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Volt-ampere characteristics, nozzle temperature and thruster performances in a low power argon arcjet

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Abstract Argon gas with simple atomic structure and favorite arcing stability at low input power was used as the propellant. The thruster with a regeneratively cooled nozzle were tested in a vacuum system capable of keeping the chamber pressure at about 10 Pa at a propellant feeding rate of 5 slm. Arc current, arc voltage, thrust, nozzle temperature and propellant feeding rate were measured in situ simultaneously. Effects of the working parameters such as the propellant feeding rate and arc current on the thruster performances, mainly the produced thrust, specific impulse and thrust efficiency, were examined. The variation of arc volt-ampere characteristics with running time and the effect of nozzle temperature on thruster property are discussed.

Keywords arcjet thruster, volt-ampere characteristics, nozzle temperature

1. Introduction

Several kinds of electric propulsion system have been successfully used for various space flight missions [1-3], mainly due to their much higher specific impulse and precise controllability than conventional chemical combustion rockets, especially for satellites of long in-orbit service. With a simple acceleration principle of heating up propellant by an arc discharge and then converting the enthalpy into kinetic energy through the nozzle expansion, the direct current (dc) arc-heated jet (arcjet) thruster is one of the most useful electric propulsion systems for north-south station-keeping of communication satellites [1, 3-4]. Great efforts have been devoted to the development of arcjet thrusters for different power levels and using a variety of propellants, over the past several decades. From the applicational point of view so far, it seems that problems affecting the arcjet performances including reliability, working stability and life-time are all in control, especially the 1 kW class hydrazine (N_2H_4) arcjet thrusters can still satisfy essentially the current commercial applications.

Researches on arcjet thruster of different power levels and propellants are necessary, in order to satisfy the diversification demands for various space flying missions [5-7]. In spite of the simple working principle of arcjet thrusters, the plasma and flow physics in the small nozzle dominating the energy conversion and thruster performance are quite complex [4, 8].

Unsuitable for relative high power level and high specific impulse production, argon is a suitable kind of propellant for arcjet thruster to satisfy the application demands where very low power can be offered or relative high thrust is needed. At the same time, argon arc shows much favorite stability at low arc current than that with a diatomic gas as the propellant. This is a strongly competitive property for small satellite application compared with the current thrust system using a cold propellant. Another excellent character of argon propellant arises from its atomic structure. Avoiding the dissociation and recombination between atoms, it suffers less frozen losses, could gain relative higher thrust efficiency and works on simpler mechanisms of the energy-conversion in the expansion section of the nozzle, compared with the case using a multi-atomic propellant.

In the present work, argon gas is used as the propellant for arcjet thruster with a regeneratively cooled nozzle. Dependence of the thruster performances on the arc volt-ampere characteristics and nozzle temperature are examined by changing the input power and propellant feeding-rate.

2. Experimental conditions

The arcjet thruster was set in a vacuum chamber of 2 m diameter and 4 m length as shown in Fig.1, with pure argon as the propellant at input power of lower than 450 W. The pumping system is capable of keeping the chamber pressure at lower than 10 Pa with a gas feeding rate of 5 slm, about 148 mg/s for argon propellant. A thruster with a regeneratively cooled nozzle was used by passing the cold propellant through the outside surface of the hot nozzle before entering the convergent section and arc-heated. The thruster had a throat of 0.7 mm in diameter, a divergent half angle of 15° and an area ratio about 240 of the nozzle exit to throat. It was fixed on a movable stage driven accurately along the thruster axial and radial directions by stepping motors. A flat plate made from heat-resistant metal of 200 mm in diameter was set perpendicular to the thruster axis, and was attached to a sensitive force transducer to receive the impact effect of the plume [9], by which the thrust produced by the arcjet thruster was measured. The temperature of the nozzle outside wall was monitored with an infrared pyrometer of working range 200-600 ℃, while the emission coefficient of the nozzle surface was estimated to be 0.31. Signals from the force, arc-voltage and arc-current sensors and the infrared pyrometer were sampled time-dependently by a data acquisition and processing system.

The specific impulse is $I_{sp} = F / m$, here F is the measured thrust and m is the mass flow rate; and the thrust efficiency is $\eta = (F^2 - F_c^2) / 2mP$, here P is the input electric power and F_c is the cold thrust when the propellant gas is fed before the arc ignition.

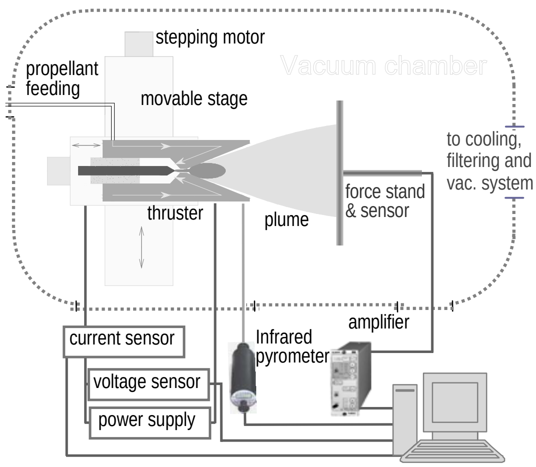


Fig. 1: Schematic drawing of the experimental system and setup

3. Results and discussions

Figure 2 shows the temperature variation of the nozzle outside surface with firing time, detected by the infrared pyrometer. Measurement data below 600 K were not used because of sensitivity problems of the pyrometer and interference signals from the plume emission of the plasma. The black solid line in Fig. 2 indicates the measured result after the firing time of about 100 s and when the nozzle temperature was over 600 K. At the ignition time, the nozzle was at room temperature, and the dashed line in the figure is estimated nozzle temperature variation after the ignition and before 100 s of firing. It can be seen that the nozzle temperature rose relatively fast until 900 s after ignition, then rose quite slowly, and finally stabilized at about 850 K after the firing time of around 2000 s, at the argon feeding rate of 100 mg/s and arc current of 8 A.

Figure 3 shows variations of the arc voltage with gas flow rate and firing time, when the arc was ignited at 8 A and argon flow rate of about 100 mg/s and then increasing the argon flow rate at the fixed arc current. Numbers in the figure indicate the firing time at which the voltage value was taken. The arc voltage increased slightly with increasing argon flow rate and firing time. After about 650 s of firing and then reducing the gas flow rate again to 100 mg/s, the arc voltage decreased from 29.2 V at 245 s to 27.4 V at 745 s of firing time, and further to 25.5 V at 2275 s. This suggests that the arc voltage decreased with the increase of firing time (nozzle temperature) at fixed arc current and propellant feeding rate.

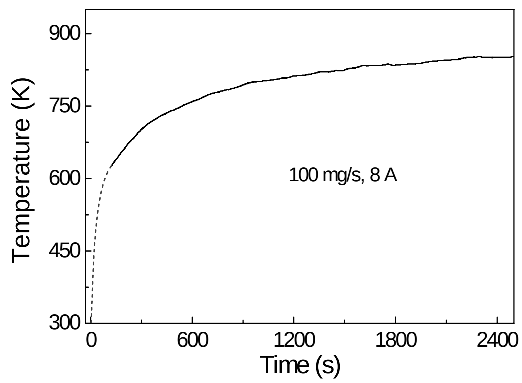


Fig. 2: Variation of the nozzle temperature with the firing time at fixed argon flow rate of 100 mg/s and arc current of 8 A

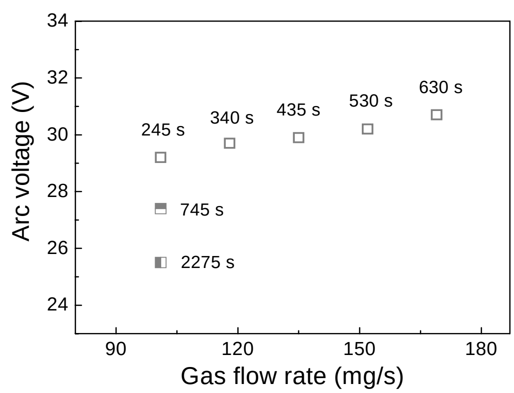


Fig. 3: Arc voltage varies with argon flow rate and firing time at fixed arc current of 8 A

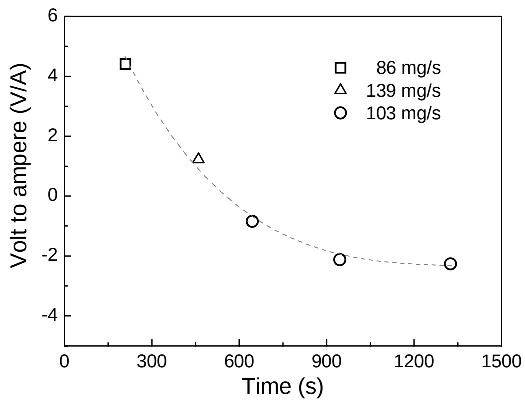


Fig. 4: Time variation of the gradient change of arc voltage to current in the regenerative cooled nozzle

The result in Fig. 4 explains more clearly the phenomenon in Fig. 3. It shows that the slope of volt-ampere characteristics curve changed with the firing time. The volt-ampere characteristics variation follows a clearly unified relationship and tends to stabilize after the firing time of about 1000 s, regardless of the different feeding rate. Ignited at the room temperature, the rising volt-ampere characteristics could be caused by the restrictive effect of the cold anode/nozzle throat on the diameter of the arc column, in the beginning stage of firing while the nozzle temperature is still relatively low, by which the current density should increase with increasing arc current. The restrictive effect of the nozzle throat on the arc column could diminish with the increase of firing time and nozzle temperature, resulting in reduced current density and falling volt-ampere characteristics.

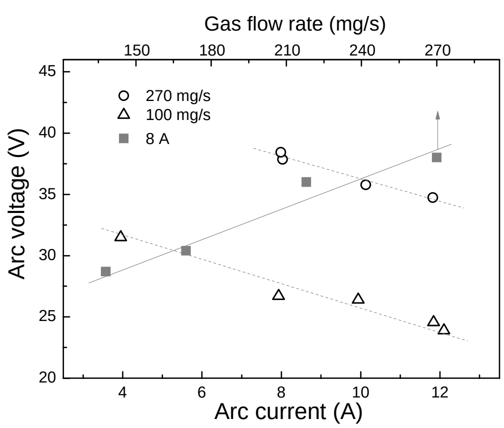
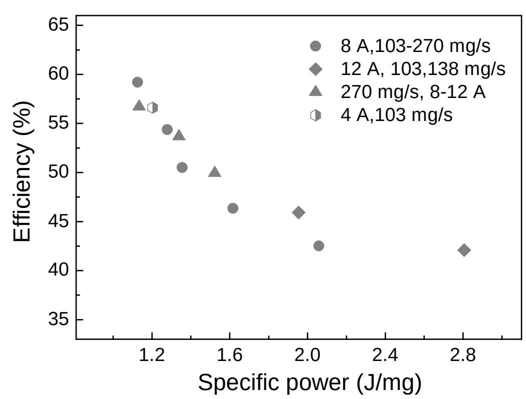


Fig. 5: Variations of arc voltage with arc current and argon feeding rate after the firing time of 1000s

Experimental results showed that the thrust and specific impulse decreased and thrust efficiency increased in the same duration with the decrease of arc voltage in the increasing stage of nozzle temperature, due to the reduced input power by the arc voltage decreasing at fixed arc current and argon feeding rate. Figure 4 indicated that the volt-ampere character tended to a steady condition after a firing time over 1000 s for the thruster with the regenerative cooled nozzle. Fig. 5 shows the volt-ampere characteristics of the thruster after 1000 s firing. It indicates that the arc voltage increased with increasing argon feeding rate and decreased with increasing arc current. Therefore, effects of the working parameters such as arc current and propellant feeding rate were examined after a firing time of 1500 s. Under the stable working condition, the produced thrust increased from 125 mN to 345 mN with the increase of input power and argon flow rate from 128 W to 408 W and 100 slm to 270 slm, respectively.

Figure 6 shows the thruster performance evaluated with the specific power (the input power to per unit mass flow rate of the propellant), because the arc voltage changed with arc current and argon flow rate, which caused the change of input power. It indicates that the thrust efficiency decreased from 59.2% to 42.1% monotonically and the specific impulse increased almost linearly from 123 s to 160 s with the increase of the specific power from 1.1 J/mg to 2.8 J/mg, despite of changes of the arc current from 4 A to 12 A and the propellant feeding rate from 103 mg/s to 270 mg/s.



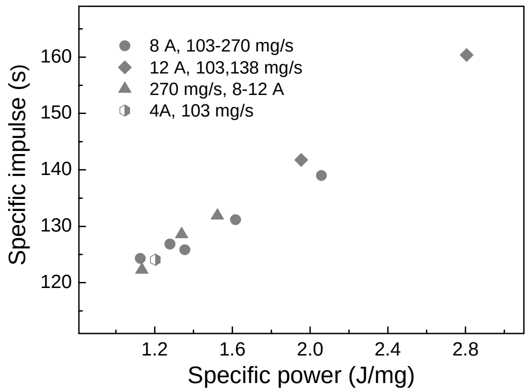


Fig. 6: Variations of thrust efficiency and specific impulse on the specific power with the regenerative cooled nozzle thruster

4. Conclusions

Experimental results indicate that the arc voltage rises with the increase of arc current in the beginning stage of firing, and then turns to the falling characteristics with increasing arc current after the anode temperature has risen to certain elevated levels. The change of gas flow rate does not essentially affect the variation of the slopes of volt-ampere characteristics curve with the firing time or anode temperature. The arc voltage increases with increasing gas flow rate and decreases with increasing arc current linearly, after a firing time of 1000 s. The anode/nozzle temperature affects the arc volt-ampere characteristics, and hence could affect the gas heating and the energy conversion processes in the nozzle from high enthalpy to increased flow speed, by which the thruster performance is affected.

Acknowledgements

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