

Development of Low-Power Cylindrical type Hall Thrusters for Nano Satellite

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Abstract: Development of Hall thrusters for nano, small and low-power satellites below 100W is expected. In lowering Hall thruster power, the cylindrical-type Hall thruster is more advantage than conventional coaxial-type Hall thrusters. In this study, a very low-power cylindrical Hall thruster for nano-satellite was designed, and the thruster performance was measured. As a result, a stable operation was achieved even with 35W. The specific impulse and the thrust are 940 s and 7.3mN, respectively, with 115W. Also thrust efficiency is 19.5%.

I. Introduction

FROM the beginning of this century, the development of nano-satellite by the private enterprises and educational institutions are becoming active because rapid advancement of electronics and deployment of piggyback launch business by each space agency were started. In Japan, Chiba Institute of Technology launched the first nano-satellite "Whale Ecology Observation Satellite (WEOS)" in December 2003. Since then, more than 10 nano-satellites were launched by several Japanese universities. In the future, development of nano-satellite which can be advanced mission such as the transfer maneuver or re-entry is expected.

Osaka Institute of Technology (OIT) focused attention of this point, started to development of the original nano-satellite "PROITERES: The Project of OIT Electric-Rocket-Engine onboard Small Space Ship" in 2007. PROITERES satellite is mounted electro-thermal pulsed plasma thruster which is type of the electric propulsion thruster. In September 2012, PROITERES satellite was launched from India, and initial operation was successful. Currently, OIT is planning to develop 50 kg class small moon exploration satellite which is mounted cylindrical hall thruster (CHT) as a next step of PROITERES. CHT that has circular cross-sectional ceramic discharge chamber was developed by Dr. Raites and his research team of Princeton Plasma Physics Laboratory, and their thruster achieved thrust efficiency of 15-32% in the power range of 50-300W.¹⁻⁴

In order to further accelerate low-power design, OIT developed low-power CHT "TCHT-4" that used permanent magnet in exchange for inner coils. The optimized TCHT-4 had a high efficiency of 30.1% in the power range of 55.5W, thrust is 0.9 mN, specific impulse is 1864 s.⁵⁻⁶

However, TCHT-4 becomes inoperable at 170 sec, and significant performance degradation, because inner permanent magnet was degaussed discharge room's overheating.⁷⁻⁸

In this study, OIT developed new CHT named "TCHT-5" which can be changed discharge room length and magnetic poles length. The performance characteristics of TCHT-5 are measured.

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II. Experimental apparatus

Figure 1 and 2 shows the appearance and cross-sectional view of TCHT-5. The anode located at the upstream end of the circular cross-sectional part is made of copper. The discharge chamber made of Boron Nitride (BN), the inner diameter is 14mm. And it can be changed the anode position and discharge room length by inside screw. TCHT-5 were employed Sm-Co permanent magnets because the degradation of magnetic property by heating is relatively small, and 8 pieces Sm-Co permanent magnets is mounted at the periphery. And this magnet is mounted 8 places at the periphery.

Figure 3 shows detailed structure of discharge room. Propellant and DC power are supplied by copper pipes with a diameter of 3mm. Magnetic poles length X_m can be changed in a range of $X_m=10-18\text{mm}$. And also, discharge

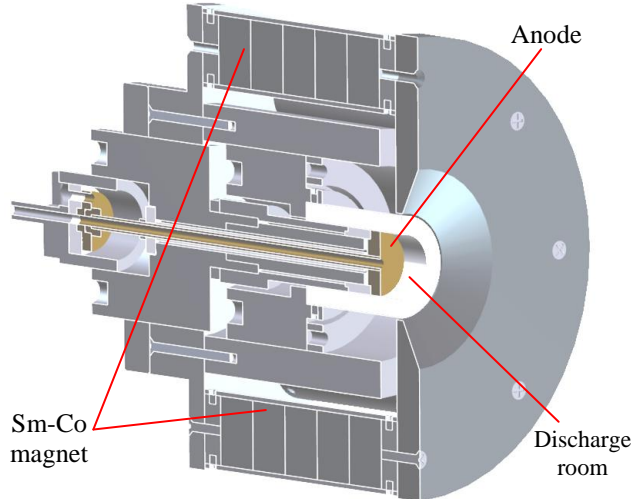


Figure 1. Cross sectional view of TCHT-5.

17mm.



Figure 2. Appearance of TCHT-5.

room length X_d can be changed in a range of $X_d=7-$

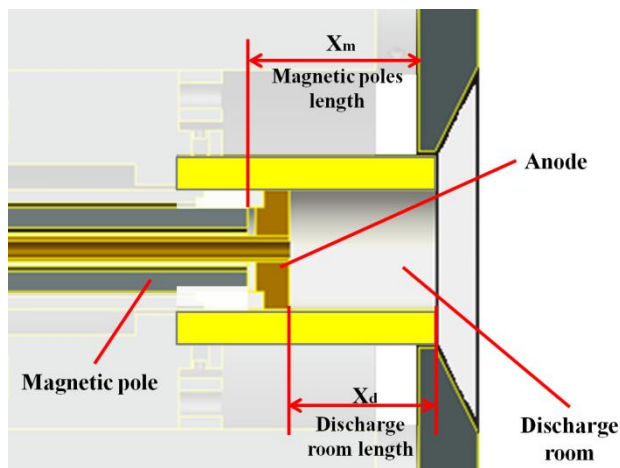


Figure 3. Detailed discharge room structure.

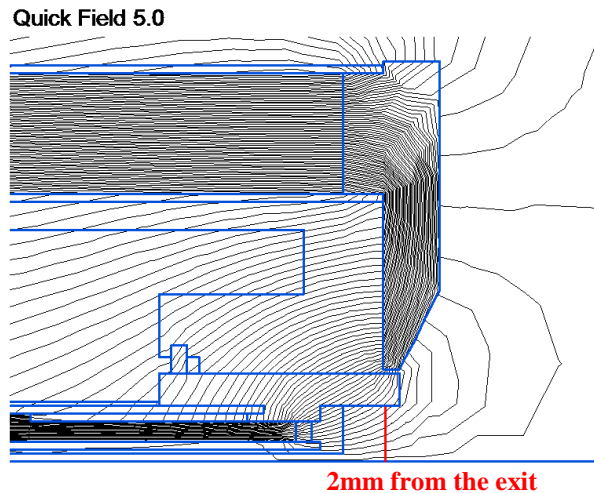


Figure 4. Magnetic field shape of TCHT-5.

Figure 4 and 5 shows the calculated magnetic field shape and strength of TCHT-5. The magnetic field has an axial component, and the strength is the highest near the anode located at the upstream region. At the discharge room length is 7mm, the maximum magnetic flux density is 184mT. The hollow cathode (Veeco-Ion Tech, HCN-252) is employed as the electron emission source. Propellant gas is injected into the discharge chamber through the copper pipe behind the anode. Xenon is used as the propellant and the working gas of the cathode.

The experimental facility is shown in Figure 6. The thruster is operated in a water-cooled stainless steel vacuum chamber with 1.2 m in diameter and 2.25 m in length. The chamber is equipped with two compound turbo molecular pumps that have a pumping speed of 10000 l/s on xenon, several DC power supplies, and a thrust measurement system. The vacuum chamber pressure is kept about 3.0×10^{-2} Pa under operation. A clean and high vacuum environment can be created by using the oil-free turbo molecular pump system.

Figure 7 shows the operation systems of TCHT-5. Thrusts are measured by a pendulum method. The thruster is mounted on a thrust stand suspended with an aluminum bar, and the position of thruster is detected by an eddy current type gap sensor (non-contacting micro-displacement meter).

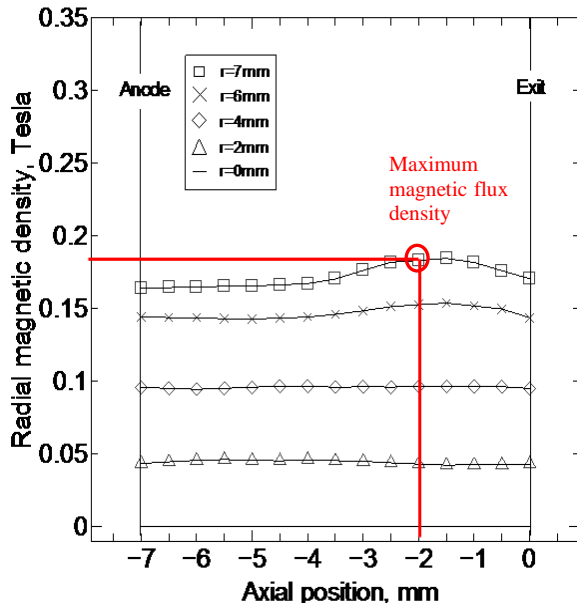


Figure 5. Magnetic flux density in TCHT-5.

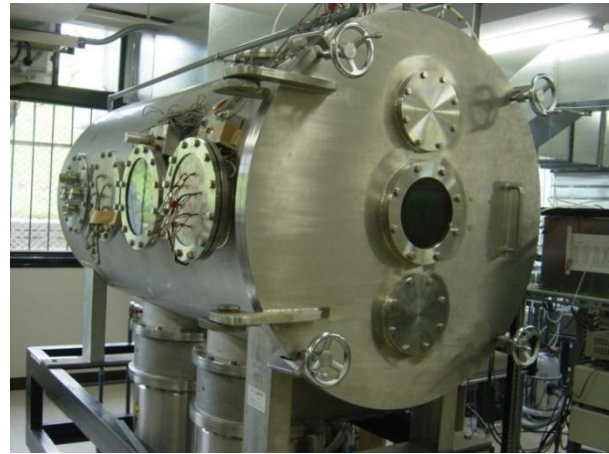


Figure 6. Vacuum chamber.

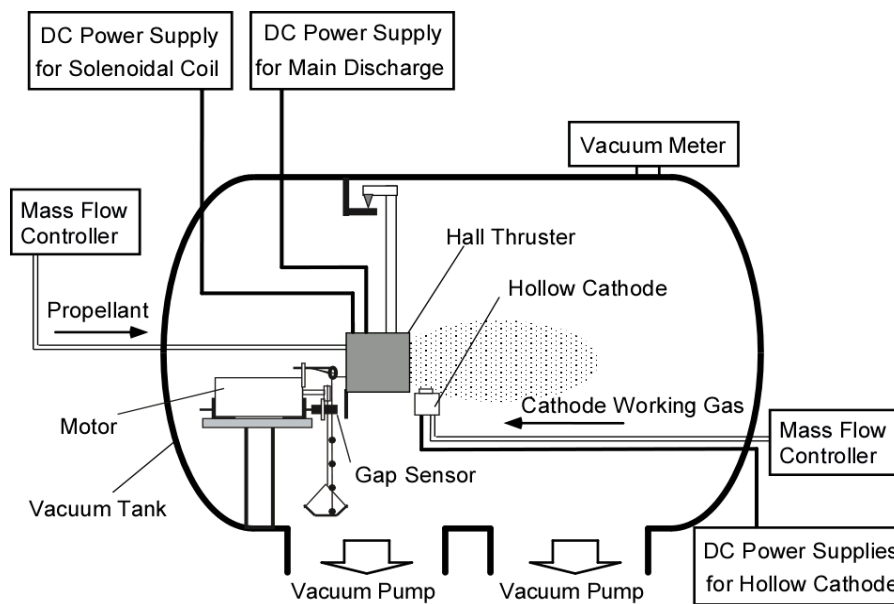


Figure 7. Operation systems of TCHT-5.

III. Experimental Results and discussion

In the experiment, the each performance of the changing magnetic poles length and the changing discharge room length are measured. Table 1 shows the operational conditions for TCHT-5. Discharge voltage ranges are from 150 to 250 V every 10 V. The mass flow rate of hollow cathode is always 0.1 mg/s.

Table 1 Operating condition.

Discharge Voltage	150-250 V	
Propellant	Xenon	
Mass Flow Rate	Thruster	0.6, 0.7, 0.8 mg/s
	Hollow Cathode	0.1 mg/s
Back Pressure	1.0×10^{-2} Pa	

A. Magnetic poles length

Figure 8 shows photographs of plasma plume for TCHT-5. TCHT-5 is stable operation with all operating conditions. In the case of $X_m=13$ and 18mm, the stable and azimuthally uniform plume is slightly expanded radially. But the case of $X_m=10$ mm, plasma plume is confirmed the funnel-shaped rapid divergence.

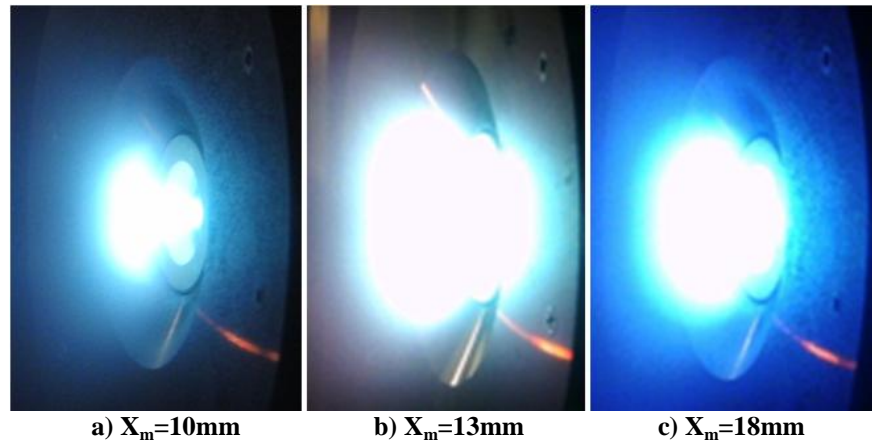


Figure 8. Plasma plume of TCHT-5.

Figure 9 shows the discharge current vs discharge voltage characteristics at xenon mass flow rates of 0.6, 0.7 and 0.8 mg/s and the case of $X_m=10$, 13 and 18mm magnetic poles length. The discharge currents are stayed almost constant with all operational conditions. When the magnetic poles length is $X_m=13$ mm, discharge current is lower about 10% than other case.

As shown in Figure 10, the thrust and the specific impulse almost linearly increase with the discharge voltage with all operational conditions. At the mass flow rate of 0.8 mg/s and length of $X_m=18$ mm, the thrust and the specific impulse are greater than other case about 10%. The thrust ranges from 3 to 7.3 mN and the specific impulse from 353 to 940 s with 0.8mg/s.

Figures 11 and 12 shows the characteristics of the specific impulse and the thrust efficiency, respectively, as a function of input power. In this experiment, input power does not include the cathode power. When the mass flow rate is low, the specific impulse and thrust efficiency are high performance.

Especially, when the magnetic poles length is $X_m=18$ mm, specific impulse and thrust efficiency are higher 20% performance than other concisions.

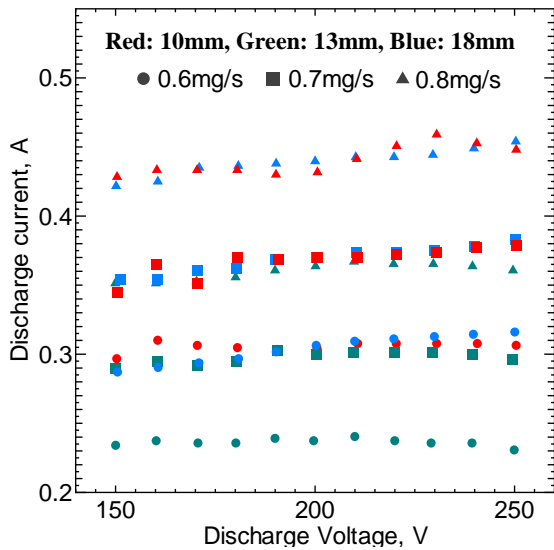


Figure 9. Thrust and specific impulse vs discharge voltage.

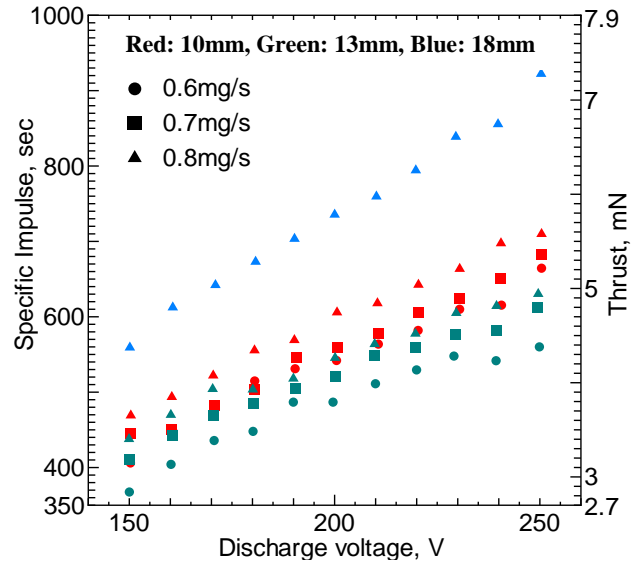


Figure 10. Operation systems of TCHT-5.

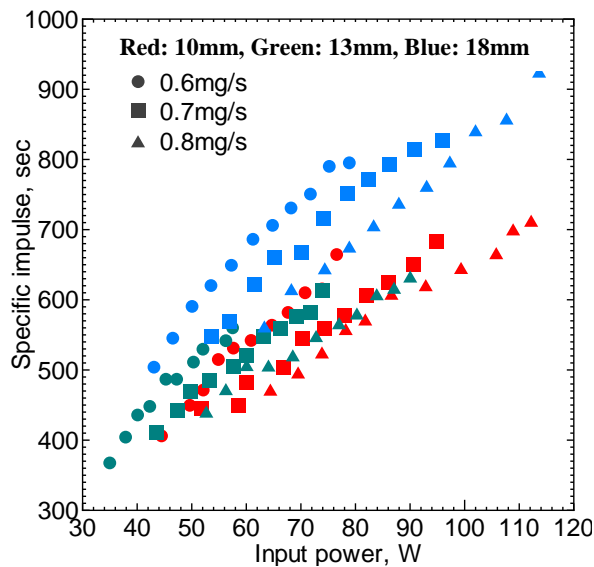


Figure 11. Thrust efficiency vs discharge voltage.

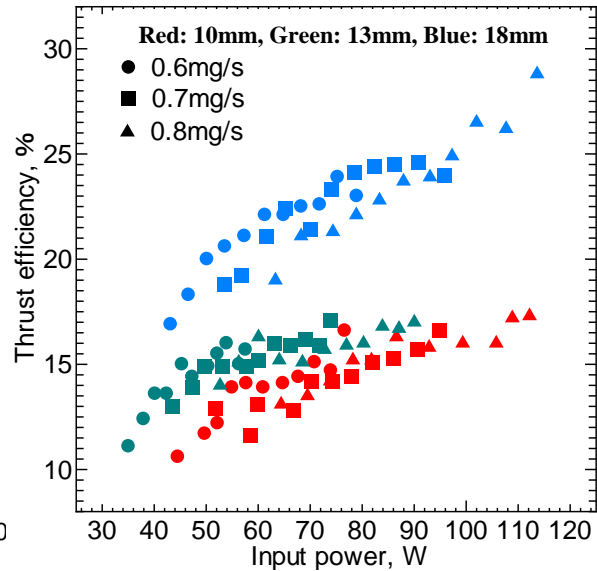


Figure 12. Thrust efficiency vs input power.

B. Discharge room length

Figure 13 shows the plasma plume for TCHT-5. At the discharge room length is $X_d=17\text{mm}$, TCHT-5 become to the extremely unstable condition.

Figure 14 shows the discharge current vs discharge voltage characteristics at xenon mass flow rates of 0.6, 0.7 and 0.8 g/s and the discharge room length of $X_d=4\text{mm}$ and 17mm. At the length of $X_d=17\text{mm}$, the discharge currents is higher 15-23% than $X_d=7\text{mm}$.

Figure 15 shows the specific impulse and thrust vs discharge voltage characteristics. At the $X_d=17\text{mm}$, each performance are lower 16% than the case of $X_d=7\text{mm}$.

Figures 16 and 17 shows the characteristics of the specific impulse and the thrust efficiency as a function of input power. At the case of $X_d=7\text{mm}$, the specific impulse is 350-640 s in the power range of 35-90W, whereas the case of $X_d=17\text{mm}$, it is only 250-400 s in the power range of 70-190W. And also, thrust efficiency is low value about 3-3.5%. From this, it is understood that the discharge room length of $X_d=17\text{mm}$ is not an optimal condition.



a) $X_d=7\text{mm}$ b) $X_d=17\text{mm}$
Figure 13. Operation systems of TCHT-5.

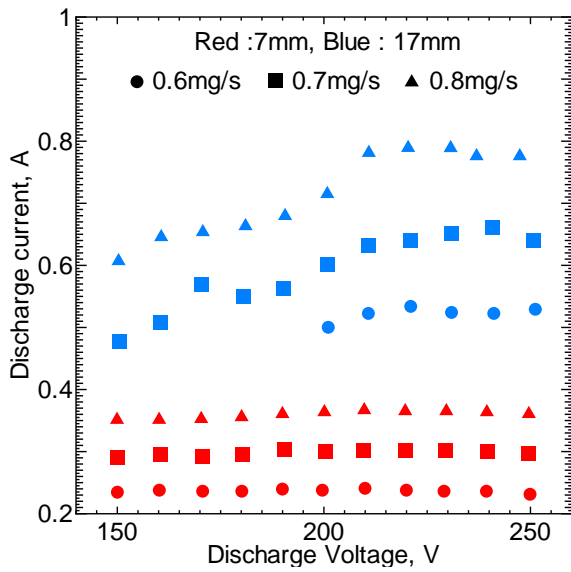


Figure 14. Discharge current vs discharge voltage.

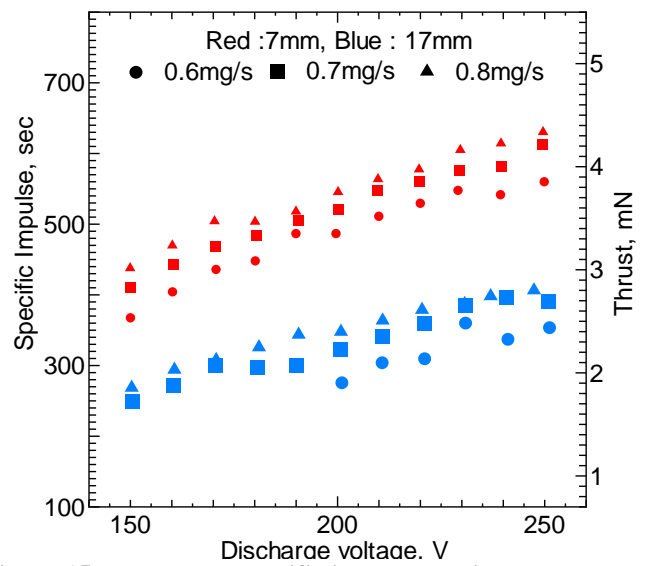


Figure 15. Thrust and specific impulse vs discharge voltage.

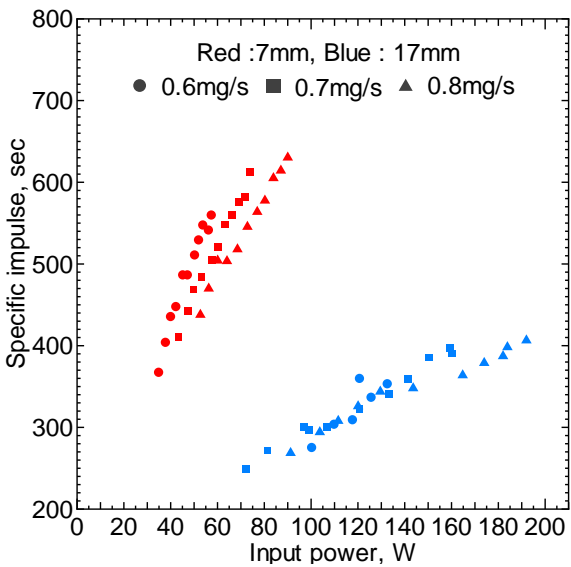


Figure 16. Specific impulse vs input power.

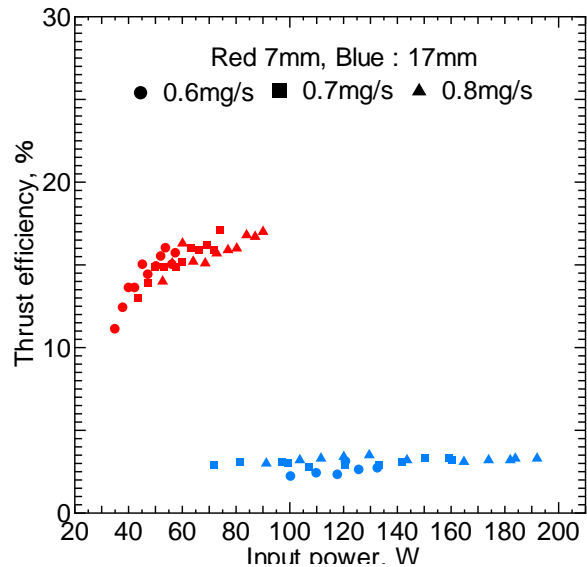


Figure 17. Thrust efficiency vs input power.

IV. Conclusion

The new low-power CHT named "TCHT-5" was developed, and the thruster performance was measured.

When the changing magnet poles length between $X_m=10-18\text{mm}$, both the thrust and the specific impulse almost linearly increased with the discharge voltage and input-power with all operational conditions. The thrust ranged from 3 to 7.3 mN and the specific impulse from 353 to 940 s. The thrust efficiency ranged from 19.5 % and 60 W to 28.5 % and 115 W with 0.8 mg/s and $X_m=18\text{ mm}$. The thruster operated stably even with very low powers.

When the changing discharge room length of $X_d=17\text{mm}$, TCHT-5 become to the extremely unstable condition. Both the thrust and the specific impulse is lower 16% than the case of $X_d=7\text{mm}$. The thrust ranged from 1.8 to 2.9 mN and the specific impulse from 250 to 350 s. The thrust efficiency ranged from 3 % and 70 W to 3.5 % and 190 W with all operational conditions.

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