AN OVERVIEW OF ELECTRIC PROPULSION ACTIVITIES IN CSSAR

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Abstract

Since the late 60's three kinds of electric propulsion system have been developed first in Institute of Electrical Engineering (IEE), CAS, after 1980, in CSSAR, CAS. They are the ion thruster, pulsed plasma thruster and arcjet thruster system.

In this paper, the electric propulsion activities in CSSAR (include its precursor-IEE, CAS) are reviewed. These activities include the building of experimental facilities, basic research, engineering development and their application in non-propulsion.

1. Introduction

Early in the 1968, the electric propulsion technology as a new type of space propulsion system had been developed with the raising of Chinese space activity. First the research on ion thruster system used as the primary propulsion of satellite orbit transfer was conducted in IEE, CAS. Then, the test of pulsed plasma thruster (PPT) for the east-west stationkeeping of synchronous satellite was also started in 1970.

The research of ion propulsion was stopped in 1973 due to no mission and then turned on the non-propulsion application. Over more than 10 years effort, two sets of pulsed plasma microthruster, MDT-2A, had been tested successfully in space in Dec.1981. After space flight test PPT's investigation focused to improve its performance and develop new thruster model. Unfortunately that work was also stopped in 1988 because no flight mission.

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The use of electric propulsion for NSSK and orbit repositioning missions offers significant advantages, compared to chemical propulsion. It is hope to develop a kind of electric thruster suitable for NSSK of future Chinese long lifetime synchronous satellite. PPT is difficulty to satisfy this requirement because its thrust is too low and its total impulse ability is not enough. A program developed an experimental system of low power (1 kw class) arcjet thruster was carried on since 1992, under the support of the National Natural Science Foundation of China (NNSFC).

In the recent years CSSAR renew the PPT research aiming at the on-board control of small satellite constellations, under the support of CAS.

2. Ion propulsion and its technical application

Ion propulsion

Under the initiation of Dr. Xuesen Qian, a famous Chinese scientist, the research of ion propulsion had been started in IEE, CAS as early as 1968. The objective was directed at the primary propulsion of satellite orbit transfer from low orbit to synchronous orbit. During the period of 1968-1973, a set of vacuum system, which is 1m in diameter and 4m long, had been built up. Two types of electron bombardment ion thruster using mercury as propellant had been fabricated. One was 12 cm in diameter, the other was 6 cm in diameter. Some of performance experiments were carried on. However, the research of ion propulsion in IEE CAS had been cancelled due to no mission and no finance support in 1973. After that the investigation of ion thruster turned on the ion source and the non-propulsion application, especially for material modification since 1981.

Table 1. The ion source and its application

Ion source	Diameter of ion source (cm)	Beam Energy (keV)	Beam Current (ma)	Application
High energy broad beam ion source	8	3-100	15-17	Ion mixing and implantation
Focusing beam ion source	3.5-10	1.5-10	100-350	Sputter coating of thin films, hard coating, alloy for H_2 storage, superconductor
Low energy broad beam ion sources	2-10	0.01-1.5	15-200	Assisted deposition of thin films, optical, cleaning, etching etc.
	18	1.5-6	1000	Hydrogen passivation of thin films
	3×20	0.1-1	100	Hard films

Ion source and its application

In the past eighteen years, a series of high energy (up to 120 KeV) and low energy (as low as 10eV) broad beam ion sources, and focusing beam ion source with or without dished grids have been designed and manufactured in CSSAR for different applications (shown in table 1). All of them are the DC electron bombardment ion sources. Recently a new type of ion source, broad beam metal ion source, is being studied. Here is the brief present of high-energy broad beam ion source and metal ion source.[1]

1). High energy broad beam ion source

The low-energy broad beam ion sources, like the Kaufman ion sources used for the space propulsion, have many advantages, such as high efficient, easy to operate and maintain. Since they can produce broad ion beam with high beam current density and good uniformity, further more, they haven't the troublesome cooling problem of high potential parts because of high efficiency. They are particularly suitable to the large area material modification, for example, the ion beam implantation, ion mixing and IBED. However the beam energy (usually 1-3 KeV) in a conventional broad beam ion source is lower than the demand by ion implantation. Therefore the high-energy broad beam ion sources must be developed. In order to increase the beam energy, the extracting voltage must be increased. The problems of the flashover between grids and discharge extinguish caused by flashover must be solved during operating in high extracting voltage level. So, in order to avoid flashover occurred between grids and broaden extracting voltage range while keeping good optics, the ion optics, the insulator and the magnetic field in discharge chamber have been redesigned. To increase the thickness of screen grid, diameter of grid hole and the gap between grids have been used in our high-energy ion sources (see Fig.1). The tow-grid ion optical system is equipped with the source. The ranges of beam energy and current extracted from one of these sources are 3-120keV, 5-70ma, the other one 2-50keV, 15-20ma. The beam uniformity ranging from 10% to 20% is achieved within the region of a 25cm diameter at the location 60cm downstream of these sources.

2). Electron beam evaporation broad beam metal ion source

To raise the IBED efficiency and broaden its application field, the intensive beams of both gaseous and metal ions are needed. The ion sources for producing high current gaseous ion beam have been used for a long time, while the development of metal ion source has just begun. The schematic diagram of the metal ion source developed in CSSAR is shown in Fig.2. In this source, the discharge occurs between filament and anode. The electron generated by discharge is focused to form an electron beam with high beam current density and to bombard and vaporize the metal material in the crucible. A high-density metal vapor is formed and ionized by the arc discharge. A set of two-grid accelerator system is used to extract the ion beams. This source can be operated with either gas or solid materials. Ion beams of several kinds of material such as W, Ta, Mo, Cr,

Table 2. The hardness of CN on the WC plate

Sample	Extraction Voltage (kV)	Beam Current (ma)	N_2 Flow rate (sccm)	Deposition time (min)	Load (g)	Hardness (kgf/mm2)
1	4	40	1.26	35	20	3100
2	4	40	1.86	60	20	4157
3	4	40	2.09	70	20	5300-5800

Ti, B, Cu, C etc. have been extracted from the source. The beam current, which has been extracted from a 4cm in diameter ion source, is 20-50ma at beam energy 4keV.

3). Applications of the new type broad beam ion sources

CN film can be formed on the substrate of Tungsten Carbide by introducing N_2 into discharge chamber of the metal ion source. When the flow rate of N_2 is modulated from 1.80 sccm to 5.04 sccm, the ratios of C/N atom concentrations will be changed from 0.14 to 0.6. The hardness of CN films on the WC substrate is Hk = 3100-5800 kgf/mm^2 (shown in Table 2). The hardness of CN film is increased with increasing the flow rate of N_2 from 1.26 to 2.09 sccm at extraction voltage 4kV and bombardment current of 40 ma.

3. PPT and its technical application

PPT for satellite control

In order to provide a new thruster for the east-west stationkeeping in Chinese synchronous satellite, the PPT was selected as a candidate because it has many advantages, such as simple structure, easy to control and fast action. The Experimental research started in 1970 and carried on in Electric Propulsion Laboratory (which merged into CSSAR in 1980), IEE, CAS. Since then, the following works have been finished.

1). **Built the experimental equipment**

a. Built three sets of vacuum system. The first one has two cylindrical vacuum chambers. Each chamber is 400 mm in diameter, 600 mm long. The pressure in the chamber is about 7x10^{-3} Pa excluded by an oil diffusion pump and mechanical pump. It was used for the test of PPT lifetime and component performance. The second is 1m in diameter and 1.6m long. It was mainly used for thrust measurement both the thruster and the thruster system (Fig. 3). The third is the same in dimension as the second system, but it is made of stainless steel and has a cooling/heating layer inside the chamber used for the temperature environment test.

b. Developed a torsion pendulum used for measuring the thrust or impulse.

c. Developed some of the ground power supply and the measuring devices of discharge current, discharge voltage, discharge pulse and propellant ablated rate.

2). **Developed the MDT-2A thruster system**

Based on a great number research and tests in MDT series thruster, the MDT-2A thruster system had been developed (Fig. 4). It uses the solid Teflon as the propellant.[2-4]

MDT-2A thruster system comprises three subsystems. They are thruster body, ignition subsystem and power conditioner and telemetry signal converter subsystem. The thruster body has two independent nozzles, which can work alternately. All of the propellant and its feed system, spark plug and ignition subsystem in each nozzle work independently without any influence to each other. But the power conditioner, the main energy storage capacitor and the discharge ignition capacitor are common. The nozzle is a kind of parallel rail electrode. In the cathode there is a spark plug which is a kind of coaxial semiconductor plug. Its working principle is well known and can be found in many references.[5, 6]

The performance parameters of the MDT-2A thruster system are presented in table 3.

Table 1. The main performances of MDT-2A

Propellant	Solid Teflon
Teflon profile	1.0 x2.5 cm^2
Main capacitor	2 uf/2 kv
Ignition capacitor	10uf/ 150v
Energy per discharge	4 j
Mass ablation per discharge	2.2×10^{-8} kg
Average impulse bit	6.5 mg-sec
Average specific impulse	280 sec
Efficiency of power conditioner	> 80 %
Thruster efficiency	>2 %
Total system weight	2.75 kg
dimension	$31.6 \times 12.5 \times 16.5 cm^3$

3). **Completed space ballistic flight test**

To push the PPT towards the practice application, a plan of doing space flight test had been proposed in 1977 after finishing the MDT-2A system. It contained two projects: the satellite orbit test and the ballistic flight test. [7]

a. Orbit test plan of MDT-2A

CSSAR (its precursor-Space Science and Technology Center, SSTC) prepared to launch an astronomical satellite in the late of 70`s. Two sets of MDT-2A system was determined as a payload of satellite to do the satellite orbit test in 1978. The purpose of flight test was follows:

- To compare the thrust measured in ground with in space;
- To verify the survivability of MDT-2A system against the launch and space environment;
- To understand the compatibility of MDT-2A with other system in satellite(electromagnetic compatibility).

In order to suit the satellite requirements, a new MDT-2A flight test unit had been built up. The thermal vacuum test, shock, vibration and acceleration tests, EMC test have been completed from 1979 to 1981. Two of MDT-2A units were integrated together with other equipment and tests as a whole satellite system in 1982.

Unfortunately, this plan of launching the astronomical satellite had been stopped in 1983, therefore the PPT`s orbit test had to be given up.

b. Ballistic flight test of MDT-2A

During conducting the plan of orbit test, the ballistic flight test project had been also provided and was approved in 1979. It was a pre-test of the satellite orbit test. The objective was to checkout the operation ability of MDT-2A system in actual space.

After completing a series of tests, especially passing the matching test with the carrier launching system and EMI test, on 7 Dec. 1981 two sets of MDT-2A system finished the space ballistic flight test. Fig. 5 shows the scheme of ballistic flight test. The region tested was between 400 km and 3400 km (started from 600km altitude, at 400 km stopped). Whole test time lasted 37 minutes. The result from the telemetry signals showed the MDT-2A systems worked very well during the flight. The flight test was successful.

4). Developed 20 j PPT

It is well known that the PPT has the disadvantages of low efficiency and low specific impulse when it operates in low power levels. After the flight test, the main works concentrated on the improvement of thruster performances. They included the efficiency, specific impulse, and the lifetime of spark plug.[8, 9] A 20 j PPT breadboard had been developed based on these research and tests.[10] However, the PPT research had to be stopped in 1988 because of no mission and no finance support.

5). Renew started the PPT research

In the recent years, to develop the low orbit satellite, especially the small and micro-satellite constellations become a new hot-point in the world. Of course, it is the same in China.

In this status, CSSAR renew the PPT research aiming at the on-board control of small satellite constellations, under the support of CAS.

The research plan includes:

- To improve the PPT performance through the theory analysis and performance investigation.
- To develop a higher power (30-60w), high efficiency PPT model.
- Continue to find the chance for doing satellite orbit flight test.

The research work have started and it was found the MDT thruster fabricated in 19 years ago operated well in the recent test. It is clear the PPT has a good storage lifetime.

PPT technology in non-propulsion application

As the ion propulsion some works have been done in non-propulsion application during the development of PPT. The following is two typical examples.

1). Developed a new type of triggered vacuum switch

It was noted that the requirement of ignition system in the triggered vacuum switch (TVS) is similar to the ignition system of PPT. Both of them are required to be capable of operating in vacuum environment, triggering at low voltage and low energy, and more than million of firings lifetime. It implies that the ignition system developed in PPT would be suitable for TVS application.

Based on this viewpoint, the semiconductor spark plug and its igniting technique developed in PPT had been used to develop a new type of TVS since 80's.[11] Fig. 6 is a picture of these TVS. There are 10, 20, 30 kv, in hold-off voltage and 60, 80, 100, 150 mm in switch tube diameter.

These TVS have been applied to a lot of pulsed power devices, such as over-voltage protection device, high current pulsed discharge device, and so on.

2). Pulsed plasma source (PPS)

In order to provide a plasma source for the space environment research, a 20 j PPS with four nozzles had been developed. Fig 7 is its picture. This PPS will not produce the interference of force and torque for the spacecraft, because the arrangement of nozzles is in the same plan and perpendicular each other.

4. Arcjet thruster

After Chinese geo-synchronous satellite had been launched successfully, It is hope to develop a kind of electric thruster suitable for NSSK of future Chinese long lifetime synchronous satellite. Because the use of electric propulsion for NSSK and orbit repositioning missions can offer significant advantages, compared to chemical propulsion. However, PPT is difficulty to meet this requirement because its thrust is too low and its total impulse ability is not enough. Based on the analysis of different electric thrusters, the arcjet system was selected.[12] Therefore, a plan developed low power arcjet thruster system had been proposed in 1988.

A project developed a experimental system of low power(1kw class) arcjet thruster was conducted from the 1992 to1994, under the support of the NNSFC.

The main work completed in this project is summarized as follows.[13]

- A laboratory experimental system of 1kw class arcjet thruster had been built. This system contained: radiation cooled thruster body-DHSL-2, ground DC power supply with a variable ballast resistor connected in series with the arcjet and the compound ignition system developed in PPT, a type of pendulum thrust balance and propellant feed system.
- Investigated the start-up characteristics, discharge characteristics in this system.
- Measured the thruster performance for different nozzles with o.6, 0.8, 1.0 constrictor diameter used Nitrogen and Argon as propellant.

Another project continued to conduct arcjet thruster research has started since 1997, under the support of the NNSFC. The objective is to develop a pulse width modulated (PWM) power supply and to investigate the performance of thruster used a mixture of N_2+$2H_2$ as propellant and PWM power supply.

Up to date, the 1kw class PWM power supply has finished and a new thruster body DHSL-3 has fabricated (see Fig.8). The performance test is conducting.

Concluding Remarks

As noted above, over the past 30 years, a lot of works on electric propulsion research and their technical application have been done in CSSAR. Although, the advance is limit for lack of mission and the finance support. These works have established the technological base on the ion thruster, PPT and the arcjet thruster system. They also provided some of candidates for the Chinese satellite on-board control application in next centenary.

Acknowledgments

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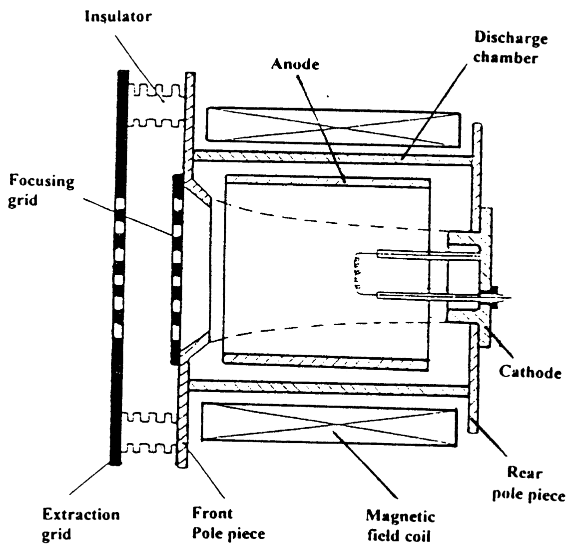

Fig. 1 High energy broad beam ion source

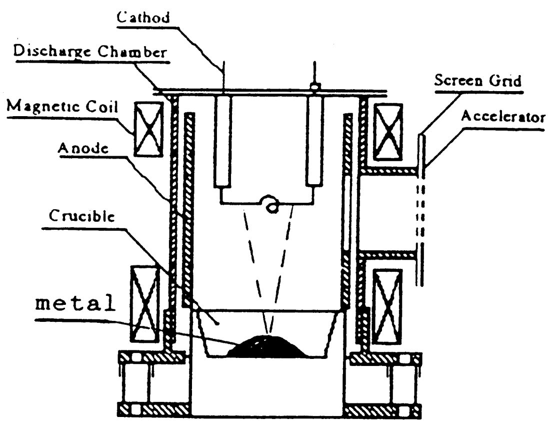

Fig. 2 Schematic diagram of EBE metal ion source

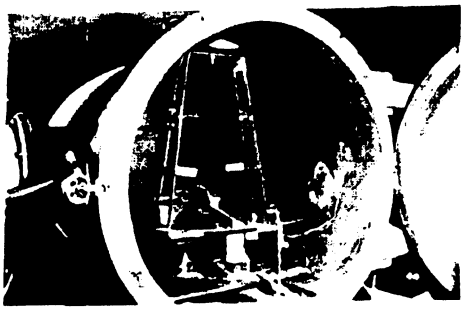

Fig. 3 The second vacuum system and torsion pendulum

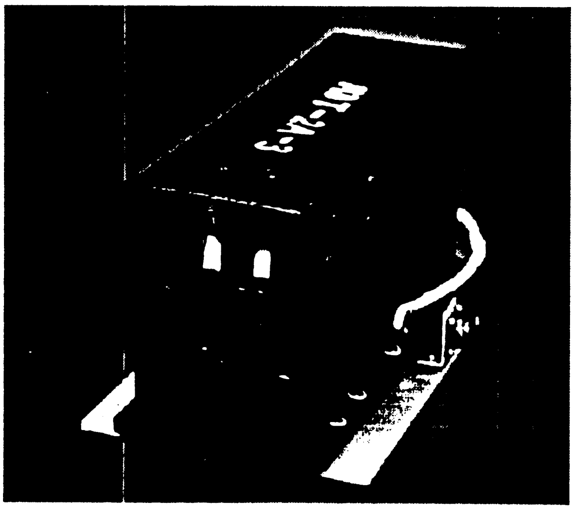

Fig. 4 MDT-2A system

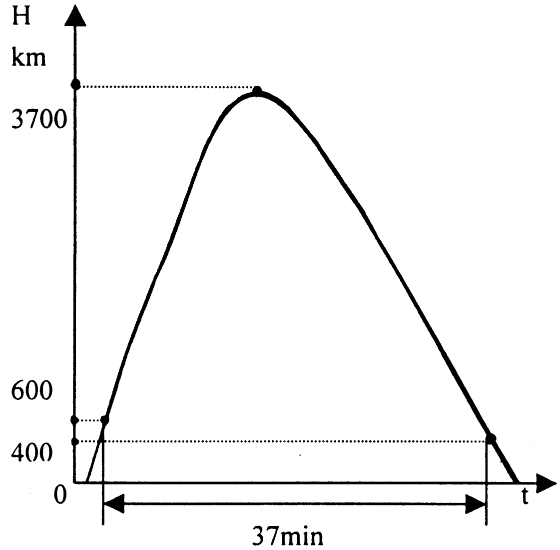

Fig. 5 Ballistic flight test scheme

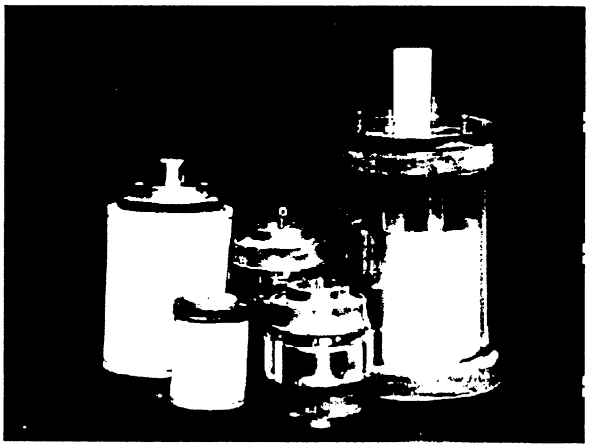

Fig. 6 The picture of the TVS

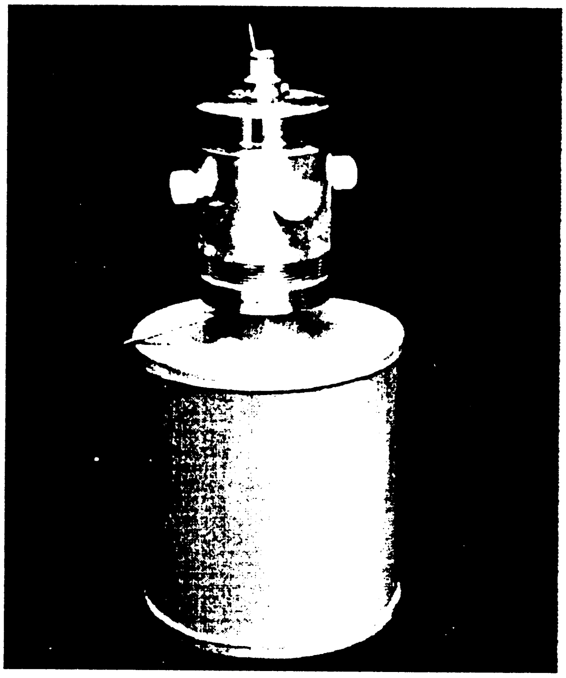

Fig. 7 20 j PPS with four nozzles

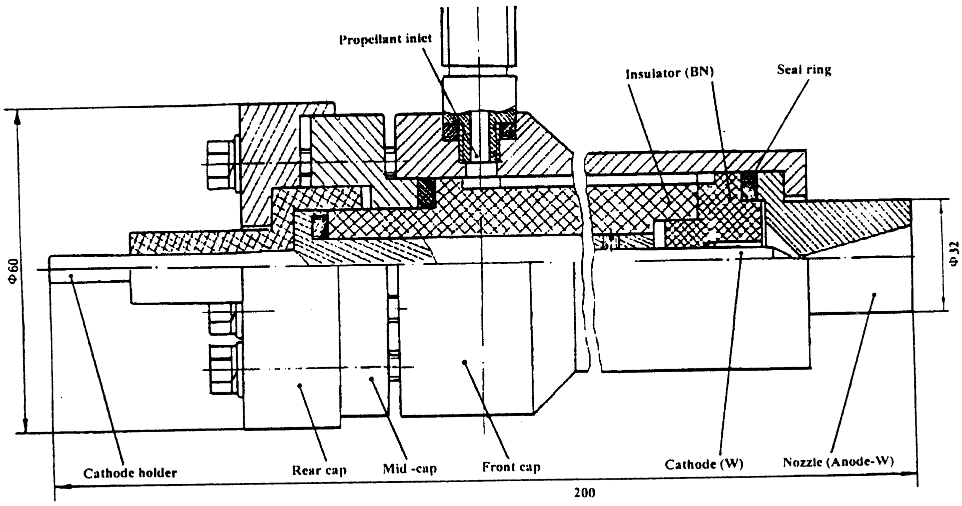

Fig. 8 DHSL-3 arcjet thruster body