Development of 10-mN Class Hall Thruster and Its Performance Optimization through Numerical Analysis

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Abstract

A small hall thruster with a thrust of about 10 mN and a specific impulse of about 1500 s is being developed with an intent to control or maintain the orbits of small satellites. The total mass, consumed electric power and efficiency of the thruster are approximately 10 kg, 300W and 30%, respectively. The thruster system consists of a hall thruster with a cylindrical cross section, a power processing unit and a Xenon (Xe) gas feed system. Laboratory examination of the thruster performance finds that the thruster meets the design specification.

Introduction

The recent trend of small satellite technology strongly suggests that distributed system of small satellites, such as formation flying or constellation, will perform enhanced space missions that would not have been possible with a single small satellite. The electric propulsion is a key element in achieving the advanced missions. The chemical thruster has been widely used for satellite propulsion. This thruster generally is implemented in two types, a mono-propellant system with a simpler mechanical and electric structure and a bi-propellant with a higher specific impulse. The chemical thruster has definite advantages of higher thrust and simpler configuration, but also has a disadvantage of lower specific impulse. This lower specific impulse requires higher propellant mass given the same satellite missions. Therefore the electric propulsion systems are particularly adequate for small satellites that are strongly limited by available mass and volume.

It is expected that a properly selected electric propulsion system will reduce 10-50 kg of propellant mass for orbit correction mission of ΔV= 200~500 m/s[1]. The reduction of the mass would allow larger payload capacity. This paper describes the design, operation and analysis of a hall thruster that is considered most adequate for orbit correction and transfer of small satellites.

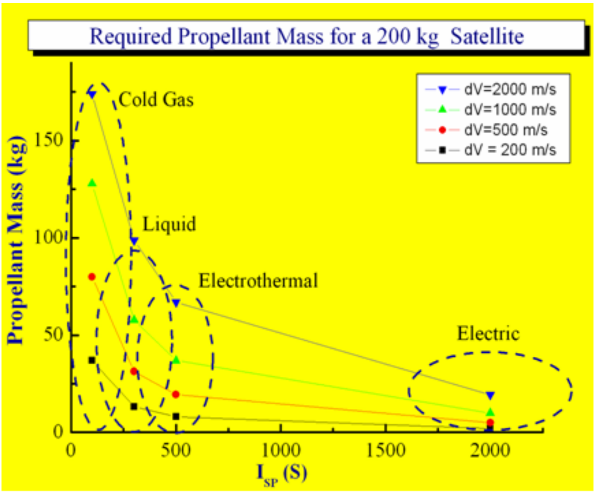

Fig. 1 Propellant Mass for Small Satellites

Thruster Design

The Hall thruster generally consists of three subsystems, thruster head, power processing unit and fuel supply unit. The power processing unit converts electric power from the solar panels of satellites to that required for the acceleration of charged particles in the channel of the thruster head. The fuel supply unit stores, regulates and supplies the fuel to the thruster head. The thruster head finally generates the necessary thrust based upon the supplied electrical power and propellant. They consist of the followings:

- Anode: Supplies the neutral Xenon gas through the annular ring and is biased as positive voltage of about +300V.
- Cathode: Emits thermal electrons through the heater. The emitted electrons in part are accelerated toward the positively biased anode and undertake ionization collision with the

neutral Xenon gas. Hollow cathodes are commonly used.

- Acceleration Channel: A physical space along the propagation direction of Xe^+. It is also a space where ionization of Xe and acceleration of Xe^+ take place. The surface of the channel is usually covered with material that reduces the secondary electron emission.
- Magnets: The directions and intensities of magnetic fields in and near the acceleration channel are critical to the operation of the thruster. The magnet must be designed to increase the trapping time of the electrons.

The physical characteristics of the thruster are shown in Fig. 2 . The electrons emitted from the cathode are accelerated through the channel and move toward the anode biased at a positive voltage. The neutral gas ejected from the anode collides with the electrons and become ionized. The Xe ions are pushed opposite to the anode and can generate the necessary thrust. The acceleration region inside the channel consists of two physically distinct regions: ionization zone and acceleration zone. The ionizations should exist close to the anode, whereas the acceleration should exit near the exit of the acceleration channel for a successful operation of the Hall thruster.

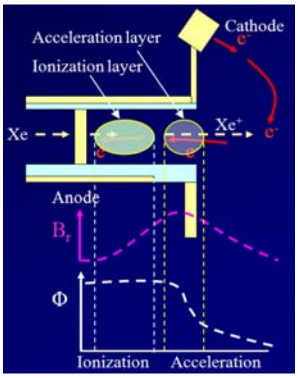

Fig. 2 Physical Characteristics of a Hall Thruster

Because of the constraint in mass and volume from small satellites, the design of the thruster system has been directed toward achieving smaller physical mass and volume. The Hall thruster consists of three electromagnets that enable change of the magnetic field strength and shape by varying electric current ratio for optimizing the magnetic field configuration. The discharge chamber includes a 28 mm diameter, 24 mm long outer channel and a long replaceable 19 mm diameter inner channel[2]. To investigate the thrust performance, a pendulum type thrust stand is used, which utilizes two independent thrust measurement techniques using a gap sensor and the newly-developed mirror-PSD position measurement method. The plasma plume angle was measured by a Faraday probe mounted on a rotational motion stand inside the vacuum chamber. In order to find an optimized operating condition, thrust and discharge current were monitored in 150 - 300 V of anode voltage range in each magnetic field configuration. Minimum discharge current and maximum efficiency were obtained at different voltages. To date, a thrust of 12.4 mN was obtained.

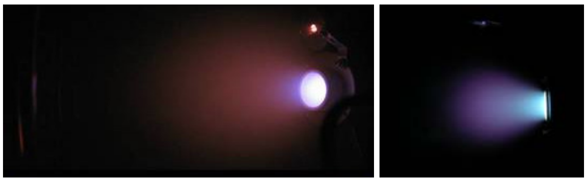

Fig. 3 Operation of the 10-mN class Hall thruster

Laboratory Facilities

The operation of the thruster is made in a laboratory vacuum facility. The size of the chamber is approximately 1.9 m × 1.0 m (Φ) and supports a pumping speed of 5500 *l*/s, which provides the base pressure of about 5×10^{-8} torr.

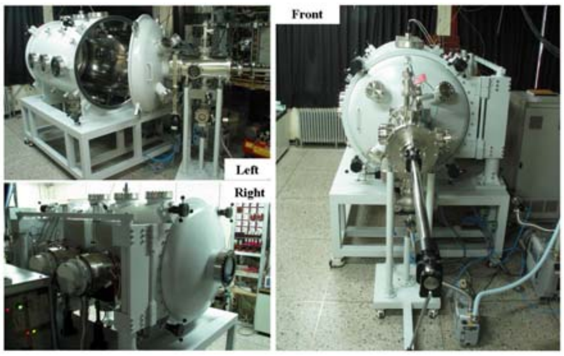

Fig. 4 Photos of the Laboratory Vacuum Facility

The thrust is measured with a gap sensor mounted at the tip of the stand. The sensor measures displacement from the unperturbed position due to the thruster operation. Collected data from the measurement can be compared with the calibration data acquired prior to the operation and can be used to calculate the thrust.

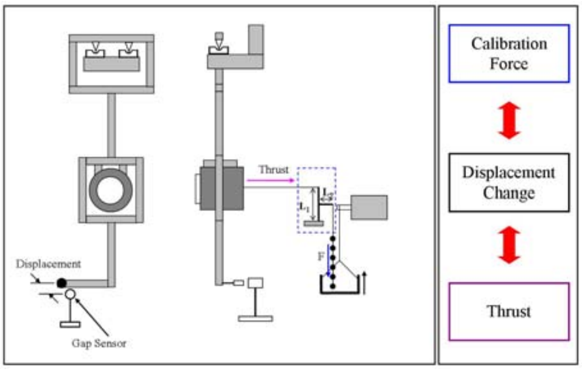

Fig 5. Thrust Measurement System

The facility is also equipped with a diagnostic system such as the Langmuir probe that samples plasma densities and temperatures and a Retarding

Potential Analyzer (RPA) is also implemented for direct measurement of ion velocity distributions.

Measurements

Parametric operation of the thruster has been extensively undertaken in order to find optimal operation conditions. A typical operational parameters are 6.7 mN thrust, 1720 Isp, 34.4 % anode efficiency, 0.66 A discharge current at 250 V anode voltage and 0.4 mg/s Xe flow rate.

Along with the measurement of thruster operations, discharge current fluctuation in the thruster plasmas has also been studied due to its possible influence on the thruster efficiency. The fluctuations in discharge current, floating potential, ion saturation current, and emission intensity were observed by electrical measurements and optical emission spectroscopy, respectively[3]. The fluctuations in discharge potential, ion saturation current, and the plasma emission were all at the same frequency as that of the discharge current, but there was a 90^o phase difference in the emission intensity. Moreover, several frequency harmonics were also observed. Measurements show that the frequency is a sensitive function of operational parameters, which was proportional to the anode bias voltage and neutral gas injection and inversely proportional to the magnetic field strength, *i.e.*, proportional to the E×B drift speed.

Numerical Simulation

In addition to the laboratory experiments, numerical analysis of the hall thruster in and near the accelerating channel is undertaken with a two-dimensional Particle-In-Cell (PIC) simulation with Monte-Carlo Collision (MCC) model[4]. The dynamics of electrons and ions are treated with PIC method at the time scale of electrons in order to precisely investigate the particle transport. The densities of the charged particles are coupled with the Poisson's equation. Xenon neutrals are injected from the hole in the anode, and they experience elastic, excitation, and ionization collisions with electrons and are scattered by ions. These collisions are simulated by using a MCC model which includes the effect of the depletion of neutral gas density. The neutral particles are simulated with a molecular dynamics method at a larger time scale. In order to improve calculation time, the simulation code has been parallelized. The effects of control parameters such as magnetic field profile, gas pressure, electron current density, and the applied voltage have been investigated. As PIC simulation contains the energy distribution of charged particles, it enables to consider the secondary electron emission effect on the dielectric surface.

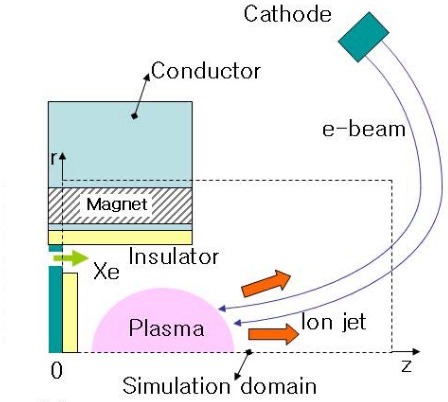

Fig. 6 Numerical simulation of the Hall thruster

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