order to improve the inherent design reliability of HEP – 140MF thruster, the coupling analysis of magnetic field and structural mechanics was carried out so as to reduce the weight of magnetic circuit parts and mounting bracket substantially and improve the resistance of structures to vibration and shock. The weight of the HEP-140MF thruster after design optimization was 9.43 kg. Weight of each part of the thruster is shown in Table 2.

Table 2. Weight list of various parts of the thruster

Part	Weight（kg）
Accelerator	7.14
Cathodes（2）	0.16×2
Mounting bracket	0.92
Pipeline, cable and other accessories	1.05
Thruster	9.43

To improve the thermal design of thruster, a large number of thermal design measures is adopted in HEP-140MF thruster. There were effective thermal shielding thin plate with low thermal conductivity and high emissivity to prevent heat transfer from discharge channel to the magnetic parts, backplate and inner coil. The outer surface of the thruster was covered with a special coating with high emissivity (greater than 0.85) and low solar absorptance (less than 0.15). In addition, a radiation cooling plate was installed on the backplate of the accelerator to increase radiation cooling area and futherly reduce the working temperature of the thruster. The thermal state of the HEP-140MF thruster was simulated by commercial FEA software without considering the solar radiation, and the steady temperature field distribution of HEP-140MF was obtained, as shown in FIG. 3. Simulation results shown that the coil temperature was below 300 ℃, the temperature of anode and the ceramic channel was below 750 ℃, the temperature of the installation interface to satellites was below 200 ℃. The thermal design of the thruster is reasonable and there was no temperature exceeding the long-term use temperature of the materials.

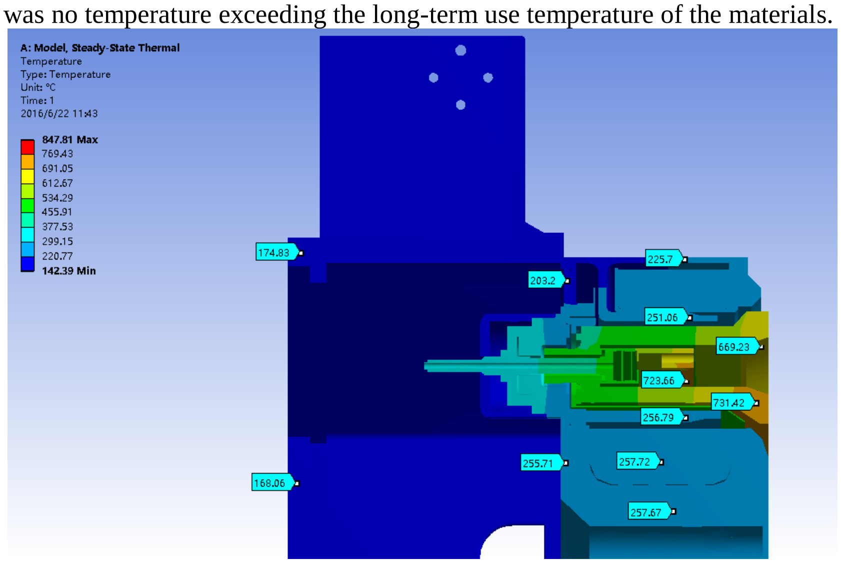

Figure 3. Steady state temperature distribution of HEP-140MF thruster running in 5kW

B. Cathode Design

The demand for electron current emitting from the cathode of the HEP-140MF thruster is 4 ~ 10 A. The cathode is a hollow cathode that its emitter is made of LaB_6 material. The cathode is a heatless cathode which is ignited by proper ignition power supply and gas pressure directly without heating process before ignition. In order to improve the success rate of cold start of the cathode, both the structure characteristic size of the cathode and the ignition parameters were optimized by a lot of testing. The cathode has experienced more than 10, 000 cold start test, then the cathode was decomposed and checked. Test results shown that the status of tungsten orifice plate and insert emitter was good and only minor erosion appeared (see figure 4 ~ 5). During the 10, 000 cold start-up period, the voltage of the cathode is small (as shown in figure 6). In the triode test mode, the voltage of the cathode corresponding to 4 ~ 10A emission current is less than 28V. The cathode can meet the requirements of more than 10,000 start-up times.

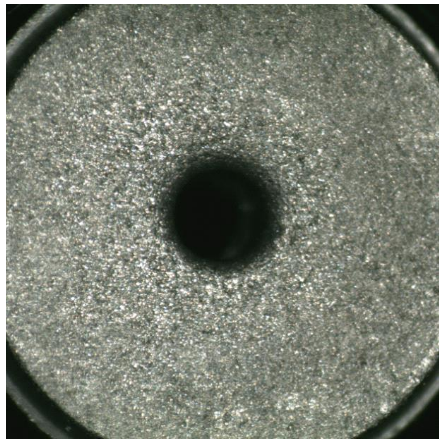

Figure 4. the photo of tungsten orifice plate after 10000 cold starts

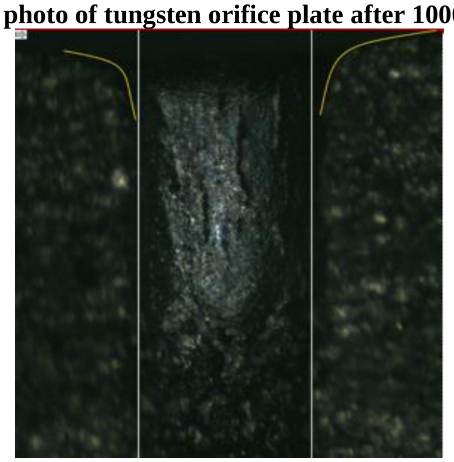

Figure 5. the photo of emitter after 10000 cold starts

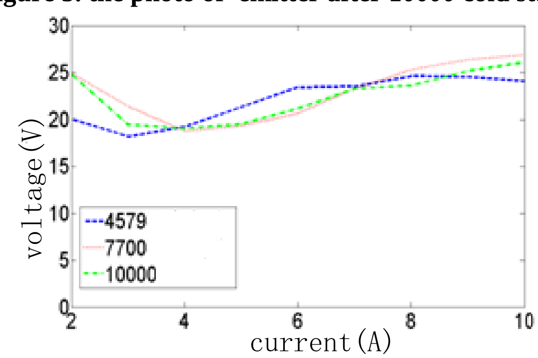

Figure 6. the volt-ampere characteristics of cathode during 10000 cold start-ups period

C. Thruster Design

The HEP-140MF thruster adopted a cold backup cathode design. The thruster is equipped with two cathodes, which can be switched to cathode B to continue working when cathode A fails. In order to reduce the erosion of the cathode sputtered by high-energy ions, the axis of the cathode was parallel to the axis of the accelerator, and the cathode outlet axis is tangent with the local magnetic field lines. The HEP-140MF thruster is shown in figure 7.

Figure 7. the photo of HEP-140MF thruster

III.Performance Testing

After magnetic circuit component, gas distributor and cathode is assembled, each of them need to conduct a performance test separately to confirm whether they meet performance requirements, and then assembly into a thruster. The performance test of HEP-140MF thruster is conducted in the EPTS - 2 (2# electric propulsion test system). The test system is free of oil, the effective size in vacuum tank is Φ 3 m x 6 m, the vacuum chamber is made of stainless steel, the pumping system is made up of three cryogenic pumps and six xenon cold panels, the test system is shown in figure 8. In order to prevent the contamination of the thruster caused by the backflow of the sputtering products of the tank materials, a titanium shield is arranged on the inner wall of the stainless steel vacuum chamber. In order to prevent heat accumulation in the chamber leading to the deterioration of thermal environment and the loss of pumping speed, metal cooling water jacket that can take away the heat generated by the thruster was installed between the stainless steel vacuum tank wall and the titanium shield plate. When HEP-140MF thruster was tested in EPTS-2 system, the pressure of the vacuum chamber can reach 4 x 10^{-3}Pa (air) at 3 kW, the pressure of the vacuum chamber can reach 7x 10^{-3}Pa (air) at 5 kW.

Figure 8. EPTS-2 electric propulsion test system

There are three industrial power supplies needed in the performance test, including the anode power supply, the coil excitation power supply and the ignition power supply. The voltage range of the anode power supply is 0 ~ 1000V, the anode current range is 0 ~ 15A, and the output power range is 0 ~ 15kW. The voltage range of excitation power supply is 0 ~ 50V, the current range is 0 ~ 10A, and the output power range is 0 ~ 500W. The voltage range of cathode ignition power supply is 0 ~ 500V, the current range is 0 ~ 2A, and the output power range is 0 ~ 1kW. Two industrial thermal mass flow controllers were used to supply the gas to anode and cathode separately, the flow range of anode flow controller is 0 ~ 200sccm, the flow range of cathode flow controller is 0 ~ 10sccm, the flow accuracy of both controllers reaches 1%. The HEP-140MF thruster adopted a specially designed ignition and filter circuit (shown in figure 9) to reduce the impact on the power supply and the cathode emitter.

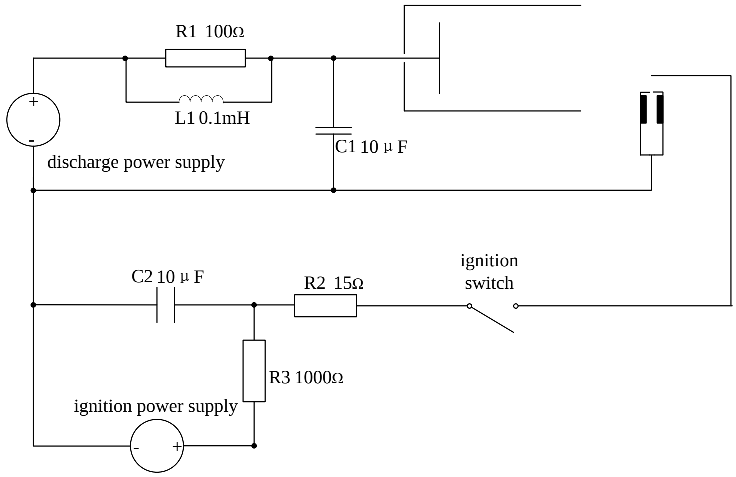

Figure 9. ignition and filter circuit of hep-140 thruster

Thrust measure equipment is based on the principle of three-wire torsional pendulum, as shown in figure 10. The thruster is hanged by three tungsten wires, the reflector and thruster are fixed on a plate. When the thrust is produced, the reflector will rotate a small angle. If a light beam incident to the reflector, the angular reflection will result in a long displacement on the gauge. If a photoelectric sensor take place the gauge, the small angle rotation caused by the thrust is converted into a voltage signal. The calibration is realized by automatically weight lifting in situ online. The measuring range of the thrust measuring equipment is 10 ~ 500mN and the accuracy is 2% of the measured value.

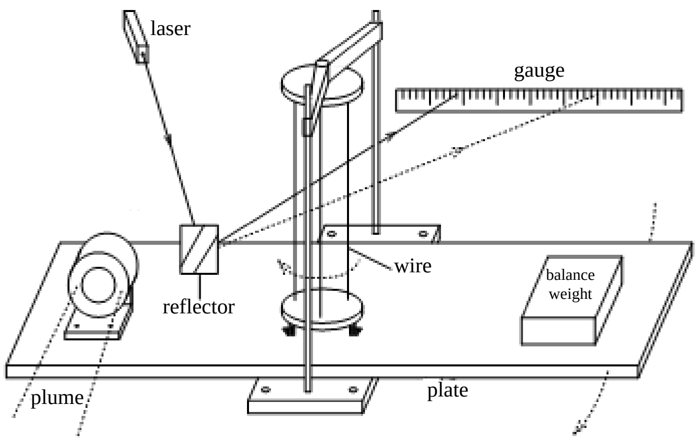

Figure 10. the principle of three-wire torsional pendulum measurement

HEP-140MF thruster must stay for at least 12 hr in the high vacuum environment (< 1 x 10^{-3} Pa) before fire to make the thruster degas fully. First of all, the thruster should work at 3 kW, 4 kW, 5 kW power in turn for a period of time until the discharge current and the pressure of the chamber remain stable for the first start after exposure to the atmosphere, then the thruster performance testing could be conducted. The online calibration of the thrust measuring equipment in situ should be conducted once before and after performance test, and the calibration results indicate that the thrust measurement accuracy is within 2%.

The discharge photograph of HEP-140MF thruster is shown Figure 11. The performance test results of the HEP-140MF in 3kW, 4kW and 5kW power are shown in the table 3. It can be seen that the performance test results of HEP-140MF meet the performance requirements listed in table 1.

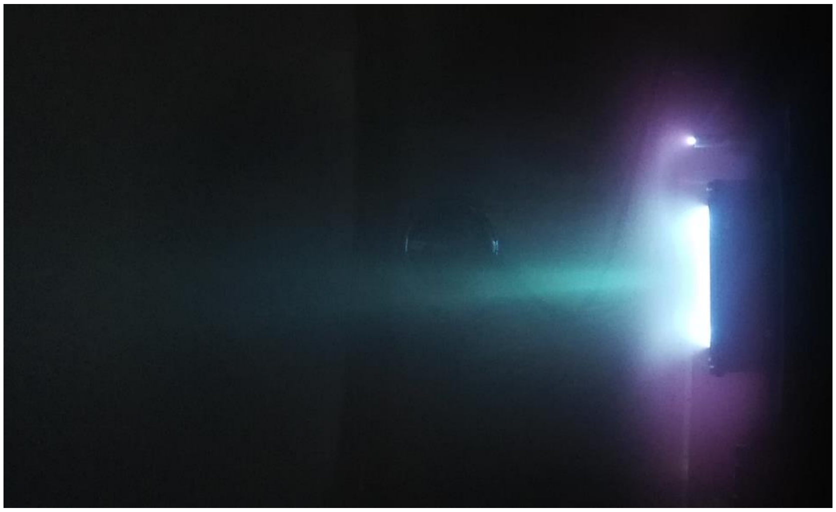
Figure 11. the photograph of HEP-140MF thruster discharge

Table 3. results of HEP-140MF performance test

No.	Anode voltage(V)	Anode current(A)	Anode flow(sccm)	Cathode flow(sccm)	Coil current(A)	Coil voltage(V)
1	540	9.12	101	3.05	3.4	19.8
2	540	9.14	101	3.05	3.4	19.6
3	540	7.28	81	3.05	3.4	19.1
4	540	7.29	81	3.05	3.4	19.0
5	600	4.89	55	3.05	3.4	18.8
6	600	4.92	55	3.05	3.4	18.5

Table 3. results of HEP-140MF performance test

No.	Anode power(W)	Coil power(W)	Thrust （mN）	Specific implulse(s)	Overall efficiency(%)	Pressure(Pa)
1	4925	67.2	246.0	2455	59%	7.45E-03
2	4936	66.6	245.6	2450	59%	7.36E-03
3	3931	64.9	196.3	2424	58%	6.14E-03
4	3937	64.6	196.5	2427	58%	6.14E-03
5	2934	63.9	136.1	2433	54%	4.41E-03
6	2952	62.9	135.8	2429	54%	4.41E-03

IV.Environmental Testing

In order to meet the environmental requirements of the full electric propulsion geostationary orbit satellite platform, the sine and random vibration and shock testing in all axes of the levels shown in Tables 4~6 was conducted in the HEP-140MF thruster. In addition to mechanical environmental testing, the HEP-140Mf thruster had experienced thermal vacuum cycle testing with the levels shown in table 7.

Table 4. qualification levels of sine vibration

Axis	Freq(Hz)	Level(0-p)	Sweep rate
X、Y、Z	5～20	12.4 mm	Once per axis, 2 oct/min
	20～100	20 g	

Table 5. qualification levels of random vibration

Axis	Freq(Hz)	PSD level	Ovrall acceleration (g)	Duration
X、Y	10～200	+6 dB/oct	16.1	2 min per axis
	200～1500	0.16 g^2/Hz		
	1500～2000	-12 dB/oct		
Z	20～100	+3 dB/oct	20	
	100～400	0.400 g^2/Hz		
	400～600	-6 dB/oct		
	600～1500	0.178 g^2/Hz		
	1500～2000	-12 dB/oct		

Table 6. qualification levels of shock

Axis	Freq(Hz)	Level	Shock times
X、Y、Z	100～1500	+6 dB/oct	3 times per axis
	1500～4000	1600 g	

Table 7. qualification levels of thermal vacuum

Temperature(℃)	Continuous working time at extremely temperature(h)	temperature change rate(℃/min)	Cycles	Pressure (Pa)
-145~+95	4	≥1	6.5	$\leq 6.65\times10^{-3}$

Figure 12. Vibration test of HEP-140MF thruster

After experienced the qualification level environment testing, HEP-140MF thruster had carried on detailed electrical and magnetic field checkouts and visual inspections. The appearance and resistance of HEP-140MF thruster was still normal. After environment testing, the thruster was successfully hot fired.

V.Flight Testing

HEP-140MF thruster has been delivered to SJ-17 satellite and planned to fly on SJ-17 in 2017, but unfortunately the Long March 5 rocket failed to launch and the flight testing was forced to cancel. However HEP-140MF thruster had finished all the related ground test and system level testing. The results of the testing indicated all key parameters were well understood and within the levels of compatibility with the overall system. The next flight testing of HEP-140MF will be planned in 2008.

VI.Future Work

The HEP-140MF thruster is expected to carry out the life test at the end of October in 2017. It is planned to sample a thruster to carry out the life test after the qualification environment testing. The life test procedure has been reviewed[5]. The life test procedure is shown in table 8. If the life test is uninterrupted in 24 hours a day, the basic life test phase will take about 285 days, the first extended life test phase will take about 389 days, the second extended life test phase will take about 325 days. The whole life test will take about 3 years.

Table 8. HEP-140MF thruster life test procedure

Start No.	Power(kW)	On time（hr）	Off time（hr）	Remarks	
89	5	11.9	1	Orbit transfer	Basic life test phase
4	5	12	1		
4	5	24	1		
2	5	200	1		
1	5	500	1		
5700	3	0.43	0.33	NSSK	
10	4	23	1	Low power Orbit transfer	
4	5	12	1	Orbit transfer	The first extended life test phase
4	5	24	1		
2	5	200	1		
1	5	500	1		
89	5	11.9	1		
3000	3	0.65	0.33	NSSK	
2700	3	1.13	0.33		
10	4	23	1	Orbit transfer	
4	5	12	1	0.5 times margin of orbit transfer	The second extended life test phase
4	5	24	1		
2	5	200	1		
1	5	500	1		
89	5	11.9	1		
5700	3	0.65	0.33	0.5 times margin of NSSK	

VII.Conclusion

HEP-140MF thruster oriented to the full electric geostationary satellite platform completed flightweight design, performance testing, environmental test, flight product development and the electric propulsion system level test. The performance requirements of HEP-140MF thruster is satisfied. HEP-140MF thruster can work in three different power levels of 3kW, 4kW and 5 kW. The specific impulse of HEP-140MF thruster reached more than 2450 s, the thrust range is 246 mN ~ 136 mN, the overall efficiency reached 59% ~ 54%. The HEP-140MF thruster will be used in the full electric propulsion geostationary satellite platform after a follow-up full life test.

Acknowledgments

Thanks to Daren Yu, Yongjie Ding, Hong Li, Zhongxi Ning, Liqiu Wei and Hui Liu et al. of the plasma propulsion laboratory of Harbin Institute of Technology (HPPL) because of the outstanding work and contribution to the development of HEP-140MF thruster.

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