Development of arc root attachment in the nozzle of 1 kW N₂ and H₂-N₂ arcjet thrusters

H. Huang, W.X. Pan, X. Meng, C.K. Wu
Institute of Mechanics, Chinese Academy of Sciences, 100190, Beijing, China

Abstract: Arc root behavior affects the energy transfer and nozzle erosion in an arcjet thruster. To investigate the development of arc root attachment in 1 kW class N₂ and H₂-N₂ arcjet thrusters from the time of ignition to the stably working condition, a kinetic series of end-on view images of the nozzle obtained by a high-speed video camera was analyzed. The addition of hydrogen leads to higher arc voltage levels and the determining factor for the mode of arc root attachment was found to be the nozzle temperature. At lower nozzle temperatures, constricted type attachment with unstable motions of the arc root was observed, while a fully diffused and stable arc root was observed at elevated nozzle temperatures.

Keywords: arcjet thruster, arc root behavior, dynamic observation.

1. Introduction

Having a higher specific impulse compared to chemical propulsion thrusters but lower thrust levels, arcjet thruster finds its application in near term auxiliary propulsion missions such as north-south stationkeeping for geosynchronous communication satellites [1]. Being recognized as a lightweight, reliable propulsion maneuvering system, arcjet thruster has sparked a research interest in improving its performance, in particular, the thermal efficiency and the thruster lifetime. These features are controlled by the characteristics of the arc discharge behavior and the arc-electrodes interactions to a large extent. The anode in an arcjet thruster is generally in a de Laval nozzle shape, which has a converging section, a throat and a conical expansion cavity. As a key component, the anode/nozzle is where the conversion of thermal energy into directed kinetic energy occurs. Propellant such as hydrazine, hydrogen, ammonia etc. is accelerated in the nozzle to generate the desired thrust. Arc root behavior, namely, the arc root attachment positions (upstream or downstream), types (constricted or diffuse) and motions (steady or moving) is a key factor affecting the process. Previous research [2] shows that the anodic arc attachment in an arcjet thruster can either be diffuse or constricted, which remarkably affects the anode heat flux. If the constricted type arc root stays steadily on the anode surface, severe erosion may occur. On the other hand, the type and the position of the arc root attachment also affects the energy conversion process and thus the thruster efficiency [3]. A better knowledge of these phenomena is required to optimize the thruster performance.

Experimental study of the dynamic arc root attachment in the nozzle of an arcjet thruster is often difficult due to the fact that the size of the electrodes are usually very small and the electrode surfaces are seemingly inaccessible. Using specially designed anode/nozzle, the arc root behavior under steady working condition was studied[4, 5]. However, the dynamic development of the arc root attachment from the time of ignition to the stably working condition is of great interest, as failure analysis show that most electrode erosion occur in the arcjet ignition process[6]. And it is also important to study the arc root behavior without changing the nozzle structure. In this paper, an attempt has been made with an optical access to study the development of the arc root attachment types, motions and positions in the nozzle of 1 kW class N₂ and H₂-N₂ arcjet thrusters.

2. Experimental details

Based on previous experimental scheme in studying arc root behavior in a specially designed non-transferred dc plasma torch operated at reduced pressure [7], continuous monitoring of the images inside the thruster nozzle was done by a high-speed-video camera (HSVC). Fig. 1 shows the schematic illustration of the experimental setup. The 1 kW class arcjet thruster was positioned in a Φ2 m × 4 m vacuum chamber. The nozzle of the arcjet
thruster was regeneratively cooled with a throat diameter of 0.7 mm and an exit diameter of 12 mm. The nozzle temperature was measured by two infrared pyrometers with a combined measuring range of 200 – 2000 °C. A 45° tilted copper mirror was used to reflect the end-on view of the nozzle to the outer HSVC. The HSVC (16 μm/pixel, 512 × 512 pixel areal) was coupled to a telephoto lens with focal length of 200 mm. In order to better distinguish the ionized region from thermal emission and cathode emission, a 460 nm, 10 nm bandwidth interference filter was mounted before the telephoto lens to obtain the nitrogen ion lines, such that the images obtained can reveal the distribution of nitrogen ions. The obtained kinetic series of images were then analysed by the software of ImageJ (National Institute of Health, USA). Pure nitrogen or nitrogen-hydrogen mixture with volume ration of 1:2 was fed into the arcjet as the propellant. The total mass flow rate was 31 - 35 mg/s and the input power ranged from 300 – 900 W.

End-on view of the nozzle shows concentric circles which represent the edges of the nozzle and the throat, as being illustrated in Fig. 2 (a). The surface of the expansion cavity is between circle 1 and 2. The converging section is not visible in the end-on view image (A-A view in Fig. 2 (a)). With an auxiliary halide lamp, such end-on view image of the nozzle before arcjet ignition was taken. In this case, the interference filter was not applied. The outer circle is the edge of the nozzle exit and the central dark spot represents the throat.

![Fig.2 End-on view of the nozzle. (a) Illustration and (b) photo taken before ignition with an auxiliary halide lamp.](image)

3. Results and Discussion

The behavior of the arcjet thruster largely depends on the type of the propellant injected. Arc voltage is much lower when pure nitrogen is used as the only propellant compared with that when nitrogen-hydrogen mixture is used.

Fig. 3 shows the IV curve of the arcjet thruster. Similar dependence of the arc voltage on the arc current is seen. However, at the same current level, the arc voltage almost doubles when hydrogen is added. This indicates that the input power doubles at the same arc current, which accordingly leads to a steeper nozzle temperature increase, as shown in Fig. 4. In Fig. 4, the temperature below 200 °C is fitted from the measured data. It is shown that with the addition of hydrogen, the nozzle temperature increases much faster, and the final nozzle temperature is 1500 °C, about 600 °C higher than that when pure nitrogen is used as the propellant. In this case, the arc current is 8 A, and the input power is 770 and 340 W respectively.

![Fig.3 IV curve of the arcjet thruster.](image)

![Fig.4 Change of nozzle temperature with time.](image)

At the ignition stage, asymmetric and constricted type arc root attachment is seen. The attachment point moves randomly on the nozzle surface. Most of the time, it moves in the region upstream of the throat and cannot be seen. Fig. 5 A1 – B10 show 20 continuous images taken at the ignition stage, from which an unstable arc root attachment can be confirmed.

As the nozzle temperature increases, the anodic arc root moves out to the expansion cavity and a symmetric, diffused type attachment is observed. At this time, the arc
root is stable, and no obvious fluctuation in continuous images can be seen (Fig. 5 C1 – F10).

Fig. 5 Kinetic series of images taken at different operating stage of the arcjet thruster. A1 – B10: during the ignition; C1 – D10: 10 s after ignition; E1 – F10: 80 s after the ignition. The propellant is pure N2 and no interference filter applied. HSVC speed is 3000 fps with exposure time of 80 μs.

However, without an appropriate filter, the HSVC images show compositive information including luminous plasma plume, cathode emission, thermal emission of the nozzle etc. It is assumed that ionization of the propellant is severe at the arc root region, thus a 460 nm interference filter was chosen to better describe the arc root region with minimum perturbation from thermal emission. It was confirmed that using such a 460 nm interference filter, the detected signal mainly contains the nitrogen ion emission lines.

Fig. 6 Nitrogen ion distributions in the nozzle with or without hydrogen addition. (a) images taken at stably working condition and (b) radial line profiles of the detected intensity.

Previous research [8] of the arc root behavior in a water-cooled dc plasma torch showed that the addition of hydrogen or nitrogen in small volume of several percent changed the arc root from diffused to constricted in argon plasma. However, for the arcjet thruster with hot anode, diffused type arc root attachment was observed for the H2-N2 plasma. Fig. 6 (a) shows the result. At stably working condition, the addition of hydrogen promotes the diffused type arc root attachment. Larger area of arc root attachment is seen, which also corresponds to the higher arc voltage when hydrogen is added. Radial line profiles across the center of the nozzle are shown in Fig. 6 (b). With pure nitrogen as the propellant, the anodic arc root attaches near to the throat exit with an attachment diameter of about 1.0 mm. With the addition of hydrogen, much wider attachment is seen clearly with the diameter of about 2.2 mm. Taking in the throat diameter of 0.7 mm and the divergence angle of 15º, such an increase of the attachment diameter leads to a downstream attachment spot of 1.2 mm.

These results suggest the determining factor of the arc attachment mode is the nozzle temperature. Higher nozzle temperature promotes diffused type attachment.

By changing the arc voltage and then compare the arc root attachment area at similar nozzle temperatures, the relationship between the arc length and the arc voltage can be established. At similar temperatures, the electric conductivity of the plasma does not change much, thus extension of the arc root to downstream attachments are observed at higher arc voltages. On the other hand, when the arc voltage keeps constant, higher temperature leads to higher electric conductivity of the plasma and the arc root attachment spot also moves downstream. Fig. 7 depicts the dependence of the arc root attachment area on the nozzle temperature and the arc voltage. The size of the spot represents the relative arc root attachment area. The smallest one has a diameter of 1.3 mm and the largest one has a diameter of 3.8 mm, which corresponds to an axial distance of 1.12 mm and 5.78 mm off the throat exit respectively.

Fig. 7 Dependence of the arc root attachment area on nozzle temperature and arc voltage. The size of the spot represents the relative arc root attachment area whose diameter is marked besides the spot (mm).

4. Conclusion

In-situ dynamic development of the arc root behavior in 1 kW class N2 and H2-N2 arcjet thrusters with regeneratively-cooled nozzles were monitored and analyzed. The
addition of hydrogen leads to higher arc voltage levels with the same arc current. The arc root attachment area is larger which makes it possible to achieve relative lower arc current density. Nozzle temperature also plays an important role in affecting the arc root attachment mode. Higher nozzle temperature promotes diffused type attachment while constricted type attachment occurs at lower nozzle temperatures.

In an arcjet thruster, high current density over 10^8 A/m^2 in a constricted arc root attachment may lead to severe anode erosion and affect the long-term performance of the thruster. Above results hint that through the optimization of plasma generation parameters the nozzle structure, it is possible to achieve diffused type arc root attachment with relatively high arc voltage and low current density. Such combination may improve the stability of the arcjet thruster and promote its lifetime.

5. Acknowledgement

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References

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