Effects of Anode Temperature on Working Characteristics and Performance of a Low Power Arcjet Thruster *

PAN Wen-Xia(潘文霞)**, LI Teng(李腾), WU Cheng-Kang(吴承康)
Institute of Mechanics, Chinese Academy of Sciences, Beijing 100190

(Received 21 August 2009)

An arc-heated thruster of 130–800 W input power is tested in a vacuum chamber at pressures lower than 20 Pa with argon or H_2–N_2 gas mixture as propellant. The time-dependent arc voltage-current curve, outside-surface temperature of the anode nozzle and the produced thrust of the firing arcjet thruster are measured in situ simultaneously, in order to analyze and evaluate the dependence of thruster working characteristics and output properties, such as specific impulse and thrust efficiency, on nozzle temperature.

PACS: 52. 75. Di, 52. 80. Mg, 52. 50. Nr

Electric propulsion with high specific impulse is playing an increasingly important role in satellite applications, due to the fact that it can achieve less consumption of propellant or more payload under a given loading constraint of satellites. Having a simple acceleration principle of heating up the propellant by an arc discharge and converting the enthalpy into kinetic energy through nozzle expansion, the dc arc-heated jet (arcjet) thruster is characterized by system simplicity and compactness, high ratio of produced thrust to input power and low development cost. It has been used as the most practical technology for north-south station-keeping of communication satellites for over ten yeas.[1] Main technical problems have been solved for its practical applications. However, many complicated working mechanisms affecting its performance enhancement and development are still not quite clear. Research efforts on arcjet thruster performance and physics have been continuing for developing various special applications with different power levels, propellants and working situations.[2−5] Relatively high thrust and low specific impulse can be obtained by using the propellant of high density such as argon, but the low-density propellants, such as hydrogen, are better for producing high specific impulse. Most of the practically used arcjet thrusters take hydrazine (N_2H_4) as its propellant for sharing the storage tank with ordinary rockets of chemical combustion propulsion. Different propellants could cause changed working characteristics including arc voltage-current feature and energy conversion process in the anode nozzle, by which performance of an arcjet thruster will be affected. In the present work, arc voltage-current characteristics, nozzle temperature and produced thrust are detected and analyzed for an arcjet thruster with argon or hydrogen/nitrogen mixture as propellant, to evaluate the dependence of thruster working characteristics and performance on nozzle temperature.

A 1 kW-class arcjet thruster was set in a vacuum chamber of 0.8 m diameter and 1.2 m length. The pumping system is capable of keeping the chamber pressure at lower than 15 Pa while a propellant of 4 slm is fed. Pure argon or a gas mixture of H_2–N_2 was used as the propellant. When H_2–N_2 was used as the propellant, about 1 slm N_2 was fed at the ignition stage for easy starting, and then the gas flow rate was increased to a total of 4.3 slm with H_2:N_2=2.8:1.5 within 20 s. As shown in Fig. 1, the arcjet thruster was fixed on a force measurement stand to detect the time-dependent thrust in situ.[6] Signals from the force sensor and current and voltage sensors were received and sampled by a data acquisition and processing system. The temperature of the nozzle outside wall was detected with an infrared pyrometer of working range 600°C to 2000°C, while the emission coefficient of the nozzle surface was estimated to be 0.31.

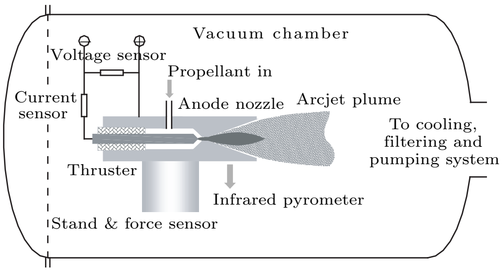

Fig. 1. Schematic drawing of the experimental setup.

Figure 2 shows the volt-ampere $V-A$ curve in firing arcjet thruster with Ar at 2.1 slm as the propellant. The arc voltage decreases with increasing arc current in the whole course after ignition, but shows relative high decreasing slope at the beginning stage of firing. The nozzle heats up slowly during this period. After about 200 s, the variation of arc voltage with the arc current tends to be stabilized at a lower changing slope with relatively low voltage value. The

*Supported by the National Natural Science Foundation of China under Grant Nos 10775164, 50836007 and 10621202.
**Email: wxpan@imech.ac.cn

change of the arc voltage during the whole course is only several volts while the maximum arc voltage is less than 30 V. This is similar to the general situation in generating a non-transferred dc plasma using argon as the working gas under free-arc conditions, having a descending $V-A$ curve with low arc voltage.

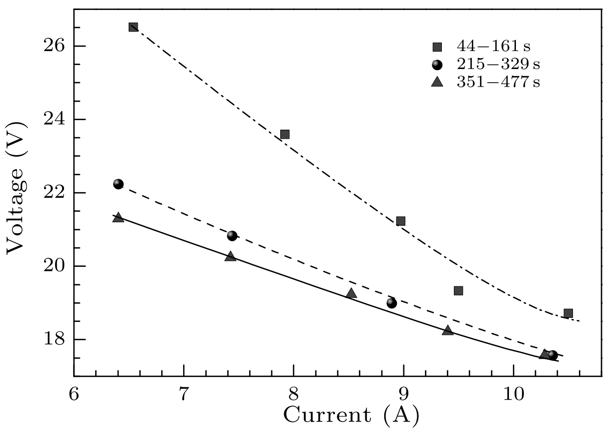

Fig. 2. $V-A$ curve during firing of thruster with Ar at 2.1 slm.

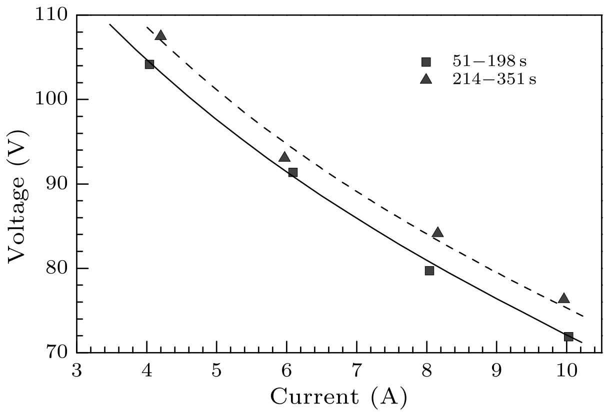

Fig. 3. $V-A$ curve during firing of thruster with $H_2 : N_2 = 2.8 : 1.5$ at 4.3 slm.

When H_2–N_2 gas mixture was used as the propellant, the arc voltage changes from about 104 V to 72 V as the arc current changes from 4 A to 10 A, as shown in Fig. 3. Its arc voltage and variation range are much higher than the case with Ar as the propellant in almost the same range of arc current, though they all have a descending volt-ampere characteristics. Besides the voltage drop at boundary layer on the electrode surface, arc voltage is generally related to the column length and intensity of electric field $E = j/\sigma$, where j is the density of arc current and σ is electric conductivity. The higher voltage of H_2–N_2 arc could be due to the lower electric conductivity and smaller cross section. On the other hand, different from the case of Ar thruster, the arc voltage increased somewhat as the firing time increases but with an almost unchanged $V-A$ curve slope when H_2–N_2 gas mixture was used as the propellant.

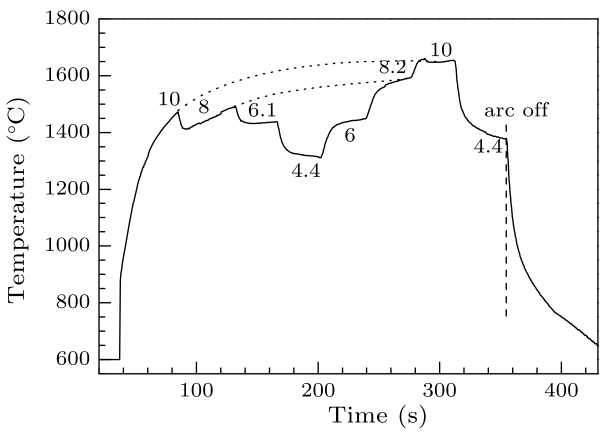

Fig. 4. Nozzle temperature variation with H_2–N_2 as propellant. Numbers in the graph show the arc current in ampere.

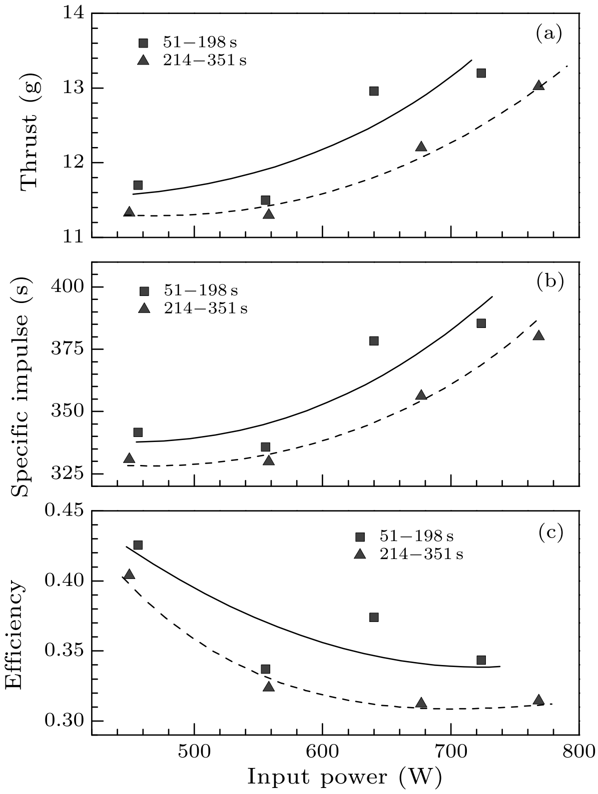

Fig. 5. Thrust (a), specific impulse (b) and thrust efficiency (c) change with the input power at different levels of nozzle temperature.

The increase of the nozzle temperature shown in Fig. 4 could be an important reason causing the arc voltage increase in H_2–N_2 thruster. Generally, argon arc shows diffused attachment on the anode surface, even with the water-cooled anode when the arc is generated at pressures lower than 3×10^4 Pa.[7,8] A very low percentage addition of hydrogen or nitrogen to argon could cause constricted attachment of the arc root at a water-cooled anode surface.[7] However, arc root attachment on the anode surface in H_2–N_2 gas mixture thruster changes from the constricted state at the ignition stage to diffused attachment when the anode is heated to a high temperature.[9] In the ignition stage of the arc, the anode nozzle is cold, but its temperature rises quickly with firing time at the beginning and then tends to level off gradually as indicated in Fig. 4. The dashed lines are added to indicate the trend of temperature variation if the arc current were kept the same. It has been confirmed that nozzle temperature dominates the arc root attachment mode in the H_2–N_2 arcjet thruster, and higher nozzle temperature promotes the diffused type of attachment and extension of the arc root to further downstream attachment.[9] Hence, the increase of arc voltage for H_2–N_2 thruster as shown in Fig. 3 with increasing time and nozzle-temperature could be caused by the increase of arc column length. In the situation of the Ar arc, total electric conductance is much higher than the case in H_2–N_2 arc and the length change of arc column contributes insignificantly to the arc voltage change. The voltage in Ar arc mainly consists of the voltage drops at the boundary layer near the electrode walls of anode and cathode. With the increase of electrode temperature, the voltage drop at the boundary layer would decrease, causing the result in Fig. 2, i.e., the arc voltage decreases with increasing time and nozzle-temperature.

Figure 5 shows the measured thrust, specific impulse and thrust efficiency with H_2–N_2 propellant under the same conditions as in Figs. 3 and 4. The thrust and specific impulse increase and the efficiency decreases with increasing input power, agreeing with previous work.[10] It can also be seen that the rising temperature of the anode nozzle at the later stage firing from 214 s to 350 s could have an unfavorable effect on the produced thrust. That is, high nozzle temperature could somehow 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. Thus, the specific impulse is also reduced under high nozzle temperature condition at the later stage of firing from 214 s to 351 s as shown in Fig. 5(b). The thrust efficiency also decreased at the later stage of firing as show in Fig. 5(c) in the same manner as for thrust and specific impulse. The efficiency decrease with increasing power input could be partly due to the increased radiation loss from the higher temperature nozzle at increased power level.

In summary, Ar and H_2–N_2 arc show appreciably different $V - A$ characteristics. Those of Ar arc show a decrease in voltage and tend to be stabilized with a low slope at relatively low voltages as the nozzle heats up. For the H_2–N_2 arc, voltages are much higher, and showing higher values for higher nozzle temperatures. The temperature rising of the anode nozzle could have an unfavorable effect on the thrust, specific impulse and thrust efficiency of the arcjet thruster.

References

[1] Wilson F C 2006 *AIAA Int. Comm. Satellite Systems Conf. and Ex.* (San Diego 12–14 June 2006) AIAA-2006-5307

[2] Toki K, Kuninaka H, Shimizu Y and Kuriki K 2002 *Acta Astronautica* **50** 285

[3] Slough J and Ewing J J 2007 *43rd AIAA/ASME/SAE/ASEE Joint Propulsion Conf. and Ex.* (Cincinnati, July 8-11) AIAA 2007-5181

[4] Fife J M, Bromaghim D R, Chart D A, Hoskins W A, Vaughan C E and Johnson L K 2002 *J. Propulsion and Power* **18** 749

[5] Walker Q E, Gascon N, Cappelli M A, Hargus W A Jr and Schiling J A 2004 *J. Spacecraft and Rockets* **41** 1023

[6] Li T, Pan W X, Lin L, Wu C K 2008 *J. Astronautic Metrology and Measurement* **28** 17 (in Chinese)

[7] Pan W X, Meng X, Li T, Chen X and Wu C K 2007 *Plasma Sci. and Tech.* **9** 152

[8] Pan W X, Li T, Meng X, Chen X and Wu C K 2005 *Chin. Phys. Lett.* **22** 2085

[9] Huang H, Pan W X, Meng X, Wu C K 2009 *17th Int. Symp. Plasma Chem.* (Bochum 26–31 July 2009) 459

[10] Kurtz H L, Zube D M, Glocker B, Auweter-Kurtz M 1992 *28rd AIAA/ASME/SAE/ASEE Joint Propulsion Conf. and Ex.* (Nashville 6–8 July 1992) AIAA 92-3116