Effect of Structure Characteristics on Start-up Process of an Arcjet Thruster

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Abstract: Arcjet thruster is character with simple structure, moderate electric power, high control precision, and good compatibility with hydrazine monopropellant propulsion system or hydrazine-MON bipropellant propulsion system. It has been widely used in GEO satellite since its first in-space flight in1993. Recently, with the rapidly growth of LEO satellite on which hydrazine is usually adopted propellant, arcjet thruster has a very good application prospect.

Two operation modes exist in an arcjet thruster, named low voltage mode and high voltage mode, which correspond to the two positions of two arc root attachment on anode surface. The arcjet thruster is designed to operate in high voltage mode normally, when the arc root attach to the expansion section or low-pressure region of the anode. In the high voltage mode, the arcjet is operated with the character of low heat flux, stable working and low material ablation rate. Comparatively, in the low voltage mode, the arc root attach to the contraction section or the throat channel of anode, where the local pressure is typically around several bar, and the arc attachment point is character with a contraction form. In the low voltage mode, the arcjet is operated with the character of high heat flux density at arc root attachment point and high material ablation rate. Therefore, the low voltage mode is quite negative for the performance and life of the arc thruster.

To avoid the occurrence of low-voltage mode, arc stability can be improved by optimizing the characteristic parameters of thruster and adopting rotation inlet flow, which functions quite good for prevent low-voltage mode from accidental disturbance during operation process. However, the low voltage mode is inevitable during the start-up process of arcjet thruster. Arc discharge always initially happens through the channel with the minimum discharge potential, which is at the contraction section or entrance of the anode throat channel, and then the anode attachment point moves to the low-pressure region of the expansion section driven by the propellant gas flow and the high voltage operation mode is established. Therefore, the mode conversion process is essentially arc root attachment point movement on the anode surface. This is the process that arcjet thruster will experience every start, and it is also one of the most important life constraints. Therefore, the mode conversion duration in

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start-up process is one of the key problems should be considered for arcjet thruster optimization and verification.

In this paper, arc root attachment point movement on the anode surface is correlated with the arc voltage signal during start-up process. Several gas feeding parameters and anode structure characters are introduced and tested to analysis discharge and mode conversion process with arc voltage signal. And suggests of design optimization for reduce the mode conversion duration is provided.

Nomenclature

Φ_t = Anode throat diameter
Φ_s = Swirl aperture cylinder diameter
L_t = Anode throat length

I.Introduction

Thermal arc-heated thruster, or arcjet thruster, heats the propellant with an arc connected between the anode and cathode crossover a narrow channel. As the temperature of arc column is much higher than the typical combustion temperature of chemical propellant, the specific impulse is usually two or three times higher than a chemical thruster. Since the 1960s, a lot of research work on arcjet thruster has been carried out. And since the first in-space application of arcjet thruster on AT&T Telstar-4 satellite in 1993[1], more and more satellites adopt arcjet thruster for its NSSK and EWSK application for its high performance, high reliability and good compatibility with chemical propulsion system, especially the MR-508/509/510 arcjet thruster family on A2100 satellite platform[2].

In the process of arcjet thruster development program, life verification is the most important and expensive task. The most success arcjet system, MR508/509 and MR510 families, have carried out many life verification programs in the development process, the longest time of which is more than 1700 hours[3, 4, 5]. In each subsequent technical state change, it is necessary to carry out a very long life-verification test.

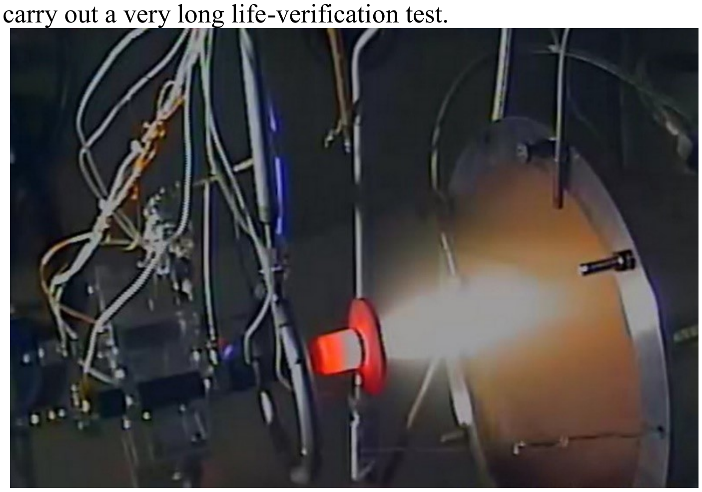

Fig.1 Engineering prototype of 2kW Arcjet thruster under test

In previous work, an engineering model of arcjet thruster with hydrazine propellant has been successfully developed, and a life verification program of over 800 hours has completed in Beijing Institute of Control Engineering in 2016[6]. Currently, some optimization for the thruster is undertaking to fulfill the flight constrains. However, for all optimization program, life verification mentioned above is inevitable and very expensive, in terms of both money and time. And, the effect of modification on life time could be confirmed only in the later stage of the experiment, as ablation of electrodes is a long process and is difficult to quantification. In the previous works, a certain period of firing test typically tens or hundreds of hours must be performed, and after that the ablation could be quantified either by weighing the electrode to get the mass loss, or by the variation of the arc chamber pressure under the same operating condition. In either way, a long ignition test must be executed to produce considerable ablation of the electrodes in order to provide a proper quantified judgment. Although this method is effective, it is undoubtedly very expensive. Therefore, a cheaper and more convenient method to verify the effect of design modification on life time for arcjet thrusters is tried in this paper.

We already know that there are two modes exist in the arcjet thruster operation process, which is so called high voltage mode and low voltage mode. While under low voltage operation mode, the arc is attached to the contraction section of the anode, where the gas flow is in low-speed and high-pressure region, and the arc root is concentrated at the anode attachment point, corresponding to extremely high heat flux density and rapid ablation rate. Therefore, all arcjet thrusters are designed to operate in high voltage mode during their steady-state operation process [7, 8, 9]. However at the igniting moment, the arc root always attaches to the contraction section of anode, and the arcjet thruster always operate in the low-voltage, high-ablation mode[10, 11], the transition duration from low-voltage mode to high-voltage mode during the start-up process has a decisive impact on the life time of an arcjet thruster [12, 13]. Through adjusting of characteristic parameters related to the aerodynamic process, this paper correlated several possible design modifications with the mode transfer duration, so as to provide a proper suggestion a quick verification for the design optimization program.

II. Experimental Setup

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The experiment was carried out in the vacuum system of Tsinghua University, shown as Fig.2. The vacuum chamber is 1.2m in diameter and 1.5m in length. It is equipped with mechanical pump, Roots pump and thermal diffusion pump vacuum system. The pressure is sustained below 1Pa for the operation flow rate, which is acceptable for arcjet thruster.

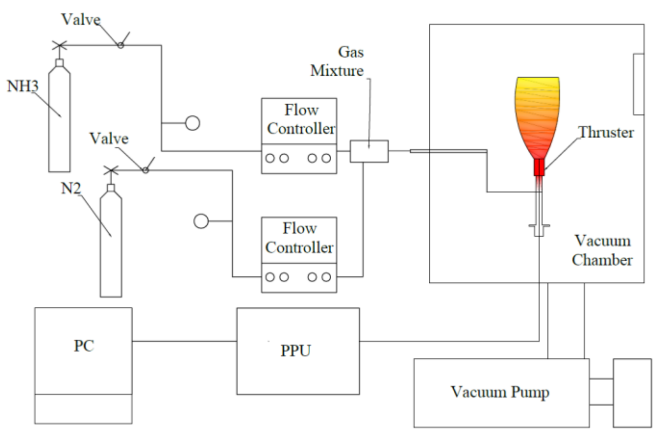

Fig.2 Experiment system layout

In the experiment, mixture of ammonia and nitrogen was used to simulate the catalytic decomposition products of hydrazine in a ratio of 4:1, which was a common method in previous studies. An engineering prototype of PPU is applied in the experiment. Its peak output voltage for ignition is about 6000V, and current regulated output mode is adopted for its main circuit, whose no-load output voltage is about 250V.

An engineering prototype thruster is employed in the experiment is, on which an easily disassembled anode is installed, so that the characteristic parameters related to the flow process, including the diameter of the swirl aperture Φ_s and the length of the anode throat L_t, can be easily adjusted. The rest of the thruster is consistent with the flight product.

III.Results and discussion

A. Typical breakdown curves and characteristics

The typical starting process of the arcjet thruster is shown in Fig.3, and the arc root transfer process in arcjet thruster is clearly revealed, where the arcjet thruster is broken down with a high-voltage pulse, which instantaneously drops from a high-voltage peak of several thousand volts to tens of volts. At this moment, the attachment point of the arc root on the anode locates at the contraction section of the anode. And caused by aerodynamic force, the arc root moves to downstream of the anode throat, or the expansion section, and the voltage rises to above 100 V, which will happen in a time interval ΔT from tens of milliseconds to several seconds, depending on thruster configuration and operate parameter, and which is correlated in the next section.

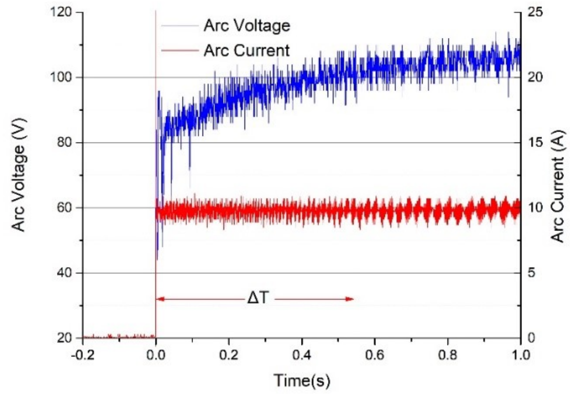

Fig.3 Typical arcjet thruster starting process obtained in the experiment

In addition, it should be noted that the arc voltage curves do not always increase monotonously as shown in Fig.3, but possibly accompanied by irregular oscillation in some cases, as shown in Fig.4, which means that the movement of the arc root on the anode surface during the start-up process is not a monotonous downstream process, but accompanied by the random jump includes upstream direction in the contraction section or throat channel, that is, the process of internal re-breakdown. The mechanism of occurrence is related to the state of electrode surface and pressure equilibrium establishment process for a thruster from cold gas flow to thermal arc flow during start-up.

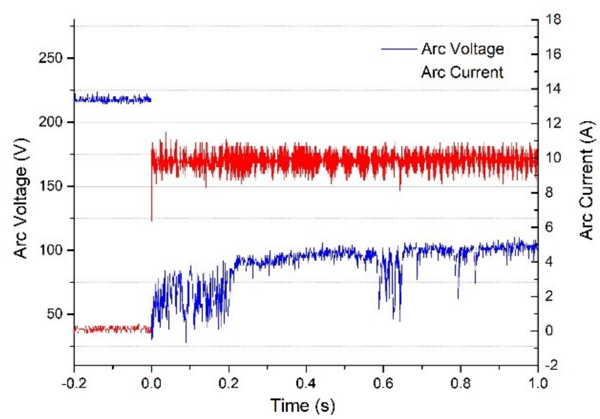

Fig.4 arc voltage with irregular oscillation during starting process

In the initial series of experiments, irregular arc voltage oscillation during the arc start-up process as shown in Fig.4 happens under a large number of operating conditions, which is quite different from the results obtained from a real arcjet thruster. We believe that this phenomenon is due to the much longer duration initial pressure equilibrium establishment process in the simulation experiment. To correct this problem, a throttle orifice of about Φ0.4mm is installed at the inlet connecter of the thruster to increase the pressure of the gas pipeline and suppresses the irregular arc voltage oscillations, which is closer to the actual operation and functions quite good in the following experiments. In the following discussions, all results are obtained with the throttle orifice if not be specified.

B. Characteristic transfer time under different structures

Since the transfer duration of the arc root in the start-up process is mainly related to the aerodynamic process, it is natural that it will be related to the gas feeding parameter and the character structure of the anode. In this section, flow rate, swirl aperture and throat length are introduced as the experimental variables. For convenience of comparison, a thruster with throat diameter Φ_t of 0.8 mm, throat length L_t of 1.16 mm, swirl aperture Φ_s of 0.5 mm is selected as the benchmark. And in all the experimental results, we labeled a symbol red "◎" for the case with irregular arc voltage oscillation happens.

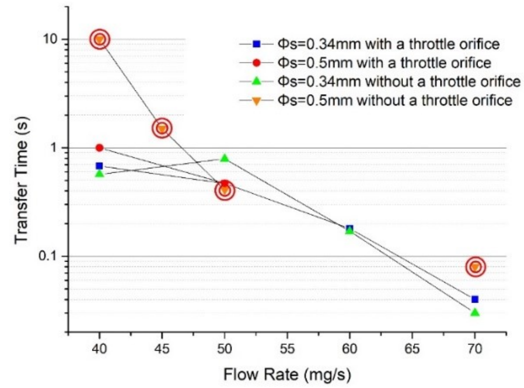

Fig.5 Arc root transfer time correlated with swirl aperture

The first factor is obviously the gas flow rate, so for all the structural dimensions mentioned below, experiments is performed in the range of 40 mg to 70 mg with the interval of 10mg.Typical result is shown in Fig.5~6, from which we can find that the arc root transfer duration decreases rapidly with the increase of flow rate, while the voltage oscillation in start-up process is more likely to occur at low flow rate. This is obvious and easy to understand: a longer arc root transfer duration at low flow rate should subject to insufficient aerodynamic force for arc root motion, whereas higher flow rate will lead to a higher re-breakdown energy potential, which leads to better arc stability.

The next characteristic considered is the swirl aperture. The experimental results of a same thruster with a swirl aperture Φ_s =0.34mm and a Φ_s =0.5mm swirl aperture installed, respectively, is shown in Fig.5. From which we can find that the variant of swirl aperture dimension has poor influence on the arc root transfer duration, whereas smaller aperture seems to be helpful to restrain the voltage oscillation. This phenomenon should be attribute to the higher inlet pressure and swirl intensity achieved with the smaller swirl aperture.

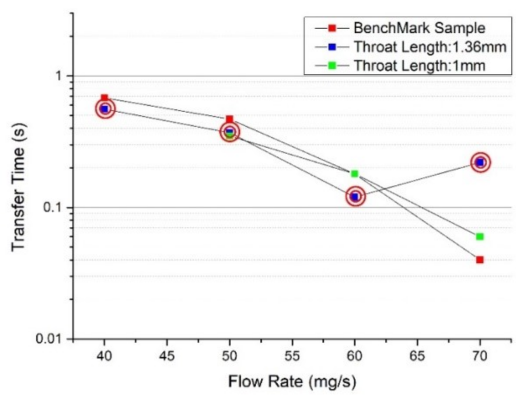

Fig.6 Arc root transfer time correlated with Length of throat channel

The following characteristic considered is throat length L_t of the anode, and a sample with L_t =1.36 mm is compared with the benchmark product, shown as Fig.6. Logically, longer throat channel means longer arc root transfer distance, which should prolong the arc root transfer duration. While on the other hand, higher arc voltage is expected to achieve better efficiency and steady-state ablation rate of electrodes for the steadily firing process for the relatively lower arc current at the same input power, which could be achieved by increasing length of the throat channel L_t. Therefore, if the arc root transfer duration is not affected obviously, the throat length should be increased as long as possible.

Whereas from Fig.6, we find that although the arc root transfer duration is not significantly increased with the increase of throat length, but the initial voltage oscillation is increasing, which is obviously not positive influence to the stability of the thruster. The increasing initial voltage oscillation can be attributed to higher arc voltages caused by prolonged channel will be benefit for arc restrike phenomenon.

IV. Conclusion

During the start-up process of arcjet thruster, transition duration from low-voltage mode to high-voltage mode has an important impact on anode ablation rate, and thereafter the thruster lifetime. Through the comparison with the benchmark protype thruster with a throat diameter of 0.8mm, throat length of 1.16mm and swirl aperture of 0.5mm, some modifications are tried and tested, includes smaller aperture to increase swirl intensity, longer throat channel to increase arc voltage, no remarkable correlation is established, and a longer throat channel tend to have a negative impact on arcjet thruster operation stability, although a relatively lower arc current could be achieved with this configure.

Acknowledgements

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