# Examination of heat exchanger for new type thruster for small satellite

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In recent years, launch missions with small satellites in various applications have been studied because of the viewpoint of cost. Since small satellites are required more constellation mission than single missions, compact, inexpensive and safe propulsion device (thruster) is required. Conventional thruster systems have disadvantages such as large and expensive tanks for high pressure gas, high-pressure gas filling work, etc. It cannot be said that this is suitable for constellation missions by small satellites. Therefore, at the Institute of Space and Astronautical Science (JAXA / ISAS), we are developing a new type thruster device which improves the drawbacks of the conventional thruster device. In this experiment, we determined indexes of the performance evaluation of new type thruster by conducting the heat exchanger function test.

# 小型衛星用新型スラスタ装置の熱交換器機能確認試験

近年，コスト面から様々な用途での小型衛星による打ち上げミッションが検討されている．小型衛星は単独ミッションよりコンステレーション・ミッションの要求が多いため，小型で安価，安全な推進装置（スラスタ装置）の実現が要求されている．従来のスラスタ装置は，高圧ガス用の大型で高価なタンク，高リスクの高圧ガス充てん作業などの欠点があり，小型衛星のコンステレーション・ミッションに向いているとは言えない．そこで，宇宙航空研究開発機構（JAXA）では従来のスラスタ装置の欠点を改良した新型スラスタ装置を開発中であり，本実験ではこの新型スラスタ装置の熱交換器根機能試験を行うことで新型スラスタ装置の性能評価の指標を決定する．

**Key Words:** Thruster, Heat Exchanger, Small Satellite

## Nomenclature

| | | |
|---|---|---|
| $V_{cg}$ | : | Volume of gas tank, m$^3$ |
| $A_g$ | : | Cross-sectional area of gas side charger, m$^2$ |
| $V_{cl}$ | : | Volume of liquid tank, m$^3$ |
| $A_l$ | : | Cross-sectional area of liquid side charger, m$^2$ |
| $L$ | : | Length of piston of charger, m |
| $\gamma$ | : | Pressure ratio |
| $\eta_t$ | : | Heat exchanging efficiency |
| $Re$ | : | Reynold's number |
| $m$ | : | mass flow rate, g/s |
| $D_H$ | : | hydraulic diameter, m |
| $\mu$ | : | viscosity coefficient, Pa·s |
| $A$ | : | Cross-sectional area of heat exchanger, m$^2$ |

## 1. Introduction

In recent years, while space development is actively being carried out, launch missions with small satellites in various applications are being studied because of the viewpoint of cost. Because of its size and ease of handling, this small satellite requires more constellation mission than a single mission. For this background, a compact, inexpensive and safe propulsion device (thruster) for small satellites is required.

However, as shown in Table 1, conventional thruster systems for small satellites each have disadvantages and cannot be said to be suitable for constellation missions by small satellites. Therefore, at the Japan Aerospace Exploration Agency (JAXA), we are developing a new type thruster system that improves the drawbacks of conventional thruster systems[(1)]. The new thruster device is equipped with a heater for changing state of the injector, and to continuously drive the system, a certain heat exchange performance or more is required. In addition, HFC (R116, R600a) which can store liquid at room temperature is assumed for the injector, and there are many points that are not clear such as heat exchange performance.

Therefore, in this experiment, in order to clarify the thermal characteristics of the injecting object by conducting the heat exchanger function test of the new type thruster which is currently being developed and to use the obtained result as a guide for the new type thruster design.

Table 1 Disadvantages of conventional thrusters.

| Type | Disadvantage |
|---|---|
| Cold gas jet thruster | High pressure, large capacity tank |
| Liquid monopropellant thruster | High toxicity of propellant, bad operability |
| Electrically powered thruster | High electric power required |
| Gas-liquid equilibrium thruster | Instability of changing gas-liquid state |

## 2. Summary of new type thruster

### 2.1 Type 1 : Supercritical gasification thruster

In this chapter, we explain the new type thruster device currently being developed at JAXA. Two methods are being studied for this new type thruster, and these two are explained respectively.

In this section, type 1 is explained. This type is called supercritical gasification thruster. In this type, a liquid ejecting object (non-toxic propellant HFC, $N_2O$, $CO_2$ etc. which can be stored in liquid at room temperature) is pressurized and heated by a charger and a heater and transited to a supercritical state, then it is adiabatically expanded by an orifice, gasified and throwed from thrusters. Outline figure of the system is shown in fig. 1. In the part from ① to ② in Fig. 1, the liquid ejecting object is pressurized and heated by the charger and the heater, and it transits to the supercritical state. The supercritical ejecting object is isentropically expanded (adiabatically expanded) at the orifice and gasified. The part of this is injected from the thruster and the remaining gas is used to pressurize the liquid by flowing it into the charger integrated with the liquid tank. In this type, when changing a liquid into a gas, it goes through supercriticality. In simple heat exchange from a liquid to a gas, boiling occurs by straddling the vapor pressure line as shown in fig. 2, and the heat exchange efficiency decreases, so it passes through the supercritical state to prevent boiling and to maintain high heat exchange efficiency.

In the conventional method, a large capacity and expensive tank for storing high pressure (about 30 MPa) gas is necessary, and so it is not suitable for a small satellite. Also, since it uses highly toxic fuels, it is not easy to handle, and it hinders the expansion of space projects using small satellites. However, since this system uses gas of about 4 MPa (assuming R116), high pressure gas filling work and expensive high-pressure tank are unnecessary. Also, it is easy to handle because it can use non-toxic propellant. Therefore, it can be improving the drawback of the conventional method. In this way, there are advantages of the new type thruster system that the same function as the conventional one can be achieved at low cost and the system can be miniaturized.

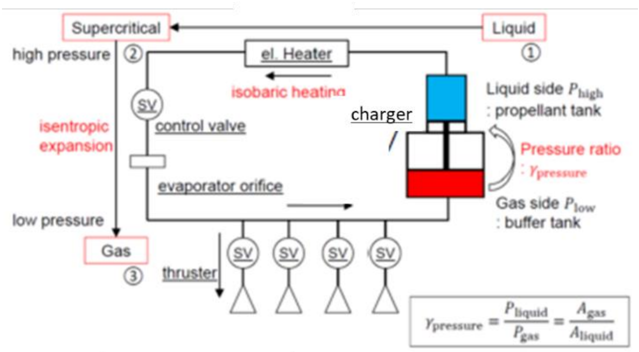



Fig. 1 System of supercritical gasification thruster.

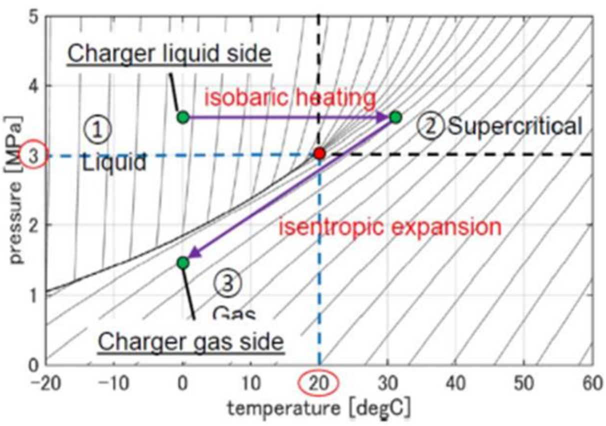



Fig. 2 P-T diagram of supercritical gasification thruster.

### 2.2 The pressure ratio of charger

The charger used in the supercritical gasification thruster method is a piston with an area ratio. This is to increase the pressure of one side object by putting liquid or gas into each of the two rooms with different cross-sectional areas. The charger on which the new type thruster device is mounted utilizes a part of the gas injecting object for boosting the pressure of the liquid. An outline figure of the charger is shown in Fig. 3 (a). The pressure ratio of this charger can be determined by balancing the forces of the liquid and the gas injecting object. The volume of tank of gas injecting object $V_{cg}$ is expressed as below,

$$V_{cg} = A_g L. \tag{1}$$

The volume of tank of liquid injecting object $V_{cl}$ is expressed as below,

$$V_{cl} = A_l L. \tag{2}$$

From Eq.(1) and (2), the relation between $V_{cg}$ and $V_{cl}$ is expressed as below,

$$V_{cg} = \gamma V_{cl}, \tag{3}$$

$$\gamma = A_g / A_l. \tag{4}$$

$\gamma$ is pressure ratio of charger.

### 2.3 Type 2: Bladder type R600a thruster

A bladder type R600a thruster system is being studied as a second type of a new type thruster. In this type, the injector (R 600a) tank is pressurized with a gas with a higher vapor pressure than the injector stored in the bladder, and the injector is stored in liquid form. Heating the injecting object taken out from the tank as liquid, gasifying it, and injecting it in the gas tank. In this way, each new type thruster system is system in

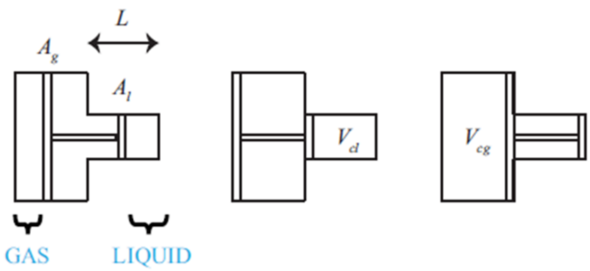



Fig. 3 Figure of charger.

which HFC or the like is stored as a liquid and is heated by a heater. IKAROS[2], a solar sail demonstrator launched by ISAS in 2010, was equipped with a gas-liquid equilibrium thruster[3]. Since this thruster stores the injector in the tank in a gas-liquid equilibrium state, gas-liquid separation cannot be perfectly performed, and liquid is injected together with the gas, which adversely affects continuous use and thrust. However, since this method can completely separate gas and liquid by storing it with gas, it is also a great advantage that liquid is not injected. However, in order to completely gasify the liquid injecting object, sufficient heat exchange performance is required.

## 3. Experiment

### 3.1 Summary of experiment

To confirm the performance of the heat exchanger of the new type thruster, in this experiment, experiment is carried out with the device as shown in fig. 4. The fluid flowing in from the gas tank section is heated by the heater section and passed through the orifice to dry gas. Heat exchange efficiency of each fluid is calculated by measuring temperatures before and after the heater section. The heater is controlled to have a constant temperature. Moreover, after the orifice, it is connected to the vacuum chamber, and making it a vacuum makes flow a choke. This makes it possible to carry out the experiment at a constant mass flow rate. The experiment parameters are the type and state of the fluid, the pipe inner diameter of the heater section, Reynold's number, mass flow rate. States of the fluid are shown as table 2. Note that the gas-liquid equilibrium in this experiment indicates the condition that the liquid at the inlet of the heat exchanger and the gas at the outlet. Consideration is made in each condition shown in Table 2.

The test method is shown below. First, the nichrome heater of the heater section is set to a certain temperature. Next, let the fluid flow from the gas tank. Adjust the state of the fluid at the inlet of the heater section with dry ice or the like so that the condition of the fluid becomes the test condition and measure the temperature of the fluid before and after the heater section.

Table 2 The condition of state of fluids

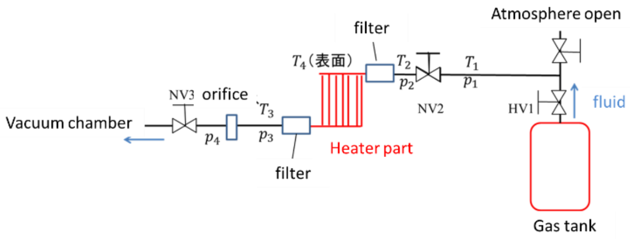
| Case | Fluid | State |
|---|---|---|
| Case 1 | R116 | Supercritical |
| Case 2 | | Gas-liquid equilibrium |
| Case 3 | R600a | Gas-liquid equilibrium |

### 3.2 Definition of heat exchanging efficiency

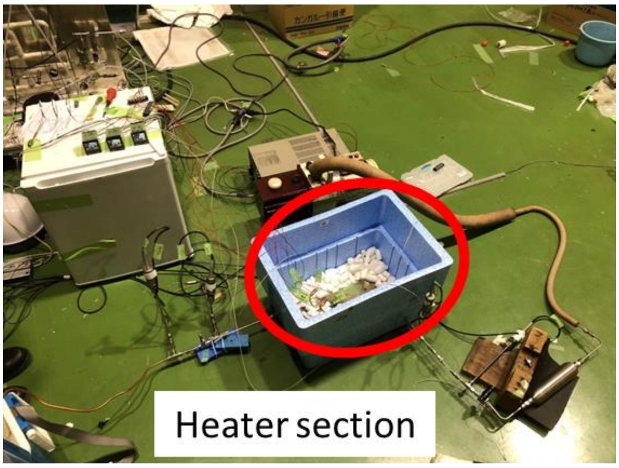
The definition of the heat exchange efficiency $\eta_t$ used in this experiment is shown below. The heat exchange efficiency is expressed as follows from the set temperature of the heater $T_h$, the temperature of the fluid at the inlet of the heater section $T_i$, and the fluid temperature of the outlet $T_o$.

$$\eta_t = (T_o - T_i) / (T_h - T_i) \times 100 \text{ [\%]} \qquad (5)$$

From this equation, $\eta_t$ becomes 0% if the temperature of the fluid does not rise before and after the heater section, and $\eta_t$ becomes 100% if the heater section outlet temperature $T_o$ becomes equal to the set temperature of the heater $T_h$.




(a) System diagram of test equipment.




(b) General view of test equipment.

Fig. 4 Test equipment.

### 3.3 The result of experiment

**3.3.1 Case 1** R116, supercritical experiment results are shown in Table 3. As can be seen from the table, when the pipe diameter is small, the mass flow rate decreases, and the efficiency decreases. The Reynolds number is expressed by the following equation.

$$Re = mD_H / \mu A \qquad (5)$$

From Eq. (5), as the mass flow rate decreases, the Reynolds number decreases, resulting in an increase in efficiency. Increasing the Reynolds number indicates that the flow is turbulent, so as the flow becomes turbulent, the flow peels off near the wall of the pipe and heat transfer tends to occur near the wall There. From this, it is shown that the efficiency increases as the Reynolds number increases, even in supercritical as with heat exchange in general fluids.

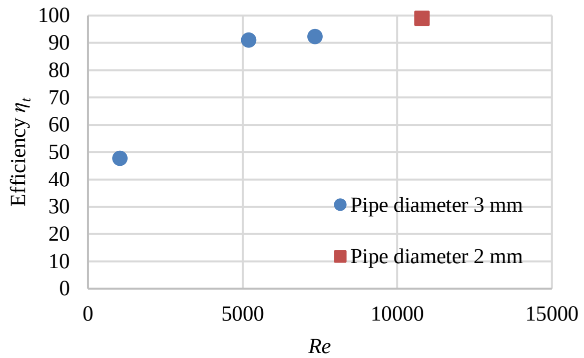
Table 3 The result of case 1.

| Pipe diameter [mm] | *Re* | Mass flow rate [mg/s] | Efficiency [%] |
|---|---|---|---|
| 3 | 11561 | 536.62 | 64.02 |
| 2 | 5581 | 267.77 | 92.42 |

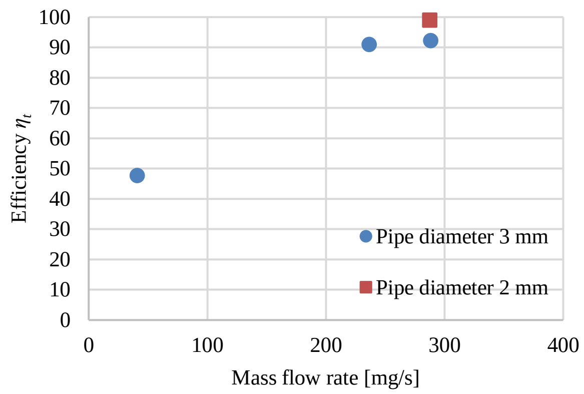
**3.3.2 Case 2** The experiment result of gas-liquid equilibrium, R116 is shown in fig. 5. As can be seen from Fig.

5 (a), as *Re* increases for both pipe diameters 3 mm and 2 mm, the efficiency also increases. This result is like case 1. In addition, in Fig. 5 (b), it can be confirmed that efficiency increases as the mass flow rate increases. This is because *Re* increases as the mass flow rate increases, as shown in Eq. (5). However, near the mass flow rate of 300 mg / s, although the mass flow rate is almost the same, the efficiency difference due to the tube diameter size. This can be explained by Eq. (5). The hydraulic diameter $D_H$ in Eq. (5) is expressed by the pipe diameter × Pi. Also, the cross-sectional area of the pipe is expressed by the square of the pipe diameter × Pi. From these, it can be said that the *Re* increases and the efficiency gets larger by decreasing pipe diameter.

**3.3.3 Case 3** The experimental results at R600a, gas-liquid equilibrium are shown in fig. 6. From fig. 6, the efficiency is increased by increasing *Re* and the mass flow rate. However, when *Re* is between 2000 and 3000, the efficiency maintains a certain range. When *Re* is from 2000 to 3000, the flow is a transition region, which is a region not coinciding with the characteristics of laminar flow and turbulence. In this region, it cannot be said that the flow easily peels off by raising *Re*, so it is considered that there is no correlation between *Re* and efficiency.

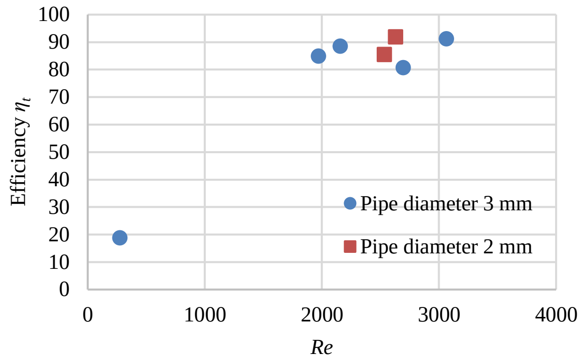



(a) *Re* - efficiency $\eta_t$ graph.

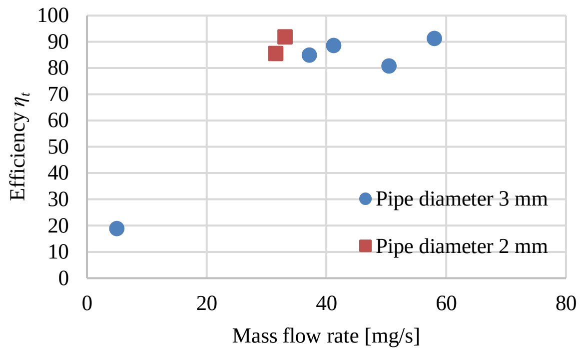



(b) Mass flow rate – efficiency $\eta_t$ graph.

Fig. 5 The result of case 2.




(a) *Re* - efficiency $\eta_t$ graph




(b) Mass flow rate – efficiency $\eta_t$ graph.

Fig. 6 The result of case 3.

### 3.4 Application to design of heat exchanger

Consider application of knowledge obtained through experiments to heat exchanger design. Low thrust and low power are required for thruster for small satellites. In addition, the orifice diameter currently considered is about 0.2, and the flow rate is small. In order to raise the efficiency while the flow rate is limited, it is necessary to reduce the pipe diameter. However, if the pipe diameter is made too small, there is also a disadvantage that increasing pressure loss and efficiency decreases. Therefore, it is considered that the pipe diameter should be appropriate according to the required thrust.

Also, if it is assumed that the mass flow rate can be adjusted, by increasing the mass flow rate too much, the energy required for phase transition and pressure loss increases. Since the amount of heat given by the heater is fixed, there is a possibility that the phase transition cannot be perfectly complete, so it is necessary to pay attention to the control of the mass flow rate.

## 4. Conclusion

In this paper, we conducted the performance confirmation test of the heat exchanger of the new type thruster for small satellite. The new type thruster currently under development needs to be phase-changed by a heat exchanger, since it injects the liquid injection body with gas. However, the non-toxic propellant HFC, which is to be used for the injector, has no clear heat exchange characteristics. Therefore, a heat exchange characteristic confirmation test using a heater was carried out. In R116 and R600a, the heat exchange efficiency also increases as *Re* increases in both supercritical and gas-liquid equilibrium. This is because flow becomes more likely to separate near the tube wall by becoming turbulent. Efficiency also increases by decreasing the tube diameter. From the above, if the heat exchanger has a small pipe diameter and a high mass flow rate, the heat exchange efficiency increases. However, setting the value extremely increases the necessary energy, and conversely the efficiency decreases.

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