Flight Demonstration and Application of Electric Propulsion at CAST

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Abstract: China Academy of Space Technology (CAST) has launched the scientific satellite SJ-9A to demonstrate the development of electric propulsion technologies in China. The on-board demonstration electric propulsion system consists of propellant feed unit, ion thruster, hall thruster, control unit and diagnosis unit. The paper will present the contents of the flight demonstration program, the ignition control mode, the performance of the electric propulsion system, the in-orbit flight test results and prospects of the electric propulsion application at CAST.

I. Introduction

CAST continues to develop electric propulsion (EP) technologies, which enables and enhances CAST’s ability to build the scientific satellite SJ-9A. EP systems will be implemented for various space missions, especially for North-South Station Keeping (NSSK) of GEO telecom satellites, like as what has been done by the major telecommunication manufactures (i.e. Boeing, Tas, Space Systems Loral, EADS ASTRIUM). As a further benefit, EP system’s performance can also significantly reduce the spacecraft mass and launch vehicle costs, due to its high specific impulse capability compared to chemical propulsion.

This paper will provide an overview of EP system development and flight demonstration activities, including the ignition control mode, the performance of the EP system, the in-orbit flight test results and prospects of the electric propulsion application that are ongoing at CAST.

II. SJ-9A flight demonstration

The SJ-9A is the first new technology demonstration satellite built by CAST, launched to a sun-synchronous circular orbit. The mission objective is to demonstrate the long life, high reliability, high capability key components and parts. The performance of the electric propulsion system is one of the

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emphases.

The EP system of satellite SJ-9A was began to be developed in 2008, having undergone three developing phases. The satellite was furnished with the flight components of the EP system in August 2011, successfully launched on October 14, 2012, and then began to be tested in orbit in December, 2012.

The EP system of satellite SJ-9A was equipped with a 20cm ion thruster and a FDT-10 hall thruster[1], which has the independent intellectual property right. And it was the first in-orbit test of EP technology in China. According to the control demands of the satellite, the EP system would produce the force for orbit maneuver and orbit maintenance, within the confines of telemetry and telecommand system, power system and thermal control system. And the flight performance, compatibility with the satellite would be tested. Furthermore, the plasma parameter change near the satellite and the contamination sediment on the solar panel would be measured when the EP system is firing, so that the technologies and experience of flight demonstration would be helpful to the future application on the spacecraft.

A. Contents of the flight demonstration of EP system

The mission objectives are to perform technology demonstrations of the electric propulsion system, which includes:

a) Verification of the space environment adaptability of the EP system.
b) Verification of the actual performance of the EP system.
c) Verification of the ignition control mode, cumulating flight experience for the future spacecraft application.
d) Verification of the compatibility of the EP system with spacecraft

B. Performance of EP system

The EP system consists of propellant feed unit, ion thruster, hall thruster, control unit and diagnosis unit. The Performance of thrusters is shown in table1.

<table>
<thead>
<tr>
<th>Item</th>
<th>Performances</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Nominal Thrust</td>
<td>20cm xenon ion thruster</td>
</tr>
<tr>
<td></td>
<td>Nominal Thrust: 40mN ± 4mN</td>
</tr>
<tr>
<td>2 Specific Impulse</td>
<td>3000s ± 300s</td>
</tr>
<tr>
<td>3 Single Burn Time</td>
<td>1600s ± 160s</td>
</tr>
<tr>
<td>4 Times of Start-up</td>
<td>5~15min</td>
</tr>
<tr>
<td>5 Mass</td>
<td>≥200</td>
</tr>
<tr>
<td>6 Power Consumption</td>
<td>Net Mass: ≤85kg</td>
</tr>
<tr>
<td></td>
<td>Power consumption of xenon ion thruster: ≤ 1350W</td>
</tr>
<tr>
<td></td>
<td>Power consumption of hall thruster: ≤ 800W</td>
</tr>
<tr>
<td></td>
<td>Average power consumption of diagnosis unit: ≤ 15W;</td>
</tr>
<tr>
<td></td>
<td>Maximum transient power consumption: ≤ 27W</td>
</tr>
</tbody>
</table>

C. Layout and control mode of EP System

- Layout of EP system
The ion thruster is placed on the -X-plane of the satellite and is used for raising the orbit. The hall thruster is placed on the +X-plane of the satellite and is used for lowering the orbit. Two kinds of thrusters work together to accomplish the demonstration of the ion and hall propulsion technologies.

![Figure 1 Sketch of SJ-9A Launching](image1.jpg)

![Figure 2 Sketch of SJ-9A Flying](image2.jpg)

- **Control mode of EP system**

  The demonstration test of the EP system in-orbit was processed in normal mode, yaw maneuver and yaw maneuver restoration mode during the first three visible cycles. The thrust was calibrated by ground orbit determination, using the Global Position System (GPS). Disturbing torque was absorbed by momentum wheel, with magnetic unloading at the same time. The hydrazine monopropellant thruster
were used for the momentum wheel unloading when their were close to saturation. The ion thruster and hall thruster ignited alternately in the in-orbit demonstration test, short-time firing test, in-orbit thrust calibration and long-term firing test, so that the design target of the system would be achieved.

D. Composition of the EP System

The electric propulsion system consists of propellant feed unit, ion thruster, hall thruster, control unit and diagnosis unit, shown in figure 3. And the detailed configuration is shown in table 2. Two kinds of thrusters work together to accomplish the demonstration of the ion and hall propulsion technologies. Besides the thrusters’ participation in orbit control, the influence of the electric propulsion system on the satellite needs to be monitored.

![Figure 3 The Electric Propulsion System](image)

<table>
<thead>
<tr>
<th>NO.</th>
<th>Name</th>
<th>amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Electric propulsion system</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>Electric propulsion control unit</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>Ion thruster subsystem</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>Ion power supply</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>Power supply switch unit</td>
<td>1</td>
</tr>
<tr>
<td>6</td>
<td>Ion thruster</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 2 Components List of the Electric Propulsion System

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E. Working Mode of EP system

The electric propulsion system is commanded by DICU and it is not powered on before the satellite is in the orbit. There are three working mode for the EP system, standby mode, ion propulsion system firing mode and hall propulsion system firing mode.

✧ **Standby Mode**

The software will run in the standby mode after a power on reset or watch dog reset. Ion thruster and hall thruster will not fire in standby mode, but the system state can be measured and software parameter can be set.

✧ **Ion Propulsion System Firing Mode**

Hall thruster can not ignite in the ion propulsion system firing mode, and only the Ion thruster subsystem part will operate. Ion thruster can ignite, sending the operating parameters of Ion thruster subsystem along with the basic state data of hall thruster subsystem. The function in this mode includes:

1) Communicating with the satellite, receiving control command, gathering and sending back the parameters of electric propulsion system.
2) Control of power supply unit and propellant feed unit of ion thruster subsystem according to commands of the satellite.
3) Pressure control.
4) Temperature control of flux controller of cathode, neutralizer and anode.
5) Failure diagnoses and disposal in the ion propulsion system firing mode.

Diamond **Hall Propulsion System Firing Mode**

Ion thruster can not ignite in the hall propulsion system firing mode, and only the hall thruster subsystem part will operate. Hall thruster can ignite, sending the operating parameters of hall thruster subsystem along with the basic state data of ion thruster subsystem. The function in this mode includes:

1) Communicating with the satellite, receiving control command, gathering and sending back the parameters of electric propulsion system.
2) Control power supply unit and propellant feed unit of hall thruster according to commands of the satellite.
3) Pressure control.
4) Current control of cathode.
5) Failure diagnoses and disposal in the hall propulsion system firing mode.

F. Electric Propulsion Tests

Electric propulsion tests include test of components, system, satellite and flight.

1. Test of components

During the development of satellite SJ-9A, components and units accomplished the environmental adaptability and reliability tests, such as sinusoidal vibration, random vibration, impact, acceleration, thermal vacuum, thermal cycling, firing at high/low temperatures, space radiation, magnetism, EMC, burn-in, life and pressure endurance etc. Figure 6 and 7 show the test of thermal cycling and firing at high (+100°C)/low (-100°C) temperatures of hall thruster[1].

![Figure 6 Test of Thermal Cycling](image1)

![Figure 7 Firing at High/Low Temperatures](image2)

2. System tests

The united firing test of ion and hall thruster, with satellite control system and power supply system was accomplished. The electric propulsion system test includes:

Diamond **Ion thruster firing**
3. Test and task of the satellite

During developing of the satellite, the system test includes assembly performance test, electric characteristic test and interface matching test, then electromagnetism compatibility, demagnetization, environmental adaptability, thermal vacuum, propellant filling and propellant purity measurement. According to the characteristic of Xe propellant, hot extrusion filling method is adopted, along with vacuumizing, gas removing by pyrogenation, gas replacement with Xe.

The tests and tasks of the electric propulsion system during the developing of the satellite include:
- components assembly and pipeline welding
- leakage detection
- special parts and instrument dismounting
- electric characteristic measurement
- electric performance test
- propellant fill and propellant purity check

4. Flight test

The flight test of the electric propulsion system in-orbit is divided into 5 processes according to time, initialization, first firing, in-orbit system debug, baseline flight test and extended flight test. Now the satellite comes to the baseline flight test successfully. The in-orbit flight test results of the thrust of ion thruster and hall thruster have been acquired. And the in-orbit flight tests will complete within 1 year after the launching time.

(1) Initialization
 Initialization includes gas removing of power supply disposal units and thrusters, initial inspection of the electric propulsion system after powered on, gas removing of the low-pressure pipeline of propellant feed unit, propellant feed unit checking, power supply checking, thrusters checking and cathode activation.

(2) First Firing
 After initialization, ion thruster begins the first firing. Data is sent back by telemetry system to verify the in-orbit state of the electric propulsion system.

(3) In-orbit System Debug
 According to the working environment in the orbit, the operating parameters of the electric propulsion system can be adjusted to optimize the working state of the electric propulsion system.

(4) Baseline Flight Test
 Baseline flight test constitutes two hundred cycles, until 50 hours of firing time for each thruster have been reached.

(5) Extended Flight Test
 After baseline flight test, extended flight test will be carried on if the propellant and the power supply are possible.
Result of Flight Test:

- **Fault Eliminating:** Right from the start of the flight, there was trouble with the ion thruster subsystem, some parameters were not correct. There was an abnormal increase of the grid current. It was first considered that PPU was short circuited, but after more analysis and checking, contaminant was deemed to result in grid short circuit. After the contaminant is gone, ion thruster was back to work normally.

- **Thrust Measuring:** The performances of the electric propulsion system including thrust and specific impulse were acquired. Thrust was calibrated in two methods, and can be crosschecked with each other. The first one is to measure the running parameters of the electric propulsion system, such as the voltage/current of screen grid of ion thruster, the voltage/current of anode of hall thruster, and calculate the thrust by comparing the data with what was got in the ground tests. The second one is to measure the orbit parameter of SJ-9A by using Global Position System (GPS), and then the thrust can be calculated. The result of flight tests indicated that thrust and specific impulse meets the design requirement.

### III. Application on GEO Satellite Platform

DFH-4 is a geostationary orbit platform developed by CAST with high capacity and long lifetime (15 years)\(^4\). Table 3 shows the technical specifications of the DFH-4 platform. To extend the GEO platform capability, the electric propulsion system can be introduced for its NSSK mission, partly in replacement of chemical propulsion function to increase the payload mass limit\(^5\).

<table>
<thead>
<tr>
<th>Name of Platform</th>
<th>DFH-4 Platform</th>
</tr>
</thead>
<tbody>
<tr>
<td>Platform Mass</td>
<td>5000kg - 5200kg</td>
</tr>
<tr>
<td>Payload Mass</td>
<td>500kg - 700kg</td>
</tr>
<tr>
<td>Attitude and Orbit Control Mode</td>
<td>3-axis Stabilization</td>
</tr>
<tr>
<td>Pointing Accuracy</td>
<td>±0.06°(Roll)</td>
</tr>
<tr>
<td></td>
<td>±0.06°(Pitch)</td>
</tr>
<tr>
<td></td>
<td>±0.2°(Yaw)</td>
</tr>
<tr>
<td>Solar Array Power Output</td>
<td>11 kW</td>
</tr>
<tr>
<td>Power Available for Payload</td>
<td>8 kW</td>
</tr>
<tr>
<td>Design Lifetime</td>
<td>15 Years</td>
</tr>
<tr>
<td>Station-keeping Accuracy (3σ)</td>
<td>±0.05°(E/W)</td>
</tr>
<tr>
<td></td>
<td>±0.05°(N/S)</td>
</tr>
</tbody>
</table>

### A. Composition of EP System

The electric propulsion system consists of propellant feed unit, ion thruster, control unit and power...
supply unit, shown in figure 9.

![Diagram of electric propulsion system]

**Figure 9  The Composition of the Electric Propulsion System**

### B. Prominent Character of EP System

Its prominent character is as follows:

- Orbit life time 15 years. Firing twice per day, and 1.5~2 hours once, more than 14000 cycles in its life time. The mission demand of the electric propulsion system of GEO satellite platform will be much higher than that of SJ-9A, which is 200 cycles in total, 15 minutes once per day. Long life test of the electric propulsion system will be carried out on the ground in a vacuum environment.

- A new kind of “MAZE” for the flux controller of the Xe feed system, as is shown in Fig.4 and Fig.5. The first generation feed system usually adopts “Bang-Bang” valves as pressure regulator to form the pressure adjustment module, and adopts the flux controller made of porous metal sinter to form the press control module, this first generation feed system was adopted for Deep Space 1 (DS1) by NASA. The second generation feed system usually adopts a proportional valve instead of “Bang-Bang” valves and a “MAZE” flux controller instead of porous metal sinter.
The Xe feed system adopts “Bang-Bang” valve as the pressure adjustment module, shown in figure 10. The pressure output precision can be within ±0.0025MPa after optimizing, equivalent to the similar international products [7]. The “MAZE” flux controller can throttle through multilevel expanding channel, shown in figure 11. The flux controller with heaters can regulate the flow rate through the temperature of Xe propellant, shown in figure 12. Its working temperature range is about 50°C~120°C. The heaters are wrapped with multilayer covers to prevent heat leak from affecting other components.
The GEO platform is based on LIPS200 ion thruster, which was developed by CAST, with 1000W power consumption, 6.5 kilograms mass, 20cm diameter, 40mN thrust and the specific impulse of 3000s\textsuperscript{[6-8]}. The electric propulsion system equips with 4 LIPS200 thrusters, which are set in the thruster pointing assembly mechanism (TPAM). TPAM is designed to provide the required pointing capability around two perpendicular axes for the Electric Thrusters. TPAM uses 2PSS-U parallel mechanism.

<table>
<thead>
<tr>
<th>Name</th>
<th>Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Angular range</td>
<td>X-axis:≥16°, Z-axis:≥±5°</td>
</tr>
<tr>
<td>Pointing accuracy(Deg)</td>
<td>/</td>
</tr>
<tr>
<td>Resolution step(Deg)</td>
<td>0.005°</td>
</tr>
<tr>
<td>Resolution speed(Deg) max</td>
<td>0.1°/s</td>
</tr>
<tr>
<td>Worst electrical consumption</td>
<td>≤32W</td>
</tr>
<tr>
<td>Maximum load(kg)</td>
<td>2×7kg</td>
</tr>
</tbody>
</table>
IV. Prospect of EP application at CAST

The electric propulsion technology has been researched and developed by CAST for many years. It tends to become mature for space applications. Along with the successful launch and orbital test of electric propulsion system in satellite SJ-9A, constitution rationality of electric propulsion, effect of working in space and compatibility with spacecraft, will be verified step by step, which will be helpful to the future application on the spacecraft.

The next challenge for EP is to improve competitiveness at world level, and CAST has increased development fund for various electric propulsion technologies, and has drawn a plan for space applications, because the electric propulsion can be applied to various spacecraft, shown in table 5. At present, the applications of EP will be mostly for NSSK mission of GEO communication satellite and orbit transfer of low orbit satellite.

<table>
<thead>
<tr>
<th>Mass</th>
<th>≤17 kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>In Orbit Lifetime</td>
<td>15 ans</td>
</tr>
<tr>
<td>Dimension (mm×mm×mm)</td>
<td>400×570×600</td>
</tr>
</tbody>
</table>

Table 5  Electric Propulsion Application

<table>
<thead>
<tr>
<th>GEO satellite</th>
<th>LEO satellite</th>
<th>Exploration mission</th>
<th>Scientific research and earth observation</th>
</tr>
</thead>
<tbody>
<tr>
<td>NSSK</td>
<td>orbit transfer</td>
<td>Primary propulsion</td>
<td>High-precision pointing</td>
</tr>
<tr>
<td>orbit transfer</td>
<td>Resistance compensate</td>
<td>/</td>
<td>Attitude control and orbit maneuver</td>
</tr>
<tr>
<td>Disposal at EOF</td>
<td>Attitude control and orbit maneuver</td>
<td>/</td>
<td>Resistance compensate</td>
</tr>
<tr>
<td>Disposal at EOF</td>
<td>/</td>
<td>Drag free</td>
<td></td>
</tr>
</tbody>
</table>

Deep space explorer is another area for the electric propulsion technology application. The Clementine (CL) mission (America, 1994) and SMART-1 mission (ESA, 2003) are of the same net weight (about 200kg), but the CL(chemical propulsion) used the chemical propulsion system with the total propellant mass more than 1000kg, while the SMART-1 used the electric propulsion system with the total propellant only 80kg\(^{10, 11}\). Therefore, the benefit of the electric propulsion application is remarkable in the deep space exploration. The electric propulsion technology can be applied for Luna explorer by CAST in the future, because large thrust is not necessarily required for orbit transfer of Luna circling, earth-Luna orbit, Luna-earth orbit, and EP can accomplish those missions. Then the launching weight of spacecraft and mission cost must be reduced enormously.

References


