DEVELOPMENT AND PRIMARY IN-FLIGHT EXPERIENCE OF ELECTRIC PROPULSION SYSTEM ON SATELLITE SJ-9a

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Abstract

To smooth over the concerns on spacecraft safety and reliability, the in-space verification project of electrical propulsion technologies in satellite SJ-9A was established in 2008, which is the first spacecraft for China to accomplish the in-fight experiments of electric propulsion system. To fulfill the mission requirements and capability limites of SJ-9A satellite, a completely new electrical propulsion system is designed, established and verified. The system consists of seven major unit, including a XIT, an XPPU(XIT power precessing unit), an IXFU(XIT xenon feed unit), a HET, a HPPU(HET power precessing unit) a HXFU(HET xenon feed unit), and a DICU(Digital Interface and Control Unit). Through the three phases development program consists of engineering model, verification products and flight products, the electrical propulsion system was deliver to the SJ-9A in January, 2012.

SJ-9A was lauched in October 2012, and till December 2012 the in-fight experiments of first stage had been completed. The electric propulsion system works extremely well. Through measurement of the obital altitude variation, the thrust and specific impulse was calibrated in standard working condition, thrust of XIT 36.1mN, specific impulse of XIT 2727s, thrust of HET 37.8mN, specific impulse of HET 1485s. This paper provides an overview of the development process of SJ-9A electric propulsion system and relevant experiments on ground, including system integration test of the electrical propulsion system, the compatibility test with the SJ-9A satellite platform, the matching test with power system and the performance calibration test of thrusters, etc. Finally, the results of in-flight experiments of SJ-9A electric propulsion system are presented.

Key words: Electric Propulsion, SJ-9A, XIT, HET, In-flight Experiments

I. Introduction

As we know a challenging and important area of current research to meet the needs of large ΔV spacecrafts is that of electric propulsion systems. Therefore, China has shown its interests in EP and devoted to EP researches for more than 30 years. And EP research experienced a good progress in its early ages. Three kinds of electric propulsion systems, ion thruster, pulsed plasma thruster and arcjet, are developed in early 1970s. And in Dec. 1981, two sets of PPT type EP device named MDT-2A was successfully verified in a space experiments. But due to constraint of application backgrounds, no other verification program or engineering developing program was performed for the following years till 1990s.

In 1990s, some successful applications of EP in U.S. and Europe greatly stimulated the passion of EP research in China[1,2]. And many Chinese institutes and universities extend or start EP developing program since then. The research fields include electrothermal type, static electric type, electric magnetic type, and some other new concepts. Two of which are considered as proper choice for NSSK mission of GEO spacecrafts, they are the 700W level HET (Hall-effect thruster) and the 200mm level XIT(Xenon ion thruster). The engineering model of 700W level HET is developed by SISP(Shanghai Institute of Space Propulsion) since 1990s. And the engineering model of 200mm level XIT is developed by LIVP (Lanzhou Institute of Vacuum Physics).

Although the XIT and HET are considered flight-ready since 2004, the application is still not realized because of the concern of spacecraft safety and reliability. To smooth over these concerns, the in-space verification project of electrical propulsion technologies in satellite SJ-9A was established. SJ-9A is the first satellite for China to accomplish the in-flight experiments of electrical propulsion system, the primary mission of which is to demonstrate both the XIT and HET technologies on the same satellite, including its compatibility with space platform, actual in-space performance and reliability in space environment, etc.

To fulfill the mission requirements and capability limits of SJ-9A satellite, a completely new electrical propulsion system is designed, established and verified by BICE (Beijing Institute of Control Engineering), which is the major manufacture of space propulsion system in China, and provides 90 percent of propulsion system for Chinese satellite[3]. BICE began its EP activities in 1990s, whose research fields includes arcjet type EP thrusters, magnetic-focus type hall-effect thrusters, propellant storage and feed models, and system integrating of EP.

Three phases of development program for SJ-9A EP system, consists of engineering model, qualification model and flight model, were performed since 2008. And the flight EP model was delivered in Januray, 2012. And from January 2012 to August 2012, acceptance tests of the EP system for SJ-9A satellite had been carried out. After that, SJ-9A was lauched in October 2012, and the in-flight experiments of first stage had been carried out till December 2012.This paper provides the introduction of SJ-9A EP subsystem and its primary in-space behavior.

II. SJ-9A EP System

The SJ-9A satellite EP system includes DICU (digital interface and control unit), XSFM (Xenon storage and feed system), HEPS (hall electric propulsion sub-system) and XIPS (Xenon ion propulsion sub-system), as shown in Fig.1.

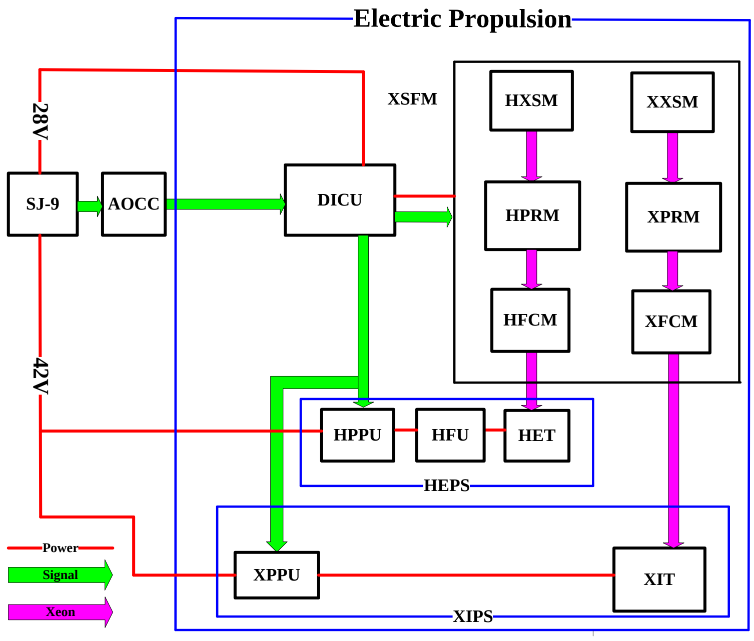


Fig.1 SJ-9A EP system schematic diagram

A. XIPS

XIPS consists of a XPPU (XIPS power process unit) and a XIT (Xeon ion thruster). The XIT is a 200mm Kaffman type ion thruster, which is developed since 1990s, on the bases of the prototype developing experience of mercury ion thrusters since 1970s.

Compare with the engineering model, the main improvement for the XIT of SJ-9A includes:

a) The magnetic field is optimized to unify the ion beam, depress the accelerate voltage and the erosion rate of screen grids;

b) A LaB6 cathode is adopted to enhance its ignition performance after months of grounding test in atmosphere.

c) To reduce the possibility of discharge between screen grids, the machining arts are improved and the distance between screen grids are increased.

XPPU is the driving electronics that supply the power for XIT, whose main function includes:

a) Conversion of the ten different power demands of XIT from the 42V power supply of platform;

b) Interlock function of the power supply of neutralizer and the power supply of accelerator and screen grids.

c) Self-protection function for malfunction of power supply and XIT, such as short circuit of XIT and overvoltage of power supply;

d) Provide analog signals of power supply and ten power modules.

B. HEPS

HEPS includes a HPPU(HEPS power process unit), a FU(filter unit) and a HET(Hall effect thruster).

The HET is a 700W level thruster, which is developed on the bases of the engineering model since 1990s. Compare with the engineering model, the main improvement for the HET of SJ-9A includes:

a) To reduce the deflection of thrust, some design improvement are performed, including the adoption of a reflection lens.

b) To fulfill the requirement of reliability and safety, some basic material and component is rechosen and reverified.

The FU is a π-type passive LC filter, and the HPPU is the driving electronics that supply the power for HET, whose function is alike as XPPU.

C. XSFM

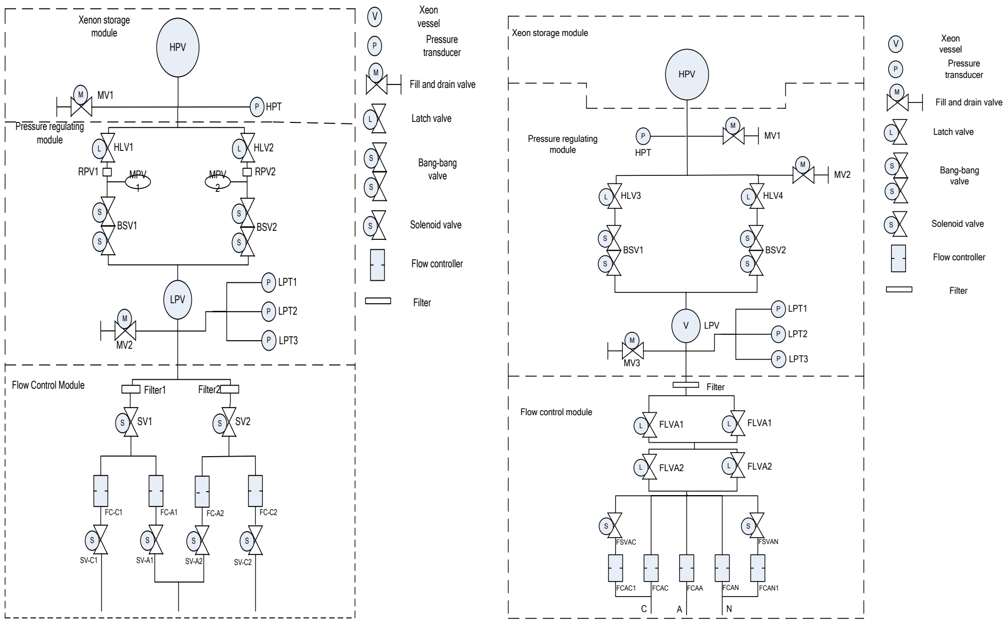
To fulfill the installation requirements of platform, the XSFM of EP system is consists of two similarly separately parts, one for XIPS and one for HEPS. Each includes a XSM (Xenon storage module), a PRM(pressure regulating module), a FCM(flow control module), which is shown schematically in fig.2.

The Xeon feed system parameters for XIT thruster are as follows:

Xenon flowrate: 1.09mg/s(Anode), 0.136 mg/s(cathnode),0.136 mg/s(neutralizer)

The Xeon feed system parameters for HET thruster are as follows:

Xenon flowrate: 2.39mg/s(Anode), 0.262 mg/s(cathnodeA), 0.262 mg/s(cathnodeB).



(a)Hall propulsion system (b)Xeon ion propulsion system

Fig.2 EP Xeon supply system schematic diagram

Xeon is stored in XSM with high pressure. When the thruster is going to be on fire, the isolation valve opens and high-pressure Xeon flows downstream into the PRM. Downstream of the PRM there are three precision low-pressure transducer, which provide feedback to the DICU for controlling the bangbang valve. Under the close-loop pressure control, the outlet pressure is maintained nearly 0.2MPa(±2%). Thermal-throttles are used to adjust the flowrate in FCM. When the temperature of thermal-throttle is under close-loop control, the flowrate could be controlled with high-precision.

D. DICU

DICU provides the communication interface between the EP system and satellite platform, and the driven command for the HEPS, XIPS and XSFM. Besides, all of the logical control function is achieved by DICU, including the pressure control of PRM, flow rate control of FCM, sequence control of the firing procedure of HET and XIT, and failure diagnostic of each parts through the analog signal.

DICU is specially developed for SJ-9A, and its main parameter includes:

CPU： 80C32

PROM：⩽ 32KB

RAM： ⩽ 8KB

Frequency：11.0592MHz

Reset：electrify reset and WATCHDOG reset

Control cycle：1000ms。

E. Function mode design

Three modes are design to fulfill the function requirement of EP and safety requirement of platform. They are MINI mode, XIP mode and HEP mode.

The EP system enters MINI mode when initially electrified. The MINI mode is specially designed to satisfy the safety requirement of platform. In the MINI mode, the XIPS and HEPS are not electrified, the analog signals from XSFM are received and inspected, and any command of the platform is not response except mode conversion command. The EP system will enter HEP mode or XIP mode depends on the mode conversion command from platform.

In HEP mode, the operation of HEPS and XFSM of HEP branch could be performed, while the operation of XIPS and XFSM of XIP branch is forbidden. All the parameter of HEPS and partial parameter of XIPS are received and inspected.

And similarly in XIP mode, the operation of XIPS and XFSM of XIP branch could be performed, while the operation of HEPS and XFSM of HEP branch is forbidden. All the parameter of XIPS and partial parameter of HEPS are received and inspected.

Thus, the possibility of mis-operation is minimized.

F. Basic specifications

The flight product and qualification model of SJ-9A EP were manufactured with the flight standard procedures. The qualification model had been through the qualification tests, while the flight product through the acceptance tests.

The basic specifications of the flight model are as shown in Table 1.

Table 1 Basic specifications of EP on SJ-9A

No.	Parameter		Unit	EP	
				HET	XIT
1	Propellant		-	Xeon	Xeon
2	Propellant Mass		kg	1.5	1.5
3	Life		Year	⩾3	⩾3
4	thruster	Thrust	mN	40	40
		Specific Impulse	s	1600	3000
		Power	W	800	1200

		Life	Hour	⩾3000	⩾3000
		Operating cycles	Times	⩾3000	⩾3000

III. Ground Tests of SJ-9A EP System

Besides the standard producers of verification test and acceptance test for space products, a series of specified ground test for electrical propulsion system were performed.

A. Tests of Main Performance parameters

Before verifying in-space, the performance tests of SJ-9A EP system should been carried out on ground, including the main parameters of thrust, specific impulse and power.

The principle of thrust measurement is as shown in Fig.3. It employs the electromagnetic balance to sense the micro-thrust, and the signal was amplifying by an amplifier, then acquired by ADQ. The specifications of the thrust test equipment are as follows:

1) Range：5~ 200 mN
2) Resolution：0.1 mN
3) Error： ±2.0 mN

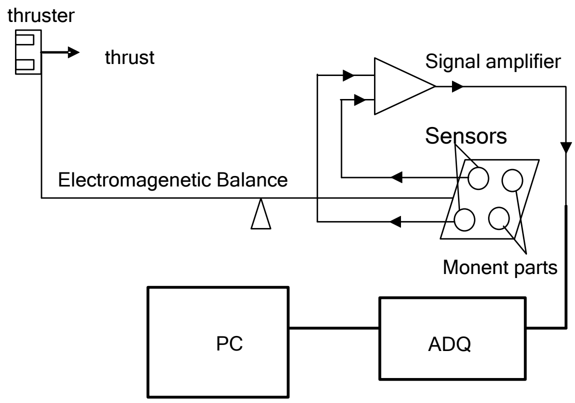


Fig.3 Thrust test schematic diagram

The specific impulse was measured indirectly. The total flowrate of anode and cathode were measuring by flowmeters. And the specific impulse was obtained by dividing the thrust by total flowrate. The power exhausted by thruster is calculated by multiplying the supply voltage and current during the fire experiments.

The test results are as shown in Table 2.

Table 2 Main performance of EP on SJ-9A

No.	Parameter	Unit	EP

				HET	XIT
1	thruster	thrust	mN	40.3	39.9
		Specific Impulse	s	1585	3136
		power	W	800	1200

B. Tests of EMC with other equipments on S/C

The aim of the EMC tests is to make sure that the EP system is compatible with S/C and would not disturb the other electronic equipments when it operates. The tests include:

a) The test of EMI characteristics of EP system (CE101/CE102/CE107/RE102) ;

b) The influence of plume on communication;

c) The EMC test of EP system with other electronic equipments on S/C.

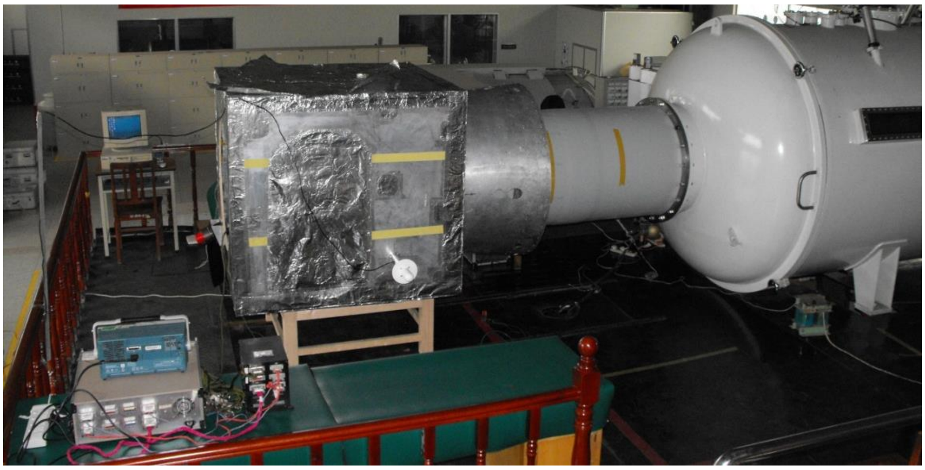


Fig.4 EMC tests

The results of experiments indicated that although some EMI signals generates when the EP system is operating, it would not affect the other electronic equipment to work normally.

C. Couple tests with power supply system on S/C

The power consumption of EP system is about 800~1200w, which is really a burden for a small LEO satellite. In order to supply the SJ-9A EP, the power supply system on S/C was redesigned by adding two specific solar panel units. Therefore, a couple test of EP and power supply system on S/C are performed to verify the adaptability of EP and power supply system.

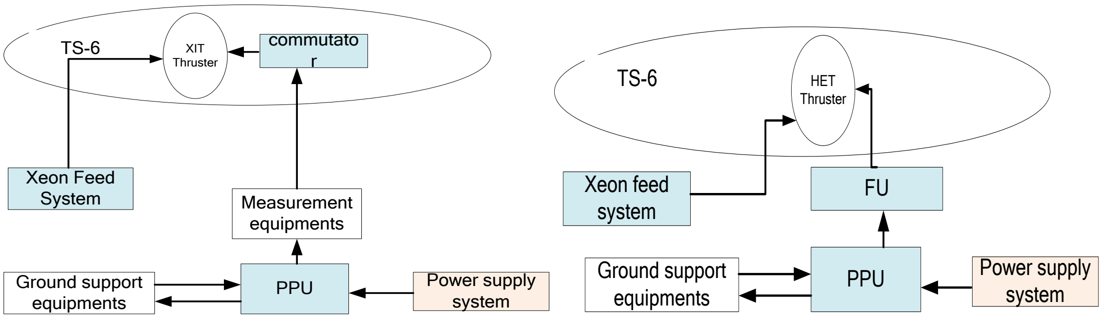


Fig.5 Couple tests with power supply system

During the couple tests, both the power supply system and the EP subsystem worked very well, and the performance is in good accordance with the design anticipation.

IV. In-flight experiments of SJ-9A EP Subsystem

SJ-9A was launched in October 2012, and till December 2012 the in-flight experiments of first stage had been accomplished. The in-flight experiments were carried out in the following sequence:

a) First step: initially checkup

b) 2nd step: the pretreatment of EP system

c) 3rd step: the first firing

d) 4th step: thrust celibration in orbit

e) 5th step: accumulate cycling test

The sequence of the in-flight experiments is as shown in Fig.6.

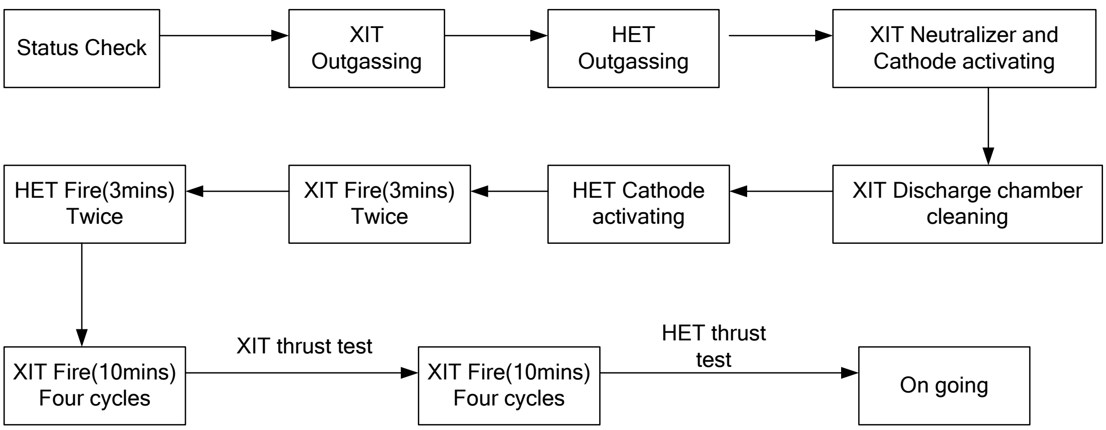


Fig.6 The in-flight experiments sequence of first stage

A. First step: initially checkup

On the first day the satellite was on orbit, initially check-up was performed to ensure that the EP system is in good condition after launch. The DICU was electrified, and all the parameter of the EP system in MINI mode shows that the EP system function is quite good.

B. The pretreatment of EP system

To fulfill the preprocessing of the thruster before firing, a series of pretreatment of EP system was performed, which includes XIT/HET outgassing, XIT neutralizer and cathode activating, XIT discharge chamber cleaning, and HET cathode activating.

To ensure the purity of the xenon feeding to thruster, XIT/HET outgassing was performed by flushing the lines and valved with the xenon from the tank, for two times under the control of DICU.

The activation period is last for about 1 hour for each cathode of XIT and HET, including the neutralizer, to clean the impurity adhere to there inner surface.

And the discharge chamber cleaning is performed by firing the XIT thruster for half an hour two times, without beam extracted out.

C. The first firing of XIT and HET

After the pretreatment precess, the EP system is ready for verify in orbit. On November 7, 2012, the first firing of XIT is performed, and on the next day, the first firing of HET is performed. In the first firing period, both XIT and HET was found to be a little variation comparing with grounding results because of the difference of environment, which were as expected. Some of the parameters, such as Xenon flowrate, range of pressure regulations and some other control parameters, were adjusted initially to adapt to the in-space environment.

D. thrust celebration in orbit

After the control parameters adjusted, XIT and HET were separately set on fire for 4 cycles to calibrate the thrust through measurement of the orbital altitude variation.

The thrust calibration method in-space is as follows:

a. Before firing, the orbital altitude was measured;

b. Then, XIT/HET was set on fire for 4 cycles, and 10mins for each cycle. And the orbital altitude will increase or decrease correspondingly.

c. After the XIT/HET power off, the orbital altitude was measured again;

d. Base on the orbital model, the thrust is calculated with disturbance compensation.

During the experiments, the EP system worked well and the main telemetries that determine the thrust are as shown in Table 3 and Table 4.

Table 3 The telemetry of XIT

NO.	Telemetry	Range	Cycle 2	Cycle 3	Cycle 4
1	Beam voltage/V	900~1100	1022.7	1022.7	1022.7
2	Beam current/A	0.7~0.9	0.785	0.780	0.785

Table 4 The telemetry of HET

NO.	Telemetry	Range	Cycle 2	Cycle 3	Cycle 4
1	Anode current/A	1.5～3.5	2.125	2.156	2.156
2	Anode voltage/V	250～380	331.25	331.25	325

Through measurement of the orbital altitude variation, the thrusts of XIT and HET were calculated. Finally, the in-flight performance of EP subsystem is attained, as shown in Table 5.

Table 5 The in-flight performance of EP on SJ-9A

No.	Parameter		Unit	EP	
				HET	XIT
1	thruster	thrust	mN	37.8	36.1
		Specific Impulse	s	1485	2727
		power	W	794	1198

Through measurement of the obital altitude variation, the thrust and specific impulse were calibrated in standard working condition, thrust of XIT 36.1mN, specific impulse of XIT 2727s, thrust of HET 37.8mN, specific impulse of HET 1485s. The electric propulsion system works extremely well after the parameters were adjusted initially, and the performance is close to the same type of electric thruster with equivalent power as reported. The results indicate that the electric propulsion technologies have been successfully verified in space.

E. accumulate cycling test

Now, the EP system is proceeding to the cycling tests for more than 120 time for XIPS and HEPS, respectively, which will last till the propellant exhausts.

V. Conclusion

To verify the XIT and HET technology and the system integration capability, an EP system is designed, developed and verified for satellite SJ-9A. Through a series of grounding tests, the EP system is qualified for the requirements of the satellite SJ-9A, which was lanched in October 2012, and initially in-space tested in December 2012. The EP system works extremely well after the parameters were adjusted initially, and the performance is very closed to the same type of electric thruster with equivalent power in USA and Europe. The results indicate that the first electric propulsion developed by China have been successfully verified in space.

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