Thrust Measurements of DC Arcjet Thruster

Koichi Suzuki [1]

Recently a thrust measurement system of DC arcjet thruster was introduced to the Aeronautical Engineering Department of Daiichi Institute of Technology. Thrust of DC arcjet is usually very small, 10 to 100mN, so it is very difficult to measure its thrust exactly. We adopted a pendulum and strain gage combination for thrust measurements. This paper presents details of thrust measuring method of DC arcjet thruster and some experiment results.

1. DC arcjet

DC arcjet thruster consists of DC (Direct Current) anode, cathode and nozzle. DC arcjet gas is supplied between anode and cathode and heated by electric arc. Temperature of arcjet gas become very high, over 6,000K , and accelerated through nozzle. This accelerated gas is delivered of thrust. The thrust is, however, very small because of its poor power supply. Electrical power applied to an arcjet thruster is usually 1 to 10kW, so thrust revel is 20 to 200mN.

The thrust of arcjet thruster is very small, but arcjet thruster performance as rocket engine is very attractive. Specific impulse, usually adopted as rocket engine performance, is almost 500 seconds when we use hydrazine decomposed gas, and 1,000 seconds in the case of hydrogen gas, compared with 400 seconds of liquid oxygen/ liquid hydrogen rocket.

Arcjet thruster had been less attractive by the end of the 1960s because many spacecrafts could not supply sufficient electric power to the thruster. In the 1980s, some satellites, communication or broadcasting satellites, became large and had power to spare, then advantage and feasibility of arcjet thruster were taken notice of satellites designers. In the USA, practical arcjet thrusters have been used for commercial communication satellites from 1993. Recently MR-510 arcjet systems made by Primax Aerospace Co. (PAC) are continually used for Lockheed Martin Corporation's A2100 communication satellites[1].

In Japan, Ishikawajima-Harima Heavy Industries Co. (IHI), and National Space Development Agency (NASDA) were making progress in development of 1 kW hydrazine arcjet[2]. They had conducted 100 hours life test successfully, but this 1 kW arcjet thruster needs to be executed more endurance test and has to demonstrate flight quality. So in Japan, arcjet thruster technology is in early stage. We are requested more effort at laboratory level and industry level.

2. DC arcjet thruster

Figure 1 shows a 1kW arcjet thruster used for acceptance tests of the thrust measuring system. The thruster has a cathode, a

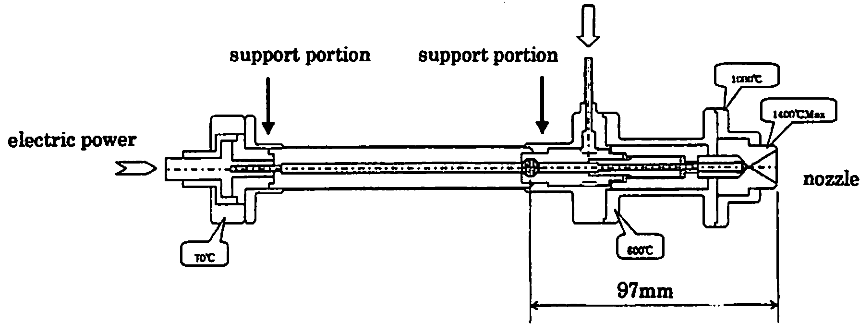

Fig.1 Arcjet thruster

[1] Professor, Dept. of Aeronautical Engineering, Daiichi Institute of Technology

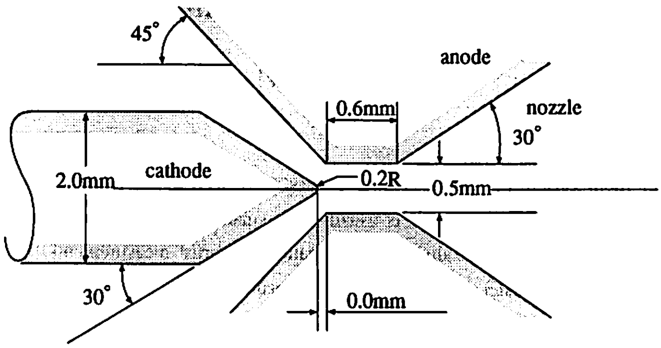

Fig.2 Electrode configuration

nozzle-shaped anode and a long body between nozzle and electrical connector. This long body is needed for thermal protection of the electrical connector. Estimated body temperatures are described in the figure. Figure 2 shows the electrode configuration used in the thruster. The cathode was made of 2% thoriated tungsten with 2.0 mm in diameter and with a tip half-cone angle of 30 degrees. The anode consists of a nozzle made of tungsten. The convergent and divergent portions of the nozzle are conical with half angle of 45 degrees and 30 degrees, respectively. The constrictor has a 0.5 mm diameter and is 0.6 mm long. The spacing between the cathode and anode (electrode gap) was set at 0.0 mm.

3. Thrust measurements

Arcjet thrusters have a low thrust to weight ratio (T/m) comparing with other rocket engines as shown in Table 1. This greatly complicates the process of obtaining accurate thrust measurements. Thrust measurement difficulties such as mechanical vibration from facility, tilting of a thrust stand and thermal drift affect on accuracy of measurements. These are all resulting from low T/m.

Table 1 Thrust to weight ratio(T/m)

Engine	Typical thrust	Typical weight	Thrust/weight
SSME	450,000lb	10,000lb	45.0
Small H_2/O_2	25lb	10lb	2.5
Resistojet	0.25lb	10lb	0.025
1kW arcjet	0.025lb	3.5lb	0.007

SSME: Space Shuttle Main Engine

We adopted a pendulum-type thrust measurement stand shown in Figure 3 to avoid these difficulties mentioned above. The arcjet thruster was attached horizontally to the stand which has two arms (one vertical and one horizontal), one bearing support and balance weights. The thruster was free in the direction of thrust axis, being hung from the vertical arm. Thrust was magnified by three times with two arms, and determined by measuring force generated from a deflection of arms with a load cell and comparing this with a calibration curve. The calibration was conducted by applying known weight, measured by a chemical balance, in the thrust direction. The thrust measurement stand and a vertical arm were water cooled and a thrust measurement load cell was heat shielded to minimize thermal drift from heat conduction and radiation from the arcjet thruster. General view of the thrust measurement stand is shown in Figure 4.

To confirm reliability of the present thrust measurements, the measured thrust datum of the arcjet thruster have been compared

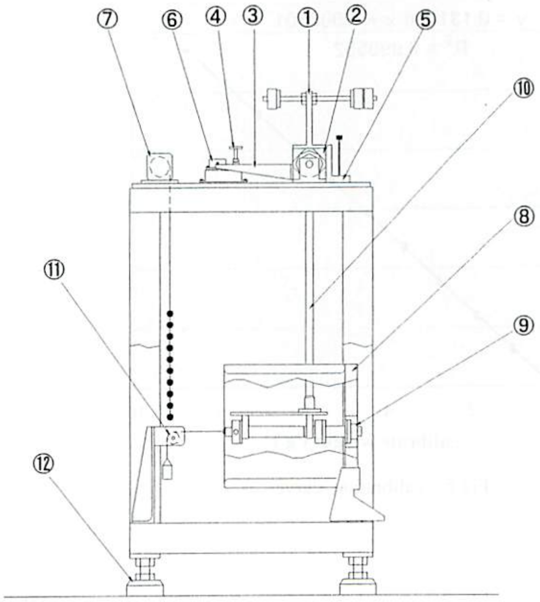

Fig.3 Thrust measurement stand

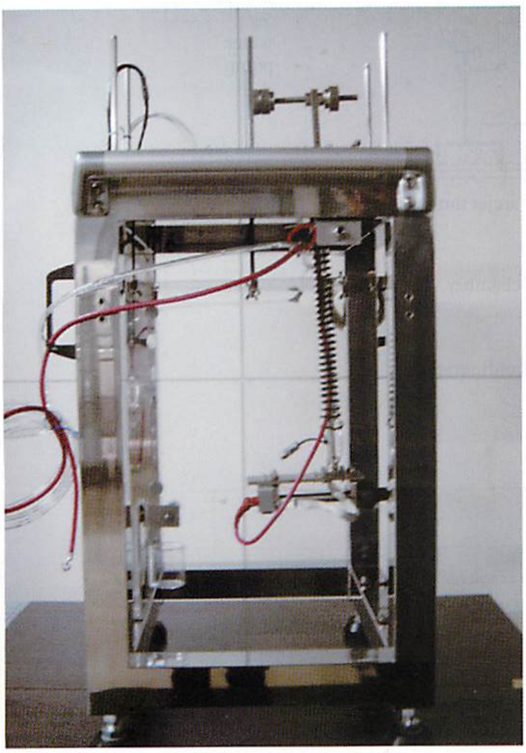

Fig.4 General view of thrust stand

with calibration curve. Figure 5 showed the typical calibration curve, the ordinate shows measured load cell output (mV/V) and the abscissa shows calibrate weight. End-to-end accuracy was expected 2% by those measuring methods.

4. System test

4.1 Test equipment

System test configuration is shown in Figure 6. The arcjet thruster was set in a vacuum chamber in which air was exhausted by vacuum pumps. Cooling water was supplied to the thrust stand and the pendulum arm by a water pump settled outside of the chamber. Nitrogen gas was used as thruster propellant. Nitrogen gas flow was controlled by flow controller installed outside. Electrical power was sent through PCU(power control unit) which supplied constant current according to electrical resistance between the anode and the cathode.

4.2 Vibration analysis

Vibration analysis of the vacuum chamber floor was conducted because operation of vacuum pumps might affect the thrust measurements of the arcjet thruster. Figure 7 shows the result of frequency analysis of the floor when

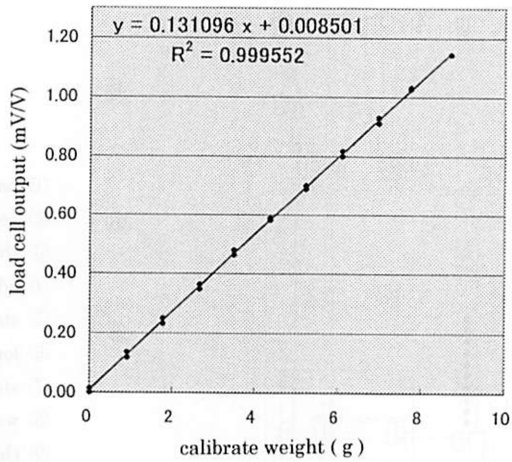

Fig.5　calibration　curve

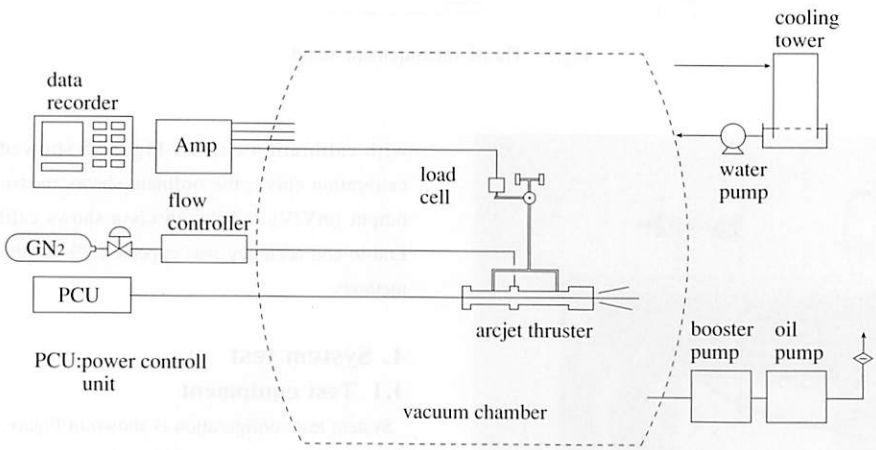

Fig.6　System　test　configuration

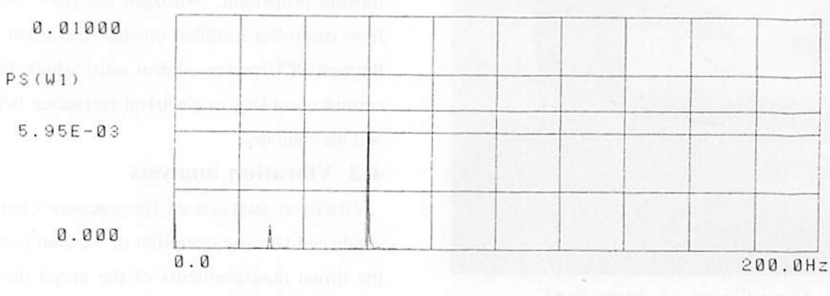

Fig.7　Frequency　response　of　the　floor

vacuum pumps were operating. There were two peaks of acceleration, one was 30 hz and the other was 60 hz. Oscillation of 30 hz corresponds to that of rotational speed of vacuum pumps. Power spectrum of acceleration was almost $8\times10^{-3}m/s^2$. This value is small itself, but had some influence on thrust of the arcjet thruster as disturbing force.

4.3 Cold flow test

We conducted cold flow test using N_2 gas without electrical power. Figure 8 shows a thrust curve obtained at this test, small effect of pump vibration on the thrust was observed. Magnitude of this effect was not changed by thrust level, 1.4 mN half amplitude was measured in this case and at hot firing described bellow, it is the order of 1% of full thrust.

5. Hot firing test result of the arcjet thruster

After the cold flow test, we conducted hot firing test with electrical power. Figure 9 shows the test view, flame was very stable as you look. We have obtained performance datum of the arcjet thruster for the first time at the Daiichi Institute of Technology.

Experimental datum were obtained at power level of 900W to 1100W with nitrogen mass flow rate of 58.35 mg/s. The specific impulse I_{sp} is calculated with the following equation:

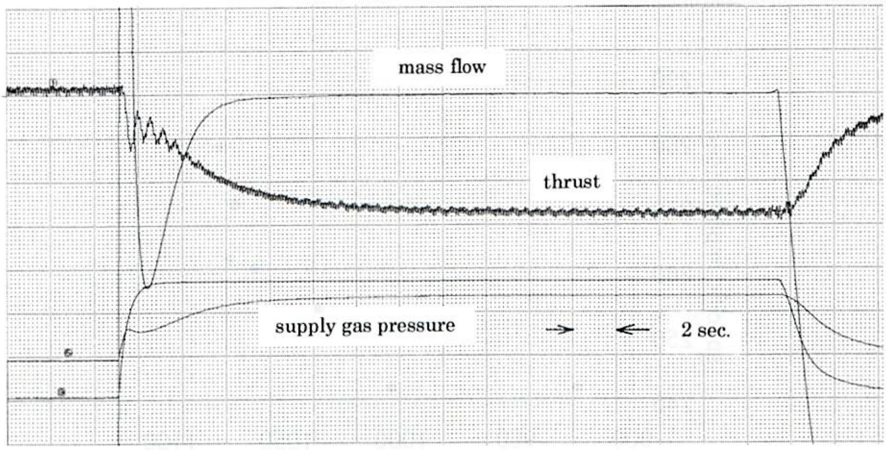

Fig.8 Cold flow test results

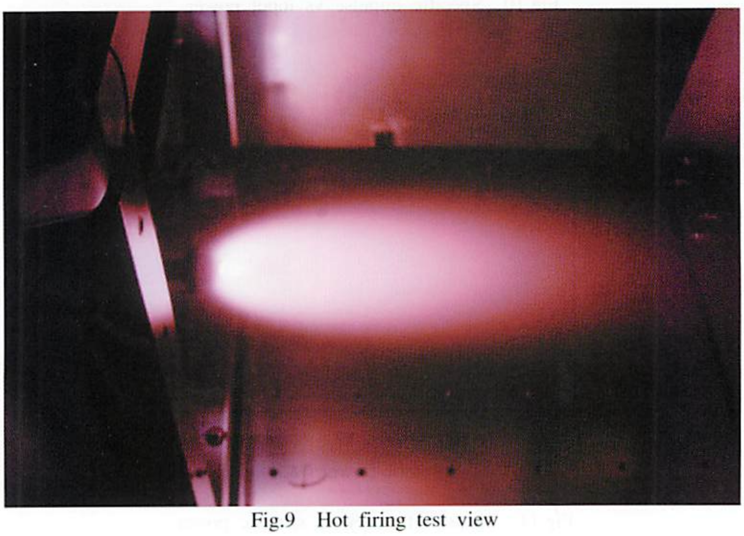

Fig.9 Hot firing test view

$$I_{sp} = F / \dot{m} g_0$$

where F is the thrust, $\dot{m}$ the mass flow rate, and g_0 the sea-level gravitational acceleration. The thrust efficiency η is defined with the following equation:

$$\eta = F I_{sp} g_0 / 2IV$$

where I is the input current, and V the input voltage, IV means the input power.

Figure 10 shows specific impulse versus input power. The specific impulse increases with the input power at a constant mass flow rate. Figure 11 shows thrust efficiency versus specific power. The thrust efficiency is almost constant at the specific power between 15 to 19 MJ/kg. The specific impulse and the thrust efficiency obtained are almost standard comparing with other low-power N_2 arcjet thruster.[3] The specific impulse may become high with higher flow rate, then we will have the specific impulse and the thrust efficiency with the high mass flow rate at a next experiment. These performance may become higher if we use hydrazine decomposed gas,[2] so we need another hot firing test with hydrazine decomposed gas (usually N_2/H_2 gas mixtures are used as simulating decomposed hydrazine).

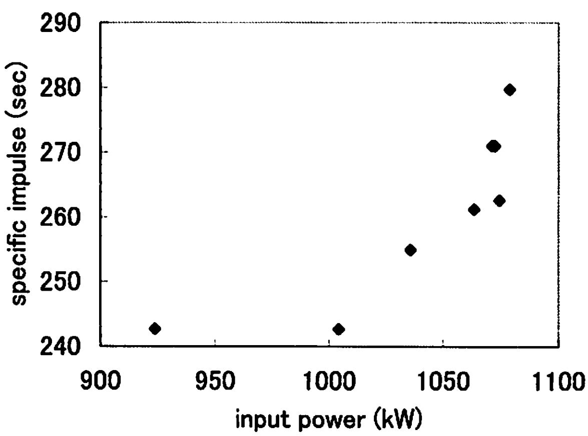

Fig.10　Specific impulse vs input power

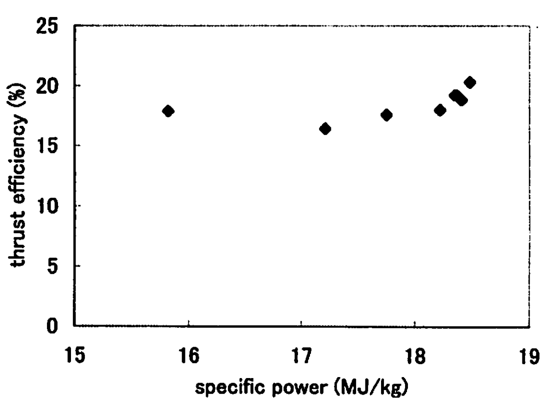

Fig.11　Thrust efficiency vs specific power

6. Conclusion

The sophisticated thrust measurement system has been introduced to the Daiichi Institute of Technology and the first hot firing test of a low power arcjet thruster was conducted. The specific impulse and the thrust efficiency were obtained satisfactorily. A more detailed study including the comparison among the different flow rate and the different gas is requested.

7. Acknowledgements

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