Effect of Nozzle Temperature on the Performance of a 1 kW H_2-N_2 Arcjet Thruster*

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Abstract A 1 kW-class arcjet thruster was fired in a vacuum chamber at a pressure of 18 Pa. A gas mixture of $H_2 : N_2 = 2.8 : 1.5$ in volume at a total flow rate of 4.3 slm was used as the propellant with an input power fixed at 860 W. The time-dependent thrust, nozzle temperature and inlet pressure of the propellant were measured simultaneously. Results showed that with the increase in nozzle temperature the thrust decreased and various losses increased. The physical mechanisms involved in these effects are discussed.

Keywords: arcjet thruster, nozzle temperature, energy conversion, experimental measurement

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1 Introduction

Having much higher specific impulse compared with ordinary chemical combustion rockets, the electric propulsion thruster consumes less propellant for a given mission and can realize more precise control of the orbit and/or attitude, when it is used for satellites' orbital station keeping or transferring and attitude adjustment. Thus, electric propulsion plays an increasingly important role in satellite or spacecraft applications [1~3]. Among several kinds of practically used electric thrusters, such as the Hall or ion thruster and the resistance-heated thruster, 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, owing to both simplicity and compactness of the system, high ratio of produced thrust to input power, moderate specific impulse and low development cost.

The arcjet thruster has a simple operational principle of heating up the propellant through an arc discharge generated between its cathode and anode, and then converting the enthalpy of high temperature gas around 20000 K into kinetic energy through nozzle expansion. However, the plasma physics and flow processes in the small nozzle dominating the energy conversion and thruster performance are quite complicated [4~6]. The anode of the 1 kW-class arcjet thruster, which is also the thruster nozzle, has a throat diameter narrower than one millimeter and an expanding-section length shorter than 20 mm [7,8]. Arc root attachment on the anode surface is generally located within a range along the beginning part of the expanding section but downstream of the throat [9,10]. Because of the very short pass in the expanding section of the nozzle, the high speed flow allows only a very short time for energy-conversion in the order of 10^{-6} s, which is about the same order as the recombination time for some ionized or dissociated species in the plasma flow. Fig. 1 indicates the possible manner of energy transfer and processes normally occurring in an arcjet thruster to produce thrust, accompanied with a series of energy losses. Even if there is no gas heating by the arc discharge, it can produce a small thrust called the "cold thrust" by the gas expansion from the relatively high-pressure in the convergent section to the low-pressure environment. Among these various losses, the "nozzle loss" could generally be a negligible portion [11]. The "exhaust heat" loss and "heat transfer loss" usually exist in all cases, because it is very difficult to accomplish the energy conversion completely to reduce the gas temperature to its inlet level in the short nozzle to avoid the exhaust heat-loss, and it is also impossible to block completely the heat transfer from the arc to electrodes and nozzle to avoid the heat transfer loss by conduction and radiation. Besides these, there is a relatively small portion of frozen loss caused by the incomplete recombination of ions and electrons in the case of atomic propellant, and a quite large portion of frozen loss due to the dissociated atoms when a polyatomic propellant is used [11].

Most of the practically used arcjet thrusters take hydrazine (N_2H_4) as their propellant for sharing the storage tank with ordinary chemical combustion rockets. Commonly used hydrazine arcjet thrusters typically have a thrust-efficiency only around 35% [6]. Many factors could affect the energy conversion in the small nozzle simultaneously and hence affect the thruster performance, including the various kinds of energy losses. It is indicated in Fig. 1 that the propellant and nozzle

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heating conditions are the most important factors dominating the thruster performance. Regenerative cooling, accomplished by passing the cold propellant around the hot nozzle for gas preheating and nozzle cooling before feeding it into the convergent section for arc-heating, can increase the thrust performance to some extent.

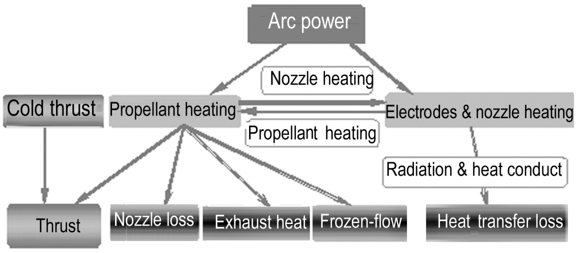

Fig.1 Schematic diagram of the main energy distribution and transition in an arcjet thruster

Since the portion of input electric energy which is converted into the kinetic energy producing useful thrust is relatively low (usually less than 50%), it is important to understand the factors that affect this efficiency of conversion and the mechanisms involved. These questions have not been extensively studied before. One of these factors might be the effect of the nozzle (or anode) temperature on thruster performance. It is the purpose of this work to experimentally study this effect and to discuss some of the mechanisms involved.

In the present work, a regeneratively cooled arcjet thruster of 1 kW-class input power was used with a gas mixture of hydrogen and nitrogen as its propellant. The time-dependent nozzle temperature and produced thrust were measured to demonstrate the effect of the nozzle temperature on thruster performance. Some of the possible physical mechanisms producing these effects are discussed. It would be highly difficult to quantitatively define the details of various effects through refined numerical modeling of this complicated process, so only a qualitative discussion of the affecting mechanisms is attempted.

2 Experimental conditions and analysis methods

2.1 Apparatus and setup

The 1 kW-class arcjet thruster of regenerative cooling structure with a throat diameter of 0.6 mm and an area expansion ratio of 120 was set in a vacuum chamber of 0.8 m in diameter and 1.2 m in length, as shown in Fig. 2. The arrows connected with the propellant-feeding pipe in the thruster indicate schematically the gas-path before reaching the convergent section. The pumping system was capable of keeping the chamber in a pressure below 18 Pa while a propellant of 4.3 slm was fed. The arcjet thruster was fixed on a force measurement stand to detect the time-dependent thrust in situ [12]. Signals from the force, current and voltage sensors were received and sampled by a data acquisition and processing system. The temperature on the outside wall of the nozzle sheath was detected with an infrared pyrometer with a working range from 600°C to 2000°C, while the emission coefficient of the molybdenum nozzle-sheath surface was estimated to be 0.31. It was assumed that the variation in the nozzle-sheath temperature would directly reflect the change in the nozzle wall temperature. A conventional video camera was used to record the luminosity conditions of the nozzle sheath and the jet plume outside the nozzle exit with a fixed exposure time of 0.04 s for each frame.

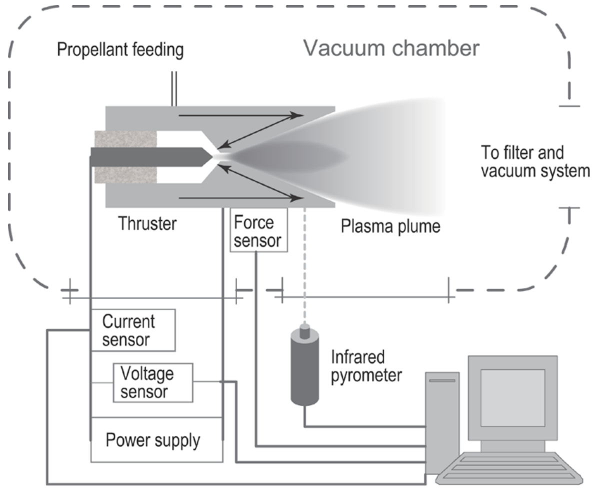

Fig.2 Schematic diagram of the experimental system

2.2 Parameters in the experiment

There are generally two input parameters, i.e., the gas flow rate and arc current, which can be regulated independently in firing an arcjet thruster. The gas composition is another alterable parameter when a gas mixture is used. In the present work a gas mixture of hydrogen-nitrogen with $H_2:N_2=2.8:1.5$ at a total flow rate of 4.3 slm was used as the propellant. Variation in the gas flow rate could cause a change in the arc voltage when the type of gas and arc current are fixed, and hence changes in the working condition and output performance. Regulation of the arc current could also cause a change in the arc voltage, even though the gas conditions are kept constant [7]. These changes in input parameters could all affect the arc power and propellant and nozzle heating conditions, and hence affect the thruster's properties such as thrust, efficiency and specific impulse. Thus, it is necessary to investigate the effect of the nozzle temperature on the thruster performance under the conditions with fixed input parameters. Fig. 3 shows the time-dependent input power, arc voltage and gas flow rates of hydrogen and nitrogen. The input power was kept at about 860 W with the arc voltage around 110 V. The gas flow rate of hydrogen was kept at 2.8 slm and nitrogen at 1.5 slm. Under these conditions the time-dependent nozzle temperature and thrust were measured simultaneously.

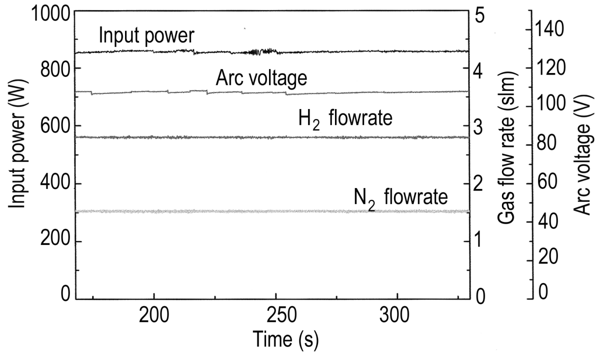

Fig.3 Variations in input power, arc voltage and gas flow rates with the firing time

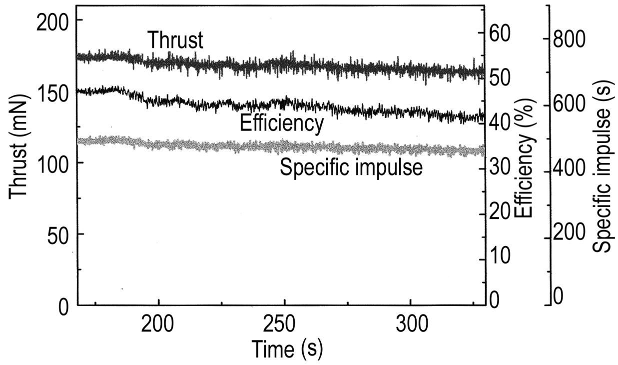

Fig.4 Measured time-dependent thrust and calculated thrust efficiency and specific impulse

2.3 Data reduction

The performance of an arcjet thruster is generally discussed in terms of specific impulse and thruster efficiency. The specific impulse is $I_{\rm sp} = F/m$ with F the measured thrust and m the mass flow rate; and the thrust efficiency is $\eta = (F^2 - F_{\rm c}^2)/2mP$, with P the input electric power and $F_{\rm c}$ the cold thrust when a gas flow is fed before firing. The temperature distribution on the nozzle sheath surface is estimated by analyzing the luminous intensity distribution from a series of pictures taken by the video camera concurrently with the infrared pyrometer measurement. The obtained temperature data is then used to estimate the radiation loss from the nozzle.

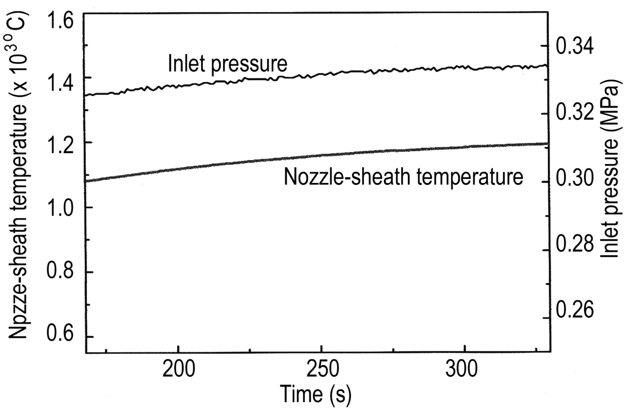

Fig.5 Measured nozzle-sheath temperature and pressure in the convergent section change with the firing time

3 Effect of the nozzle temperature on thruster performance

Fig. 4 shows the measured time-dependent thrust, the calculated thrust efficiency and specific impulse according to the measured thrust and input parameters of the power and propellant flow-rate. The thrust decreased continuously from 174 mN to 164 mN for the time of 168 s to 330 s, under all unchanged input conditions in the same time period as shown in Fig. 3. The corresponding temperatures of the nozzle sheath varied from 1080 K to 1193 K as shown in Fig. 5. The measured changes in these parameters, though not very large, are clearly beyond experimental errors and the trend of decrease in thrust efficiency with an increase in nozzle sheath temperature is quite definite, further confirming the preliminary data given in Ref [13]. The change in the parameters all occurred at a slow rate, so the measured quantities can be considered to be under quasi-steady conditions.

4 Discussion

It was noticed that the nozzle sheath temperature and pressure in the convergent section increased with time, as shown in Fig. 5. With a constant mass flow rate, an increase of the pressure in the convergent section suggests an increased gas temperature fed into the cavity due to the regenerative heating of the propellant when it passes through the hot nozzle wall before reaching the cavity. The increase in both gas pressure and temperature in the convergent section during the test period should have caused the thrust to increase. However, this effect was evidently overshadowed by other losses of the process which are discussed below.

The temperature increase of the whole nozzle wall, especially on the expanding section, promotes a diffusive type of attachment extending the arc root to further downstream [10]. This possible phenomenon, although causing little effect on the arc voltage and therefore the input electric power, could adversely affect the conversion of electric power expended in the arc through the enthalpy of arc-heated high-temperature gas into kinetic energy for producing thrust by expansion in the nozzle [13]. When heat is added during the lower temperature part of the expanding process, the conversion to kinetic energy would be less efficient, in accordance with the laws of thermodynamics. The heat added to the gas in the expanding section of the nozzle would largely go into raising the temperature of the exhaust gas but not into kinetic energy, which constitutes an important loss item of the arcjet. Experimental results in Ref. [13] also indicate that the temperature rise in the anode nozzle has an unfavorable effect on the thrust of the arcjet thruster with a normal anode-nozzle without regenerative cooling. It is worth to mention that the thrust producing process in arcjet is quite different from that in a conventional chemical rocket in which the combustion process is completed in the combustion chamber before the nozzle throat.

Fig. 6 shows the time-dependent radiation loss calculated according to the measured temperature and its distribution, surface area of the nozzle-sheath and its emission coefficient. The radiation loss increases from 8.7% to 12.4% of the input power for the time of 168 s to 330 s, i.e., with the increase in nozzle temperature from 1080 K to 1193 K. This is quite significant in the total energy balance.

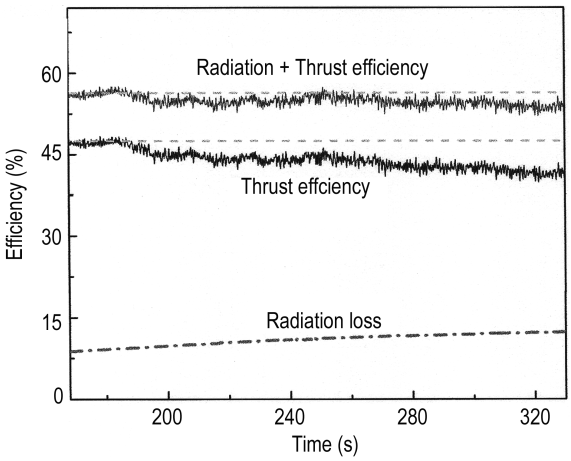

Fig.6 Calculated time-dependent radiation loss, thrust efficiency and the sum of these two data

The part of input energy going into the useful kinetic energy and the radiation loss, indicated by the sum of the thrust efficiency and radiation loss, changes from 56.2% to 54.0% of the input energy during the time period. Heat conduction loss, i.e., the loss by heat conduction to other parts, is generally much lower than the radiation loss and its change with the nozzle temperature is hence thought to be quite negligible. Assuming that the inlet gas to the convergent section is heated to the same temperature as the nozzle sheath while it cools the nozzle, the gas enthalpy of $H_2:N_2=2.8:1.5$ of a total flow flux of 4.3 slm is about 75 W and 86 W at 1080 K and 1193 K, respectively [14,15]. The change in the gas enthalpy is about 1.3% of the input power of 860 W. Only a small portion of this increased enthalpy could be converted into useful kinetic energy. Accordingly, considering the above factors, there could be increased exhaust losses, including thermal and frozen losses.

The luminosity situation of the exhausted plasma plume and the nozzle sheath surface near the nozzle exit are shown in Fig. 7. The circles in the figure are added to indicate the temperature measurement area where the infrared pyrometer was focused. It can be seen that not only the luminous intensity of the nozzle sheath but also that of the jet plume increases with

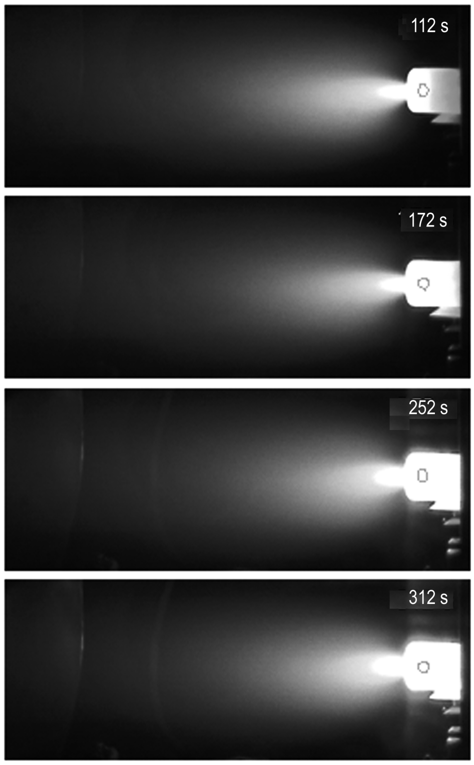

Fig.7 Pictures of the nozzle sheath and plasma plume taken at different times in the thruster firing: 112 s, 172 s, 252 s and 312 s

time. This suggests that the enthalpy of the exhausted gas increased with the increase in temperatures of the nozzle wall, and hence exhaust losses increased.

Based on the above analysis and experimental results, one can conclude that, although the nozzle temperature has a contradictory effect on the arcjet thrust, adverse effects dominate under the conditions studied.

5 Conclusions

Under the fixed input power and propellant feeding conditions, experimental results show that the thrust produced in firing the arcjet thruster decreased with the increase in nozzle temperature. The energy conversion process in the thruster is affected in a complicated manner involving many factors. The radiation loss and the exhaust loss of propellant gas energy could all increase to different degrees with the increase in nozzle temperature, resulting in a reduced output performance of thrust, efficiency and specific impulse.

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