Development of Xenon feed system for a 300-W Hall-Thruster

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Abstract: A Xenon Feed System (XFS) has been developed as a subsystem of 300W hall-effect thruster for small satellite propulsion system. The XFS delivers low pressure gas to the Anode and Cathode of thruster head unit from a xenon storage tank. Accurate throttling of the propellant mass flow rate is independently required for each channel. The mass flow rate is controlled to each channel using the accumulator tank pressure regulation. This paper discusses the Xenon Feed System design including the component selections, performance estimation and functional test.

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>q̇</td>
<td>mass flow rate</td>
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<tr>
<td>C</td>
<td>orifice discharge coefficient</td>
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<td>A</td>
<td>orifice discharge hole cross-sectional area</td>
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<td>k</td>
<td>specific heat ratio of the gas</td>
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<td>ρ</td>
<td>real gas density at P and T</td>
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<td>P</td>
<td>absolute upstream stagnation pressure</td>
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<tr>
<td>M</td>
<td>the gas molecular mass</td>
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<tr>
<td>R</td>
<td>universal gas constant</td>
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<tr>
<td>T</td>
<td>absolute gas temperature</td>
</tr>
<tr>
<td>Z</td>
<td>the gas compressibility factor at P and T</td>
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I. Introduction

A Hall Effect Propulsion System (HEPS) has been developed to control or maintain the orbits of small satellites.
The system consists of a hall-effect thruster head, a power processing unit and a xenon gas feed system. The consumed
electric power and the efficiency of the thruster are 300 W and 30 % respectively, with aimed thrust range
near 10 mN and specific impulse of about 1500 s. The function of Xenon Feed Subsystem (XFS) is accurate
controlling of the gas xenon propellant supply to thruster head. Owing to the recent development of fluid control
technology, the realization of XFS may be possible with selected small-sized components commercially available
in the market. However, the allowed flow rates from the components are variable in a limited range or occasionally
fixed. On the other hand, the electric propulsion system often requires relatively large variations of flow rates,
especially in a deep space mission for which the electrical power from the spacecraft continuously changes. The
purpose of this paper is to present a discussion on this XFS that is capable of providing accurate and largely variable
flow rates to the electric propulsion system.

II. System Description

The characteristics and performance of a XFS are defined according to the requirements from the thruster. For
the case of anode, the thrust level needs to be changeable by charging amount of injected fuel, whereas, the flow rate
of the cathode is usually smaller than that of the anode. Therefore, the XFS selects a method of independent
throttling of the anode and cathode by controlling the applied pressure across them. The fuel tank pressure is a
traded between system performance and system safety with higher tank pressure in general yielding greater system
performance.

A design point of the system is stable and accurate operation in vacuum condition like a space environment.
Thus, through the Failure Mode and Effect Analysis, the critical hazards of system such a leakage or malfunction of
each component were eliminated.

A. General Specification

There are several requirements on XFS; first, storage of the propellant for a long period of about 5 years, second,
prevention of unexpected internal or external leakage, third, independent control of the flow rate on anode and
cathode. The realization of the requirements is achieved through the selection of isolation valves which is composed
of a pair, and applies the weld method. The mechanical configuration of the control device is arranged in a row with
respect to the anode and cathode for independent throttling of the flow rate.

The Xenon Feed System was designed to satisfy the following requirements:

- Xenon storage tank pressure range: 3 to 150 bar (absolute)
- Accumulator tank pressure range: ~ 3 bar ± 1 %
- Internal leakage: $1 \times 10^6$ sec/s GHe
- External leakage: Non allowable
- Flow rate:
  - Anode: 4 ~ 7 sccm ± 1 %
  - Cathode: 0 ~ 2 sccm ± 1 %
- Flow response time: < 1 sec
- System dry mass: < 5 kg
- Fuel mass: ~ 3 kg
- System volume: 450 mm × 380 mm × 220 mm
- Independency of the anode and cathode

B. System Configuration

The system consists of fuel tanks, isolation valves along with micron-sized orifices, and pressure transducers.
The mass flow rate of the system can be controlled by the pressure control using Xenon gas fuel. The pressure of the
accumulator can be controlled by the mass flow control using the high pressure orifice, and the mass flow rate is
determined by the accumulator tank pressure and the low pressure orifice. For the increase of the pressure accuracy
of the accumulator tank, the three pressure sensors and their mean value are used. The high pressure isolation valves
are controlled in order to maintain the constant pressure of the accumulator tank with a certain range. The pressure
of the accumulator tank and the orifice size for the low pressure part determine the mass flow rate. Therefore, the
mass flow rate can be controlled by adjusting the accumulator tank pressure and the orifice size.
The system is composed of two channels for independent control of Anode and Cathode such as Fig. 1. If one channel between the high pressure tank and the accumulator tank is fails, another channel can be used for the redundancy by the connected valve between the accumulator tanks. The system can be divided into the high pressure part and the low pressure part. The high pressure part can define as a main fuel tank part which is about 120 bar pressure; the low pressure part is defined as accumulator tank part operated with about 2 bar pressure. The increasing speed of the accumulator tank pressure is determined by the supplied flow rate from the high pressure part. The components of anode and cathode are composed of same, except the orifice size difference to control the flow rate. The interrelation of the accumulator tank pressure according to orifice size and accumulator tank volume is verified through the performance test of the test model.

C. Flow control

The mass flow rate for supply to anode and cathode is determined depending on the accumulator tank pressure and the orifice size located at downstream of the accumulator tank. Two orifice discs are mechanically mounted with fixture at the entrance side of the anode and cathode each. These orifices determined the required flow rate change, to anode and cathode. The low pressure solenoid valve located between the accumulator tank and the orifice performs on-off control of fuel supply to thruster head unit. Hence, XFS can operate independently anode and cathode throttling the mass flow rate through the pressure control of accumulator tank.

Similarly, the high pressure solenoid valves and orifices are used for the control of accumulator tank pressure. Through the sized orifice, supply the high pressure fuel to accumulator tank continuously, thus XFS is able to control the high pressure solenoid valve through the comparing setting up pressure and pressure sensors signal at the accumulator tank. The valve control module shall control the XFS to sustain of accumulator tank pressure within the setting up pressure tolerance constantly. The mean values of three pressure sensors are used for increase of the accuracy, in some case role of the redundancy.

D. Component selection

The component selection was significant impact to determine of system performance such as environmental or functional stability. All components of this system are allowed to space environment and some of important components have flight heritage. The characteristics and functions of each component are described as below.

**Isolation Valve**

The inline type solenoid valve is used for on-off control of fuel supply. The valve is normally closed state when it is unpowered and is opened when it is powered of electric source. In order to prevent the internal leakage required by the specification of the isolation valve, the valve consists of a series of two identical solenoid valves. The valve needs voltage down of electric source after pull-in which is sustaining the open state for reducing the caloric value, because the valve generates huge heat when it is operating long time continuously.

**Flow Restriction Orifice**

The micron orifice with solenoid valve is used for accumulator tank pressure control, which controls the valve open time depends on determined flow rate by upstream pressure with orifice size. The orifice is made by precision laser drilling hole such as a thin disc, and fixed by housing. There are four orifices used at high pressure part and low pressure part placed at the anode and cathode each other, which executes choked flow.

**Pressure Transducer**

Pressure transducers perform monitoring of the xenon storage tank and accumulator tank. The pressure transducer placed at xenon storage tank is able to calculate the residual fuel mass and monitor the system condition which is measuring of pressure 0 to 150 bar. The low pressure transducers measure the accumulator tank pressure.
Xenon Storage Tank
In order to store the high pressure xenon fuel in a gas state, the composite tank was selected. The tank was made by carbon fiber winding on an aluminum liner which had advantages of low mass and was stable for high pressure. The temperature controller settled on xenon storage tank to sustain supercritical condition for storage the gas state xenon. Hence it has no liquid sloshing effects. The tank volume and operating pressure are 2 liter and 120 bar.

Accumulator Tank
The accumulator tank required appropriate design especially volume, because the valve control time is affected by tank volume. For this project the selected volume is 240 cm$^3$; operating pressure range is 2 bar to 50 bar. The design takes aim at compact, because the tank occupies much space of system.

Fill and Vent Valve
The function of the Fill and Vent Valve is to provide an interface port which will allow accessing to the XFS and equipment of propellant pressurization, propellant filling and venting while providing a sealing capability between the system and outside environment at low and high pressure. This valve also shall act as test ports and shall allow the system to be serviced with the leak detection agents necessary for system test. It provides the secondary metal-to-metal seal by seating against the valve body and it engages with locks the screw mechanism.

III. Design and analysis

A. System Design
The characteristics of a system are highly dependent on the regime in which that system is operated. That is; design choices, such as tank pressure, and environmental factors can have a significant impact on the operational characteristics of the propulsion system.

The xenon feed system arrangement has been compacted to minimize the volume that the propulsion system requires based on configuration. The design space was conservatively limited by pressure tanks. Thus the system is modulated including xenon storage tank and accumulator tanks; the total volume is 450 mm × 380 mm × 220 mm. The xenon storage tank placed at middle of module for system stability, and divided into anode and cathode division. The components are consisted of sub-module those are classified by function in order to minimize the volume and also convenience of integration; the arranged components are fixed by bracket. Each component is integrated with 1/8 inch or 1/4 inch stainless steel tube by using orbital weld tool, because the system required minimum space for integration.

The system can classify into the charging part, pressure control part, and flow control part. The charging part placed under the first base plate for reducing the volume, and the flow control part is constructed with connection to the thruster head unit under the secondary base plate directly. All components are integrated on the base plate which is aluminum honeycomb plate for reducing mass. The fill and vent valve located at bottom of secondary plate to connect through the bottom-deck of satellite in case of fuel charging. Also, secondary plate is used for radiating of the heat generated from thruster head unit. The Fig. 2 shows accomplished arrangement and Fig. 3 shows thruster head which is installed under secondary plate.
B. Theoretical Analysis

Prior to the design, the theoretical analysis is performed for estimate of the XFS performance. Performance of the system is variable significantly according as accumulator tank volume and orifice size. The operating time of the solenoid valve is determined by accumulator tank volume, and the pressure accuracy depends on orifice size. Accumulator tank pressure was changed according to fuel consumption as thruster operating, and then duration of valve open time is decided by fuel supply for sustaining accumulator tank pressure within the tolerance. Especially, the accumulator tank volume and orifice size are requiring sufficient estimation and verification in system design, because these are not able to change after design is fixed. Also, the mass flow rate is able to control through only pressure after physical sizes of these components are determined, because the correct estimation of pressure is important.

In this project, a flow rate variation according as upstream pressure and orifice size are estimated by choked orifice flow equation as Eq. (1), and verified through the orifice calibration test. Through this result as Fig. 4, the accumulator tank pressure and low pressure part orifice size are selected for anode and cathode flow rate.

\[ \dot{m} = C_A P \sqrt{\frac{k M}{RT}} \left( \frac{2}{k+1} \right)^{\frac{k+1}{k-1}} \]

For increase the accuracy of mass flow rate, the accumulator tank pressure increased as decreased orifice size. In this way orifices size are selected to 15 micron and 9 micron for anode and cathode. The manufactured orifice discharge coefficient has calculated by calibration; verification of surface condition and measurement of hole cross sectional area are accomplished by SEM analysis.

Figure 4. Theoretical value of mass flow rate as applied upstream pressure and orifice size.

The orifice size of high pressure part need determined to control of selected accumulator tank pressure. Because the xenon storage tank pressure was decreased as fuel consumption, the supplied mass flow rate to accumulator tank is reduced. Therefore, operating time of pressure control valve is longer, and causes increase of a load like power or heat. It is necessary to estimate pressure control valve operating time by considering compressibility factor variation according to pressure variation. Especially, the xenon gas has a great compressibility, because it should be considered. Like this, accumulator tank pressure was changed by supplied mass flow rate through the high pressure part orifice; the variation rate of pressure is changed according as accumulator tank volume. We can select the moderate volume of 240 cm$^3$ for this system by repeatable trial. Also, we calculate the pressure variation rate of accumulator tank according to valve open time for estimate of pressure control valve operating time at specific upstream pressure. On the assumption that orifice coefficient and upstream pressure are 0.97 and 120 bar each, accumulator tank pressure was setup with 3 bar ±1 %. As a result of calculation such as Fig.5, in case of 9 micron orifice the valve open time is calculated as 15 s from decided fuel supply reach to within tolerance of +1 %.

In this way, we can estimate the valve control time according as xenon storage tank pressure and orifice size.

Figure 5. Theoretical value of accumulator tank pressure according as operating time of isolation valve.
C. Experiment

For verifying of accumulator tank pressure variation according as accumulator tank volume and orifice size, such an experiment was performed. The test model is composed as Fig. 6; the supply pressure can be adjusted by pressure regulator, the orifice size can be change by fixture, and fuel on off control can achieved by isolation valve. The sizes of orifices are 5.7 micron, 7.3 micron, 16.4 micron and accumulator tank volume is 830 cm$^3$ for this test model.

Supply pressure is sustained at 86.4 bar through the pressure regulator, and orifice size changed to verifying dependence of pressure variation rate on size effect. The test is performed as measuring of accumulator tank pressure rising time by isolation valve operating, on this condition initial pressure of accumulator tank was selected as 1.04 bar.

As a result of this test, we could measure pressure rising time according as orifice size and supplied pressure of main storage tank. Because pressure rising time was reduced as decrease of orifice size, the valve opening time is increased. But, the accuracy of pressure shall be lower caused by orifice size increased too much, because valve control time was become shorter. For this reason, the selection of moderate orifice size is important. Also, because pressure rising time was changed by accumulator tank volume, the moderate numerical value of volume should be selected according to system specification.

Through the Fig. 7, we can find out that accumulator tank pressure is still rising when isolation valve was closed. It is caused by volume of between isolation valve and orifice, which is still having pressure deference at upstream and downstream of orifice, because fuel was supplied continuously. Through the result, we can confirm design requiring minimize of distance and volume of between isolation valve with orifice. And also, accumulator tank volume and orifice size are finalized based on this result.

IV. Conclusion

Through this project, we could confirm a possibility of technology to usable in space, according as design and performance estimation of the XFS under low cost. The interrelations of the components specifications are estimated through the feasibility study and functional test of the test model; the system design was completed through these results. Based on the design, the manufacturing of the XFS is in progress; and then the system performance will be verified by the functional and environmental tests.

References