JOURNAL OF PROPULSION AND POWER
Vol. 27, No. 1, January–February 2011

Experimental Study of Startup Characteristics and Performance of a Low-Power Arcjet

Hai-bin Tang,* Xin-ai Zhang,† Yu Liu,‡ Hai-xing Wang,* and Chen-bo Shi§
Beijing University of Aeronautics and Astronautics, 100191 Beijing, People's Republic of China
and
Bin Cai¶
Beijing University of Technology, 100124 Beijing, People's Republic of China

DOI: 10.2514/1.47380

A radiation-cooled low-power arcjet thruster is tested in order to study the startup characteristics and performance with nitrogen and ammonia mixtures as the propellant in a vacuum with chamber pressures lower than 5 Pa. In the ignition tests, two different starter circuits, i.e., high-frequency and high-voltage pulse ignition techniques, are used to initiate the discharge. The results of the ignition tests show that arc current, electrode temperature, inlet pressure, and mole fraction of ammonia in the propellant have significant effects on arcjet startup characteristics. Experimental studies are also carried out to reveal the effects of different molar mixing ratios of nitrogen/ammonia mixtures on arcjet thruster performance. It is found that the important performance parameters of arcjet such as thrust, specific impulse, and thrust efficiency increase with an increased amount of ammonia in the propellant. The molar mixing ratio of the nitrogen/ammonia mixtures has significant effects on arcjet current-voltage characteristics.

Nomenclature

F	=	thrust of operating arcjet
F_{cold}	=	thrust of cold gas
I	=	arc current
I_{sp}	=	specific impulse
g	=	the gravitational acceleration
M	=	molecular weight of propellant
$\dot{m}$	=	mass flow rate of propellant
T	=	chamber temperature
U	=	arc voltage
η	=	thrust efficiency

I. Introduction

A THERMAL arcjet thruster with high specific impulse and moderate thrust levels is playing an increasingly important role in satellite applications. The hydrazine arcjet thruster, after 35 years of research and development, has been applied to commercial satellites since the early 1990s [1–4]. Arcjet thrusters of the 1–3 kW power class are now used for north–south station keeping of geostationary satellites [1–12]. In those applications, arcjet thrusters could provide significant propellant savings, launch-mass reduction, and longer service life in comparison with monopropellant hydrazine engines or resistojet thrusters. It is considered that hydrazine is the best propellant of choice at present for low-power arcjets, due to the compatibility with the existing space qualified propellant feed systems. Correspondingly, a lot of research results have also been published concerning the characteristics and basic working processes of the arcjet thruster (e.g., see [5], [13], and the references cited therein).

Although there have been many successful applications, in order to remain competitive with next-generation electric propulsion devices, significant increases in the service life and performance of the present arcjet technology must be achieved [11]. The improvement of performance can also qualify the arcjet thruster to be used on small geostationary satellites and low-Earth-orbit spacecraft for orbit raising. It has been found that the principal life-determinant factor for a high-performance arcjet is the electrodes erosion during long duration of operation with hundreds of startups [13,14]. To start the arcjet, a high-frequency or high-voltage pulse is applied to break down the gas propellant. Once the Paschen breakdown occurs within the gas propellant, an arc voltage below the open-circuit voltage of the PPU is established. Before the high-voltage mode operation is achieved, the arcjet operates in the low-voltage mode, in which the arc attaches to the anode along the converging side and the anode attachment is highly localized, resulting in high heat loads on the anode. Hamley and Sankovic [13] demonstrated a starting technique incorporating a soft-start current profile, which reduced starting damage at low mass flow rates. In that study, the arcjet was started at a current level substantially below the steady-state current, in order to reduce the anode heat load during the period spent in the low-voltage mode. The current was then ramped to the steady-state value after the high-voltage mode operation was attained. Electrode damage was negligible at flow rates corresponding to a specific impulse level of 620 s. The technique was not effective at very low mass flow rates, and an alternate technique is required. Reference [14] presents the development and demonstration of a technique that provides for nondamaging starts at low mass flow rates. This technique employs a brief propellant pressure pulse at ignition to increase gas dynamic forces during the critical ignition transition phase of operation. Starting characteristics obtained using both pressure-pulsed and conventional starting techniques were compared across a wide range of low propellant mass flow rates. The pressure-pulsed starting technique provided reliable starts at mass flow rates down to 21 mg/s, typically required for 700 s specific impulse level operation of 2 kW thrusters. Following the comparison, 600 start tests were performed across a wide mass-flow-rate range. Posttest inspection showed that there was minimal erosion of critical arcjet anode/nozzle surfaces.

In most cases of practical application, hydrazine was usually used as the propellant for the arcjet. For the sake of safety, 2:1 hydrogen/nitrogen and 1:4 nitrogen/ammonia mixtures simulating fully decomposed hydrazine were often used as the propellant instead of

Received 27 September 2009; revision received 23 July 2010; accepted for publication 7 October 2010.

*Associate Professor, School of Astronautics.
†Ph.D. Student, School of Astronautics.
‡Professor, School of Astronautics.
§M.S. Student, School of Astronautics.
¶M.S. Student, College of Mechanical Engineering and Applied Electronics Technology.

hydrazine in experimental studies. Meanwhile, due to the decomposed products of hydrazine varying with the catalyst degradation in practical applications, it is important to study the effects of propellant gas composition on arcjet performance. The current-voltage characteristics of a 1 kW class arcjet operated with 3:1 hydrogen/nitrogen mixture (simulated ammonia), 2:1 hydrogen/nitrogen mixture (simulated hydrazine), 9:9:2 hydrogen/nitrogen/ammonia mixture, and 2:2:1 hydrogen/nitrogen/ammonia mixture have been reported previously. It was found that at similar mass flow rates the 3:1 mixture ran approximately 10 volts higher than the 2:1 mixture. This result is due to the fact that the hydrogen is more effective at transferring energy from the arc [15]. Reference [16] reports that an arcjet starting reliability test was conducted to investigate the arcjet startup characteristics of the arcjet operated with 2:1 hydrogen/nitrogen gas mixtures simulating fully decomposed hydrazine. The results of this test indicated that there was a link between startup characteristics and long-term thruster operation. A cyclic endurance test of an arcjet operated at 1 kW using a 2:1 hydrogen/nitrogen mixture was performed previously in [17]. The average thrust and specific impulse were 162 mN and 425 s with the propellant mass flow rate of 39 mg/s during the 300 h endurance test [17]. Although a large number of studies concerning the low-power arcjet operated with nitrogen/hydrogen/ammonia mixtures have been reported as mentioned above, the effects of propellant gas composition or different molar mixing ratio nitrogen/ammonia mixtures on the startup characteristics and performance of arcjet have not been completely understood.

The objectives of this experimental work were to reveal the effects of the propellant gas composition on startup characteristics and performance of a 1 kW arcjet. For the sake of safety, hydrogen was not used as the propellant in our studies. Pure nitrogen and nitrogen/ammonia mixtures at molar mixing ratios of 2:1, 3:2, and 1:4 (simulated hydrazine) were chosen as the propellant. The first part of this study focuses on the startup characteristics of the arcjet operated with nitrogen and simulated hydrazine with a pulse-width-modulated power processing unit. The effects of arc current, upstream pressure (the inlet pressure of arcjet thruster), electrode temperature and the fraction of ammonia in the propellant on arcjet startup characteristics are presented. The following part lays emphasis on the operation and performance of the test arcjet thruster operated with nitrogen/ammonia mixtures at different molar mixing ratios. The current-voltage characteristics of an arcjet operated with pure nitrogen and 2:1, 3:2, and 1:4 nitrogen/ammonia mixtures are shown in this paper. The performance of an arcjet operated with different propellants as a function of propellant mass flow rate and arc current are discussed in detail.

II. Experimental Apparatus

All the tests were conducted in the arcjet experimental system, which includes a vacuum system, propellant feed system, data acquisition system, power processing unit (PPU), and thrust stand, as shown in Fig. 1.

The vacuum chamber is 1.8 m in diameter and 3.2 m long and is equipped with four rotary vane vacuum pumps, two roughing pumps, and two oil diffusion pumps. Each oil diffusion pump has a rated capacity of 26,000 liters/s at the pressure range of 1.3×10^{-3} to 6.7×10^{-2} Pa. Over the range of propellant mass flow rates tested: 18 to 50 mg/s, the chamber pressure ranged from 1.6 to 3.2 Pa. The propellant feed system could supply propellant to the arcjet thruster in single-gas mode or mixed-gas mode according to experimental requirements. In the mixed-gas mode, the mass flow rate of each kind of propellant would be set to a certain value to obtain nitrogen/ammonia mixtures according the required molar mixing ratios. Two thermal laminar-flow-type mass flow controllers (Seven Star Instruments, model D07-7A) with a full-scale mass flow output of 10 slm were used to control and measure the nitrogen and ammonia mass flow rate.

The functional diagram of the PPU used in this test is shown in Fig. 2. The PPU is a current-mode-control, pulse width modulation (PWM), push–pull topology, which consists of a main circuit, control circuit, safety circuit, and starter circuit. Once the Paschen breakdown is achieved, the PPU provides rapid current regulation output. An EMI filter was designed to remove the signal interference probably brought in through the bus bar. To reduce the startup resistance and allow a user to shut the PPU down rapidly, a power metal-oxide-semiconductor field-effect transistor was used as the power switch. The safety circuit gives a signal to PWM to shut down

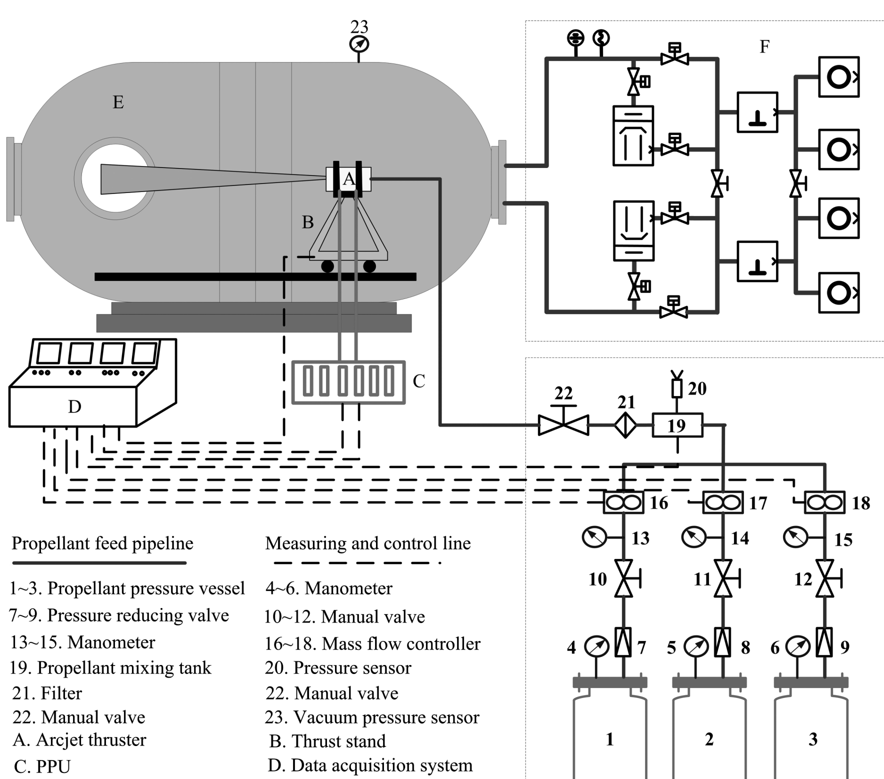


Fig. 1 Arcjet experimental system schematic.

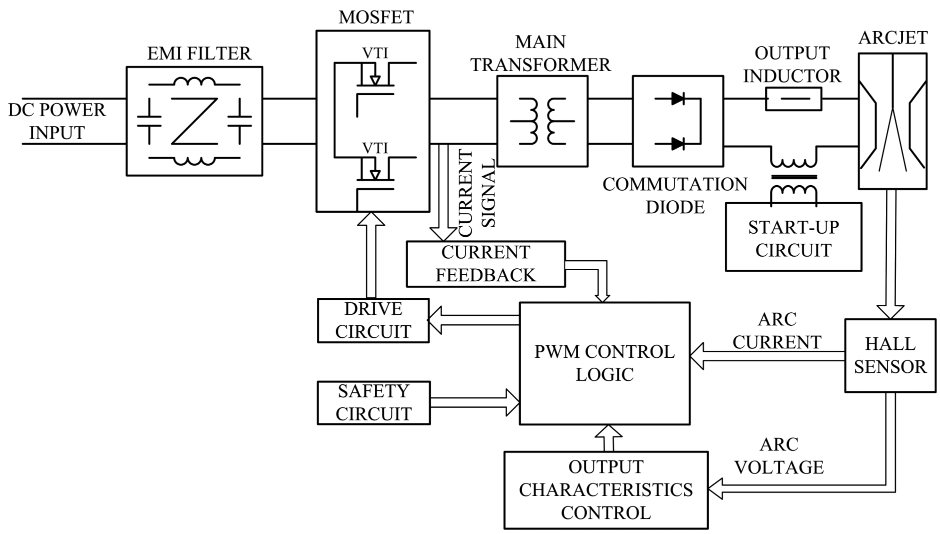


Fig. 2 Functional diagram of power processing unit.

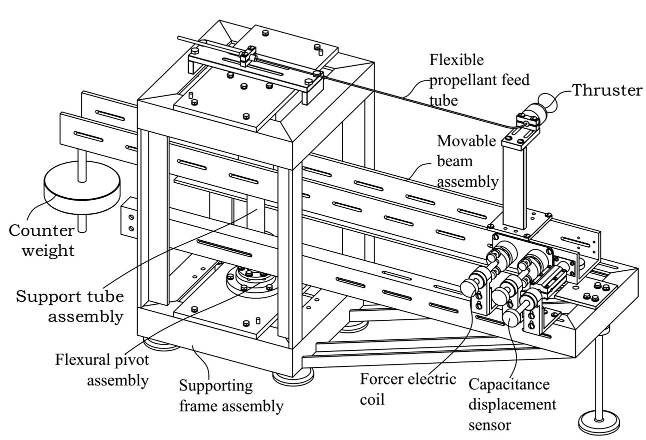


Fig. 3 Schematic diagram of arcjet thrust stand.

the PPU in the case of high temperature. In this study, two different starter circuits, i.e., high-frequency and high-voltage pulse ignition techniques, were used to initiate the discharge. The high-frequency starter circuit could output 8 kV pulse at a frequency range of 40 kHz–1 MHz to initiate the arc. The high-voltage pulse starter circuit provided a 3 kV pulse per 6 ms until arc current was established. The open-circuit voltage of the PPU with the high-frequency starter circuit was 240 V, and the open-circuit voltage of the PPU with the high-voltage pulse starter circuit was 200 V. The maximum current output of the PPU was 14 A.

Thrust measurements were performed using a calibrated displacement-type thrust stand with the thrust measurement range of 0–200 mN and an accuracy of $\pm 2\%$. The arcjet thruster was mounted on the movable beam for the thrust-measuring test, and the propellant was supplied to the arcjet through a flexible stainless steel propellant feed tube, as shown in Fig. 3. The capacitance displacement sensor system measured the displacement caused by the thrust generated by arcjet thruster and then transmitted a signal to a reactive circuit and forcer electric coil system to resist the motion of the movable beam assembly. The thrust stand was calibrated before thrust-measuring test using a set of known free weights that were suspended from the thruster mount.

Experimental data measured through the tests include the arc voltage, arc current, thrust, mass flow rate, temperature, and propellant feed pressure. Arc voltage and arc current are measured by Hall-effect sensors with an accuracy of $\pm 1\%$. Thrust is measured by the thrust stand with accuracy of $\pm 2\%$, as mentioned above. Propellant mass flow rate is measured by mass flow controllers with accuracy of $\pm 2\%$. The measurement methods and uncertainties of data measured in this study are listed in Table 1. The signals of the corresponding sensors are recorded by the Dimension 4i data acquisition system manufactured by LDS Test and Measurement. The Dimension 4i data acquisition system has 16 channels at sampling rates of up to 200 kHz per channel. In this study, the sampling rates are all set to 1 kHz. Isolation amplifier modules and shielded cables are used to avoid the signal interference.

The schematic diagram of the arcjet thruster used in this study and the temperature measurement locations are illustrated in Fig. 4. The arcjet thruster is a conventional, constricted-arc, vortex-stabilized, radiation-cooled design. The arcjet thruster is 200 mm long and 22 mm in diameter. The anode, which forms the nozzle of the thruster, is made of tungsten–rhenium alloy. The half-angles of converging and diverging parts of the thruster are 30 and 20°, respectively. The constrictor of the arcjet thruster is 0.7 mm in diameter and 0.5 mm in length. The cathode is made of a 2% thoriated tungsten rod of 4 mm diameter. The tip of the cathode is conical with a 30° half-angle. The arc gap in this test is set to be 0.4 mm. In the test, the arcjet thruster was mounted on the thrust stand, which was placed on the platform in the vacuum chamber.

III. Results and Discussion

A. Startup Characteristics

The starting process of an arcjet can be characterized by three steps, which are arc initiation, arc transition, and arc stabilization [18]. In the process of arc initiation, Paschen breakdown occurs with a steady-state flow rate of propellant injected into the arcjet chamber, with high-voltage pulse or high frequency applied between the cathode and anode. As the current is established and arc spot attachment moves to the edge of the constrictor, the arc voltage drops rapidly to a certain value. The case in which the arc attaches to the anode along the converging side in the form of spot attachment is usually defined as low-voltage mode. In the process of arc transition, gas flow forces the arc through the constrictor and the arc voltage increases. Finally, the arc attaches to the anode along the diverging

Table 1 Data measurement uncertainty

Parameter	Method	Accuracy, %
Arc voltage	Hall-effect sensor	±1
Arc current	Hall-effect sensor	±1
Thrust	Thrust stand	±2
Mass flow rate	Mass flow controllers	±2
Temperature	Thermocouple	±1
Pressure	Pressure sensor	±1

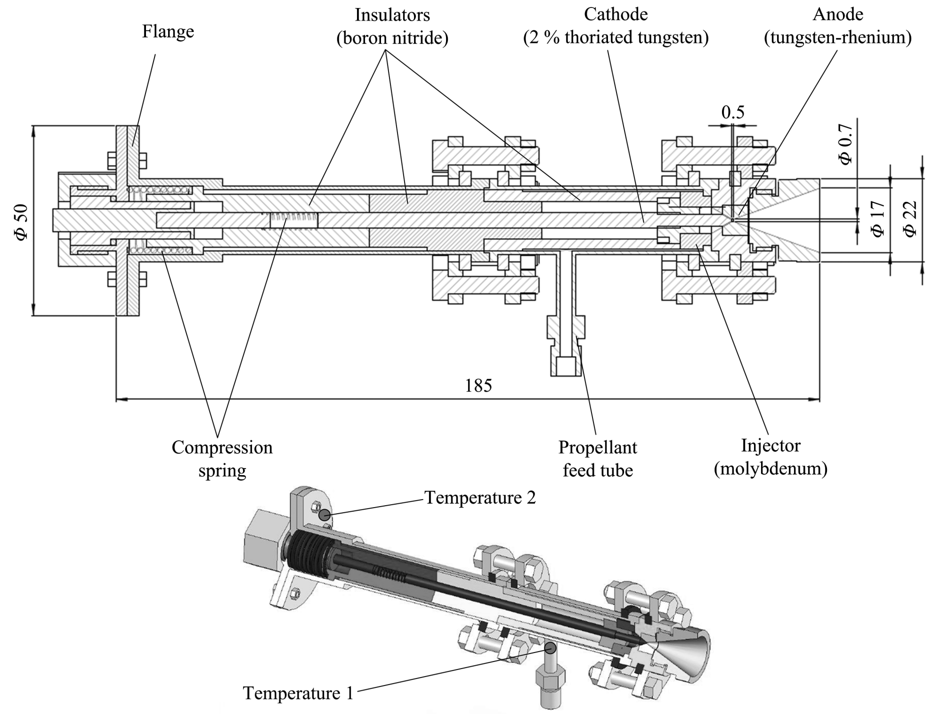


Fig. 4 Schematic diagram of the test arcjet thruster.

side in the form of diffuse arc attachment with a steady voltage, this case is usually called high-voltage mode [13,19,20].

A typical mission will involve literally hundreds of starting cycles of arcjet thruster. Depending on the interval between two ignitions of the arcjet, the ignition can be classified into hot and cold ignition modes. In cold ignition mode, the thruster was allowed to cool down to environmental temperature after the PPU was turned off before the next ignition. In hot ignition mode, ignition was initiated quickly after the last operation when the electrode temperature and upstream pressure in propellant feed tube were still high. In this study, tests were conducted to investigate the startup characteristics in both cold ignition mode and hot ignition mode for the case in which the PPU was equipped with a high-frequency starter circuit. In these tests, pure nitrogen and nitrogen/ammonia mixed at molar mixing ratio of 1:4 simulating hydrazine were selected as the propellant. The mass flow rates of nitrogen and simulated hydrazine were set to 30–60 and 20–28 mg/s, respectively, and the arc current varied from 6 to 10 A. Table 2 gives a summary of the startup characteristics test procedure.

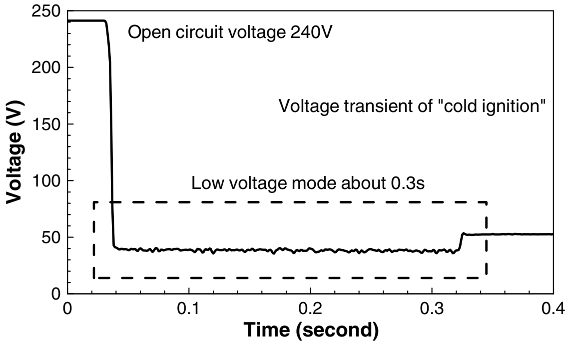
Reliable and repeatable ignitions were achieved when the test arcjet thruster operated with pure nitrogen as the propellant over the whole range of mass flow rate with arc current varying from 6 to 10 A. The arcjet thruster could not be ignited using simulated hydrazine as the propellant when arc current was set to 6 A and 8 A. Successful ignition was achieved when the arc current was increased to 10 A at the mass flow rate of 26 mg/s for the case with simulated hydrazine as the propellant. Because of the higher enthalpy of the mixtures of nitrogen/ammonia, the low power corresponding to the current of 6 or 8 A cannot sustain the arc after gas breakdown with the high-frequency starter circuit. Similar phenomenon has also been found in previous studies in which low arc current would cause the arc attachment point to move upstream to the converging side accompanied by an unstable arc [19,20].

Further attempts were made to initiate arc in hot ignition mode so as to reveal the effects of electrode temperature and upstream pressure on startup characteristics for the case with a nitrogen mass flow rates of 50 mg/s, simulated hydrazine mass flow rate of 26 mg/s, and arc current held at 10 A. The arc voltage transition processes of the arcjet thruster ignited in cold ignition mode and hot ignition mode with a nitrogen mass flow rate of 50 mg/s and arc current of 10 A are shown in Fig. 5. The open-circuit voltage of about 240 V was recorded after the PPU was activated. As can be seen from Fig. 5, the arc voltage dropped to about 40 V quickly after the occurrence of gas breakdown in both ignition modes. In the low-voltage mode, the arc voltage fluctuated within the range of 30–40 V accompanied by arcjet plume flickering. The low-voltage mode duration for the case of cold ignition is 0.3 s, and the corresponding time is 0.2 s for the case of hot ignition. After transition processes, the voltage increase to 52.8 V and tends to stabilize. Obviously, the nozzle temperature has a significant effect on the arcjet startup characteristics. In cold ignition mode, the divergent part of anode nozzle is cold and needs time to for arc to heat the nozzle to a high temperature. It has been confirmed that nozzle temperature affects

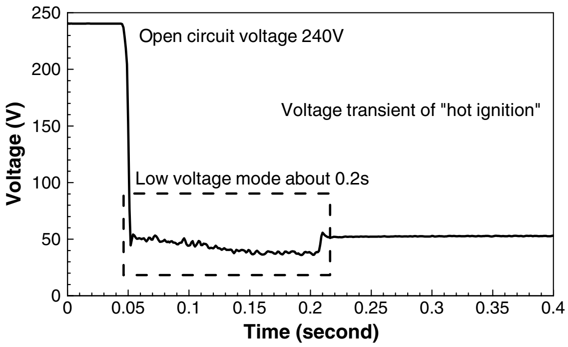
Table 2 Summary of the startup characteristics test procedure

Propellant	Mass flow rate, mg/s	Starter circuit	Arc current, A	Ignition mode	Objective
Nitrogen	30–60	High frequency	6–10	Cold ignition mode	a
Simulated hydrazine	20–28	High frequency	6–10	Cold ignition mode	a
Nitrogen	50	High frequency	10	Cold ignition mode	b
Nitrogen	50	High frequency	10	Hot ignition mode	b
Simulated hydrazine	26	High frequency	10	Cold ignition mode	b
Simulated hydrazine	26	High frequency	10	Hot ignition mode	b
Simulated hydrazine	26	High-voltage pulse	10	Cold ignition mode	c

[a]Test the capability of the PPU.
[b]Test the arcjet startup characteristics in both cold ignition mode and hot ignition mode.
[c]Compare the startup characteristics ignited with different starter circuits.

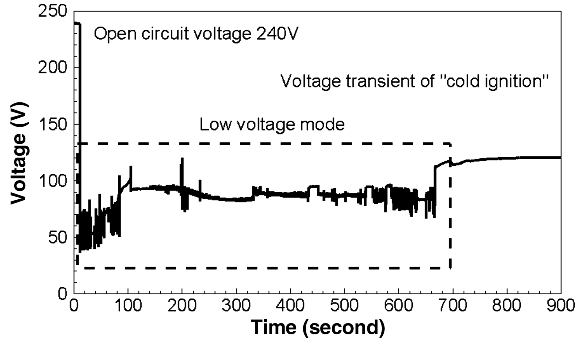


a) Arc voltage transitions in cold ignition mode with I=10 A, N_2, 50 mg/s

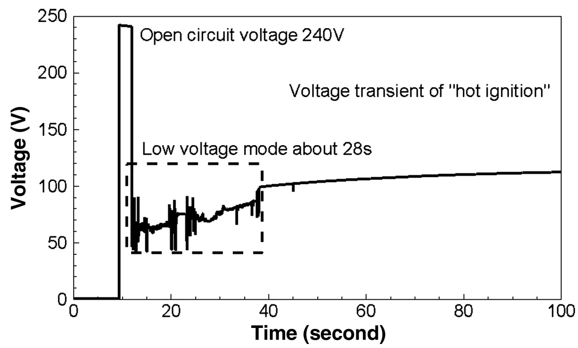


b) Arc voltage transitions in hot ignition mode with I=10 A, N_2, 50 mg/s

Fig. 5 Arc voltage transitions in cold ignition mode and hot ignition mode with $I = 10$ A, N_2, 50 mg/s.



a) Arc voltage transitions in cold ignition with I=10 A, simulated hydrazine, 26 mg/s



b) Arc voltage transitions in hot ignition with I=10 A, simulated hydrazine, 26 mg/s

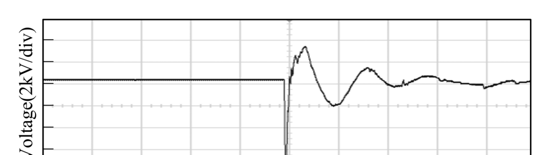
Fig. 6 Arc voltage transitions in cold ignition and hot ignition with $I = 10$ A, simulated hydrazine, 26 mg/s.

the arc root attachment mode in the arcjet thruster, and higher nozzle temperature promotes the diffused type of attachment and extension of the arc root to further downstream attachment.

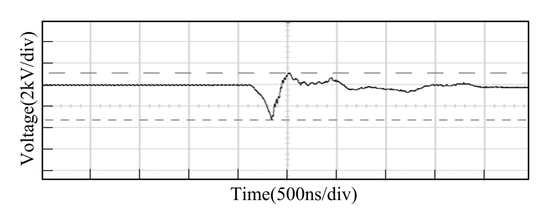
Figure 6 shows the arc voltage transition processes for an arcjet thruster ignited in cold and hot ignition modes using 1:4 nitrogen/ammonia mixtures simulating hydrazine with a mass flow rate of 26 mg/s and arc current of 10 A. It was found that the duration of low-voltage mode in cold ignition mode was much longer than that of in hot ignition mode. In the low-voltage mode of ignition processes, the arc voltage fluctuated more intensive than that of the case with nitrogen as the propellant. As mentioned above, the enthalpy of the nitrogen/ammonia mixtures is higher than that of nitrogen propellant and it needs more power and time for the arc to heat the nozzle to a high temperature. In this low-voltage mode, the arc usually attaches to the anode in constricted state and it is not easy to stabilize. The arcjet plume is faint and unstable in low-voltage mode, whereas the arcjet plume is brighter in the high-voltage mode.

In both ignition modes, the arcjet plume was not stable until the high-voltage mode was achieved. The result indicated that electrode temperature affected arcjet startup characteristics. This result is due to the fact that a higher electrode temperature can enhance the thermionic emission effect. Meanwhile, a higher electrode temperature allows the thruster body to attain thermal equilibrium as well as steady-state voltage in a shorter time; i.e., the duration of low-voltage mode for a thruster with a higher electrode temperature is shorter than that for a thruster with an environmental temperature. It is also believed that a higher pressure established in the upstream propellant feed tube by previous operation facilitates transition of the arc to a steady state in a shorter time. This result is due to the fact that a higher pressure established in the upstream propellant feed tube by previous operation can increase gas dynamic forces to rapidly push the arc anode attachment to its steady-state position in the diverging section of the nozzle.

During the low-voltage mode, the anode attachment of arc is high localized, resulting in high, potentially damaging, heat loads on the anode. Therefore, minimizing the time during which the arcjet spending in low-voltage mode operation will decrease the amount of startup erosion of the anode and increase the life of the arcjet. In this study, a high-voltage pulse starter circuit was used to improve the startup characteristics. The high-voltage pulse starter circuit provides a 3 kV pulse per 6 ms until arc ignition is achieved. Because the high upstream pressure could facilitate transition of the arc to low-voltage mode, a fluid resistor was used to increase upstream pressure in the propellant feed tube. Figure 7 displays the voltage variation from the PPU output recorded with an oscilloscope during the startup processes of the high-frequency and high-voltage pulse starter circuit. In this test, arcjet operated with simulated hydrazine as the propellant at a mass flow rate of 26 mg/s and arc current of 10 A. The arc voltage transition in cold ignition mode with the high-voltage



a) Start-up pulses of high frequency starter circuit with I=10 A, simulated hydrazine, 26 mg/s



b) Start-up pulses of high voltage pulse starter circuit with I=10 A, simulated hydrazine, 26 mg/s

Fig. 7 Startup pulses of high-frequency and high-voltage pulse starter circuits with $I = 10$ A, simulating hydrazine, 26 mg/s.

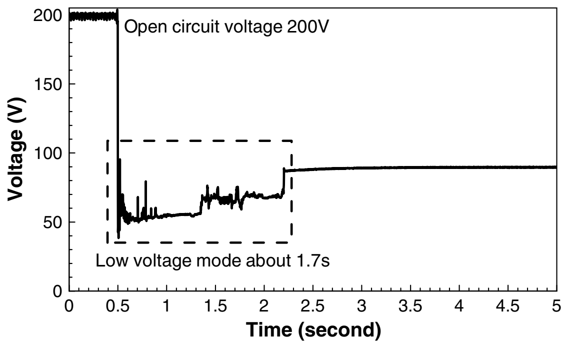


Fig. 8 Arc voltage transition in cold ignition mode using high-voltage pulse starter circuit with $I = 10$ A, simulated hydrazine, 26 mg/s.

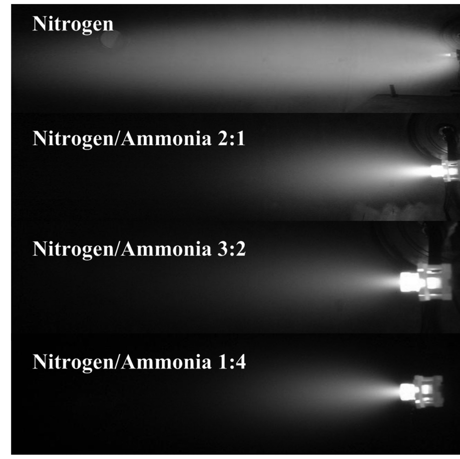


Fig. 9 Arcjet operating with N_2 and N_2/NH_3 mixtures at mixture ratios of 2:1, 3:2 and 1:4 in vacuum chamber.

pulse and higher upstream pressure in the propellant feed tube was plotted in Fig. 8. It can be seen from this figure that the duration of the low-voltage mode was 1.702 s, which was much shorter than the case with a high-frequency starter circuit. This technique forces the arcjet through the low transition much faster than before. Although this phenomenon cannot be explained clearly at the present time, further experiments should be conducted to investigate the effects of the starter circuit and gas dynamics on the startup characteristics of the arcjet thruster.

B. Operating Characteristics and Performance

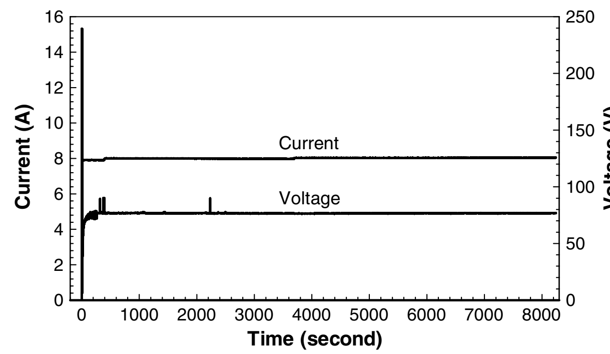
Tests were conducted in this study to determine the operating characteristics and performance of an arcjet operated with nitrogen and nitrogen/ammonia mixtures with propellant mixing ratios of 2:1, 3:2, and 1:4. The mass flow rates of N_2, $2N_2 + NH_3$, $3N_2 + 2NH_3$, and $N_2 + 4NH_3$ were set to 30–50 mg/s, 28.68–39.11 mg/s, 28.10–39.33 mg/s, and 19.46–31.29 mg/s, respectively, and arc current varied from 8 to 11 A. The duration of each operating condition was 2 h to ensure thermal equilibrium of arcjet thruster could be achieved. Arc current, arc voltage, mass flow rate of propellants, and thrust were measured through the tests. The operating conditions in the performance tests were listed in Table 3.

The steady plumes of the arcjet operated with nitrogen and nitrogen/ammonia mixtures with molar mixing ratios of 2:1, 3:2, and 1:4 are pictured in Fig. 9. With nitrogen as the propellant, the luminous arcjet plume was long and diffuse. When the 2:1, 3:2, and 1:4 nitrogen/ammonia propellant mixtures were used as the propellant, the plumes were constricted and short. The plumes became longer and brighter when the arc current increased. The nozzle became redder when the arcjet used nitrogen/ammonia propellant mixtures compared with the case using pure nitrogen propellant and indicates that the nozzle temperature with mixtures of nitrogen/ammonia propellant is higher than the case with pure nitrogen propellant.

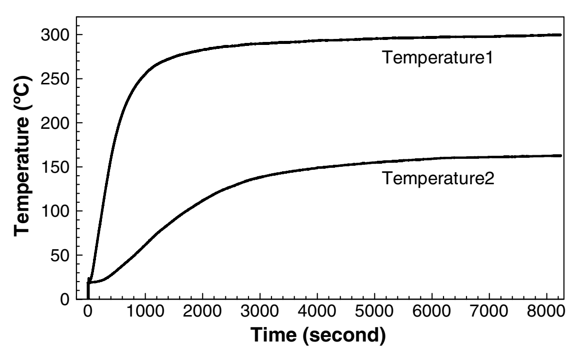
Figure 10 shows typical operating characteristics of the arcjet thruster. Variations of arc current and arc voltage (Fig. 10a) and surface temperature (Fig. 10b) with operation time when the arcjet was operated with 50 mg/s of N_2 and an arc current of 8 A are plotted in this figure. Temperature 1 and temperature 2 represent the measured temperatures at inlet of propellant feed tube and the flange edge upstream from the arcjet thruster, respectively. It can be seen that a steady-state arc with voltage of 76.72 V was established in a short time after ignition. The temperature of the outer surface of

Table 3 Summary of operating conditions in the performance tests

Propellant	Mass flow rate range, mg/s	Arc current range, A
N_2	30–50	8–11
$2N_2 + NH_3$	28.68–39.11	8–10
$3N_2 + 2NH_3$	28.10–39.33	8–10
$N_2 + 4NH_3$	19.46–31.29	8–10



a) Current and voltage versus operation time



b) Temperature versus operation time

Fig. 10 Variation of parameters versus operation time with $I = 10$ A, N_2, 50 mg/s.

propellant tube at the entrance increased faster than the temperature at the flange edge on the upstream end of the arcjet thruster. It shows that it took about 30 and 60 min for temperature 1 and temperature 2 to achieve thermal equilibrium, which is similar to the result of previous study [21].

Figure 11 shows the variations of thrust and specific impulse with mass flow rate for pure nitrogen and nitrogen/ammonia mixtures at different molar mixing ratios in the cold-flow tests. As shown in Fig. 11, all the curves display the general trends that the thrust increased with an increased mass flow rate for different propellants. The specific impulses were almost constant for each kind of propellant as shown in Fig. 11. It is found that the specific impulse level increased with an increased amount of ammonia in the mixtures. From energy conservation, the I_{sp} scales as

$$I_{sp} \sim \sqrt{\frac{T}{M}} \tag{1}$$

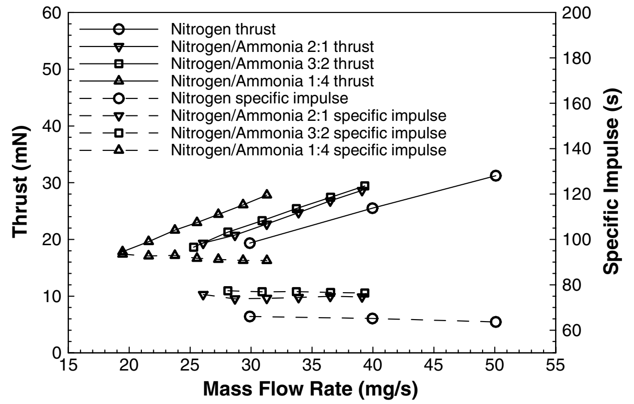


Fig. 11 Variations of thrust and specific impulse versus mass flow rate for different propellant in cold-flow test.

where I_{sp} is specific impulse, T is chamber temperature, and M is molecular weight of propellant. It suggests that specific impulse decreases with an increased propellant molecular weight at same chamber temperature. The fact is that the average molecular weight of nitrogen/ammonia mixtures decreases with an increased amount of ammonia present in mixtures. As a result, simulated hydrazine shows the highest specific impulse in a cold-flow test, due to its smallest average molecular weight among all types of propellant used in the tests.

Arc voltages were measured when the arcjet was operated with nitrogen and nitrogen/ammonia mixtures. Figure 12 shows that the arcjet operated in different voltage or power ranges with different levels of ammonia present in propellant, when arc current was set to 10 A. Arc voltage increased with an increased mass flow rate for all propellants used in the tests, as shown in Fig. 12. For all types of propellant, increasing mass flow rate increased the chamber pressure upstream of arcjet, which forces the arc root to move downstream toward nozzle exit, resulting in a higher arc voltage. At the same time, a higher input power was needed to sustain the arc when mass flow rate increased.

Figure 13 displays the current-voltage characteristics for the cases with N_2, $2N_2 + NH_3$, $3N_2 + 2NH_3$, and $N_2 + 4NH_3$ propellant at mass flow rates of 29.90, 28.68, 28.10, and 25.55 mg/s, respectively. It shows that the arc voltage decreased with an increased arc current for all propellants examined. This is similar to the general situation in generating a nontransferred DC plasma torch using argon as the working gas under free-arc conditions, having a descending V-I curve with low arc voltage [22,23]. It can also be seen from Fig. 13 that the arc voltage increased with an increase in the level of ammonia in the propellants. Correspondingly, the $N_2 + 4NH_3$ simulating hydrazine runs at the highest arc voltage level, whereas N_2 runs at the lowest arc voltage level at mass flow rates of 25.55 and 29.90 mg/s. Figure 14 shows the current-voltage characteristics of an arcjet operated with $N_2 + 4NH_3$ simulating hydrazine at four different mass flow rates. It also shows the arcjet thruster had a descending current-voltage characteristic for the different mass flow rates in the test.

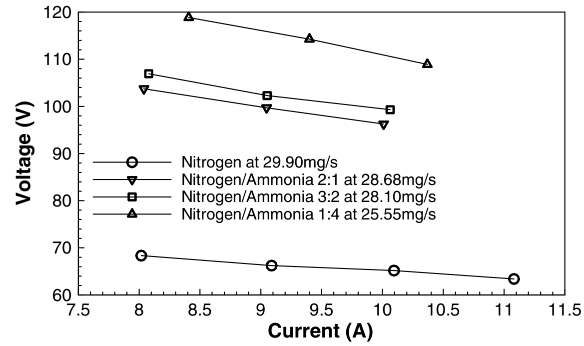


Fig. 13 Current-voltage characteristics for different propellants.

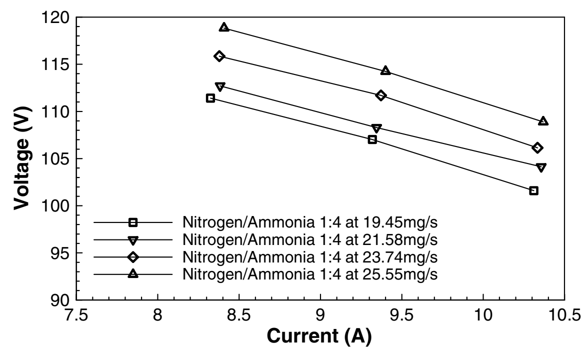


Fig. 14 Current-voltage characteristics for $N_2/4NH_3$ simulated hydrazine at different mass flow rates.

Figure 15 shows the variations of surface temperature (temperature 1) at the inlet of the propellant feed tube and arcjet body, along with specific power with mass flow rates of N_2, $2N_2 + NH_3$, and $3N_2 + 2NH_3$ for the cases in which the arc current was held at 10 A. It can be seen that the temperature at the inlet of the tube decreased with an increased mass flow rate of propellant. The specific powers also decreased with mass flow rates.

Typical performance data, such as thrust, specific impulse, and thrust efficiency for the thruster operated with nitrogen/ammonia mixtures at different molar mixing ratios with $I = 10$ A are shown in Figs. 16 and 17. Figure 16 shows that the thrust of the arcjet increased with an increased mass flow rates of N_2, $2N_2 + NH_3$, $3N_2 + 2NH_3$, and $N_2 + 4NH_3$ when arc current was set to 10 A. While the variations of specific impulse with mass flow rate for N_2 and $N_2 + 4NH_3$ could not keep constant in the examined ranges of mass flow rate, as shown in Fig. 16. The specific impulse with mixtures of $N_2 + 4NH_3$ was approximately 500 s, which is higher than those cases with 3:2 and 2:1 $N_2 + NH_3$ mixtures and 250 s higher than the

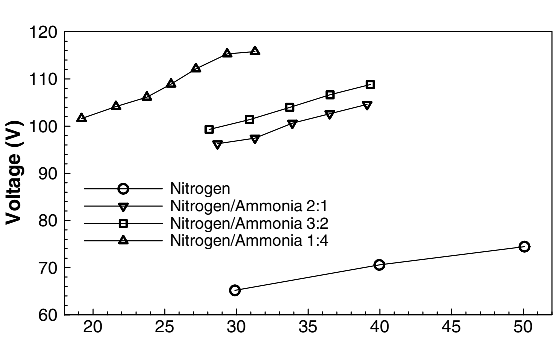


Fig. 12 Variations of arc voltage versus mass flow rate for different propellants with $I = 10$ A.

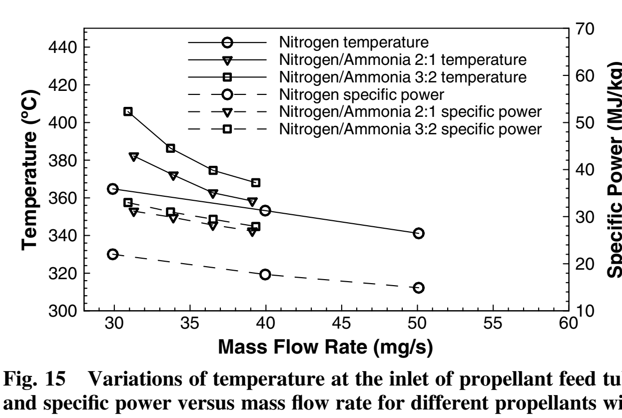


Fig. 15 Variations of temperature at the inlet of propellant feed tube and specific power versus mass flow rate for different propellants with $I = 10$ A.

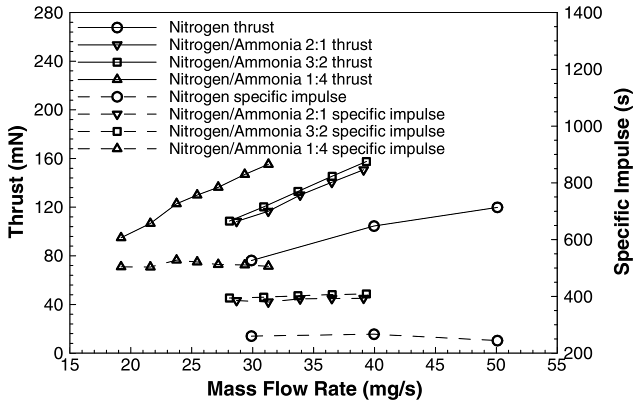


Fig. 16 Variations of thrust and specific impulse versus mass flow rate for different propellants with $I = 10$ A.

case with N_2 as the propellant. The maximum specific impulse of 528 s was achieved with a mass flow rate of 23.75 mg/s on simulated hydrazine. The thrust efficiency can be calculated according to the following formula [24,25]:

$$\eta = \frac{F^2 - F_{\text{cold}}^2}{2\dot{m}UI} \tag{2}$$

where F is the thrust of arcjet thrust, $\dot{m}$ is the mass flow rate of propellant, g is the gravitational acceleration, η the thrust efficiency, F_{cold} is the thrust of cold gas, U is the arc voltage, and I is the arc current. Figure 17 shows the variation of arcjet thrust efficiency with the mass flow rate for the different gases used as the propellant. Over the range of mass flow rates tested, it was found that the thrust efficiencies were in the range of 20.45–26.56%, 20.18–27.74%, and 21.57–31.10% for the cases with the 2:1, 3:2, and 1:4 $N_2 + NH_3$ mixtures, respectively. The performance data for the arcjet operated with nitrogen and nitrogen/ammonia mixtures at different molar

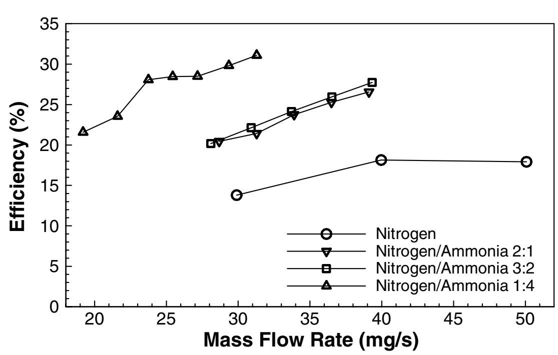


Fig. 17 Variations of thrust efficiency versus mass flow rate for different propellants with $I = 10$ A.

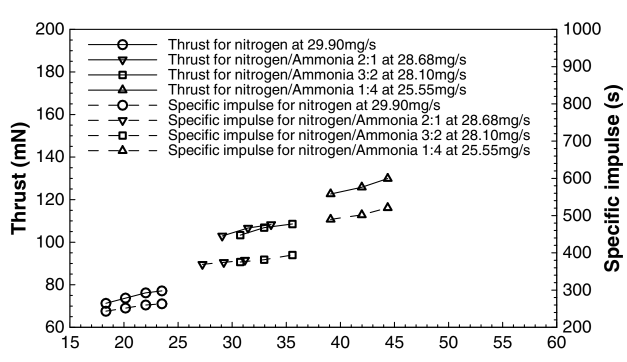


Fig. 18 Variations of thrust and specific impulse versus specific power for different propellants at different mass flow rates.

mixing ratios also reveal that the level of ammonia present in propellant had significant effects on arcjet performance. The higher the level of ammonia in propellant mixture, the higher the efficiency that could be achieved.

Thrust and specific impulse versus specific power for four different propellants are plotted in Fig. 18. The specific power varied between 18.33–25.50, 27.24–31.18, 30.75–35.57, and 39.09–44.38 MJ/kg with pure nitrogen, 2:1, 3:2, and 1:4 nitrogen/ammonia mixtures at mass flow rates of 29.90, 28.68, 28.10, and 25.55 mg/s, respectively, when arc currents were set to 8–11 A. It is found that thrust and specific impulse increased with the increase of specific power for different gases used as the propellants.

IV. Conclusions

Experimental investigations were conducted to determine the startup characteristics and performance of a 1 kW arcjet thruster operated with various mixtures of nitrogen and ammonia. The results show that the level of ammonia in the propellant stream can affect arcjet startup characteristics and performance.

The first part of the ignition test focuses on the arcjet startup characteristics in both cold ignition mode and hot ignition mode with pure nitrogen and simulated hydrazine. A high-frequency starter circuit was used to initiate the arc in this part. The results show that arc current, electrode temperature, upstream pressure, and the fraction of ammonia present in the propellant had significant effects on arcjet startup characteristics. The high upstream pressure and high electrode temperature facilitate arc transition to steady state in a shorter time. It was found that it became more difficult to initiate the discharge with an increased percentage of ammonia in the propellant mixtures. To compare the arcjet startup characteristics with the high-frequency and the high-voltage pulse starter circuits, a high-voltage pulse starter circuit was used to initiate the arc with a simulated hydrazine mass flow rate of 26 mg/s and arc current of 10 A in the second part of the ignition test. The results show that the PPU with the high-voltage pulse starter circuit works better than the one with a high-frequency starter circuit. The duration of the low-voltage mode was much shorter than the case with a high-frequency starter circuit under the same operating condition.

Tests were also performed to reveal the effects of different nitrogen and nitrogen/ammonia propellant mixtures on thruster performance. The current-voltage characteristics for all propellants used in this study indicated that the arc voltage decreased with an increased arc current as has been reported in previous studies. The fraction of ammonia in the propellant had a significant effect on current-voltage characteristics. The arc voltage increased with an increased percentage of ammonia in the propellant. The results also show that the propellant gas composition had significant effects on the arcjet performance parameters such as thrust, specific impulse, and thrust efficiency. The thrust, specific impulse, and thrust efficiency of the arcjet thruster all increased with an increased levels of ammonia in the propellant at a mass flow rate of 30 mg/s and arc current of 10 A. It indicated that the arcjet performance can be improved by increasing the mole fraction of ammonia in the propellant.

Acknowledgment

The work is supported by China National Nature Science Funds (grant no. 50836007).

References

[1] Lichtin, D. A., "An Overview of Electric Propulsion Activities in US Industry—2005," AIAA/ASME/SAE/ASEE 41st Joint Propulsion Conference and Exhibit, Tucson, AZ, AIAA Paper 2005-3532, July 2005.

[2] Lichtin, D. A., Chilelli, N. V., Henderson, J. B., Rauscher, R. A., Jr., Young, K. J., McKinnon, D. V., Bailey, J. A., Roberts, C. R., Zube, D. M., and Fisher, J. R., "AMC-1 (GE-1) Arcjets at 12-Plus Years on Orbit," AIAA/ASME/SAE/ASEE 45th Joint Propulsion Conference and Exhibit, Denver, Colorado, AIAA Paper 2009-5364, Aug. 2009.

[3] Sackheim, R. L., "Overview of United States Space Propulsion Technology and Associated Space Transportation Systems," *Journal of*

Propulsion and Power, Vol. 22, 2006, pp. 1310–1333.
doi:10.2514/1.23257

[4] Boyd, I. D., "Numerical Modeling of Spacecraft Electric Propulsion Thrusters," *Progress in Aerospace Sciences*, Vol. 41, 2005, pp. 669–687.
doi:10.1016/j.paerosci.2006.01.001

[5] Lichon, P. G., and Sankovic, J. M., "Development and Demonstration of a 600-Second Mission-Average I_{sp} Arcjet," *Journal of Propulsion and Power*, Vol. 12, 1996, pp. 1018–1025.
doi:10.2514/3.24139

[6] Cappelli, M. A., and Storm, P. V., "Interior Plasma Diagnostics of Arcjet Thrusters," *Journal of Propulsion and Power*, Vol. 12, 1996, pp. 1070–1076.
doi:10.2514/3.24145

[7] Burton, R. L., and Bufton, S. A., "Exit-Plane Electrostatic Probe Measurements of a Low-Power Arcjet," *Journal of Propulsion and Power*, Vol. 12, 1996, pp. 1099–1106.
doi:10.2514/3.24149

[8] Deininger, W. D., Cruciani, G., and Glogowski, M. J., "Performance Comparisons of Low-Power Arcjets," *Journal of Propulsion and Power*, Vol. 11, 1995, pp. 1368–1370.
doi:10.2514/3.23982

[9] Bufton, S. A., Burton, R. L., and Krier, H., "Measured Exit Plane Properties of a Low-Power Simulated-Hydrazine Arcjet," *Journal of Propulsion and Power*, Vol. 15, 1999, pp. 735–736.
doi:10.2514/2.7650

[10] Deininger, W. D., Attili, M., Vulpiani, M., and Detoma, E., "Low Power Arcjet System Requirements Definition for North-South Station Keeping," AIAA/SAE/ASME/ASEE 29th Joint Propulsion Conference and Exhibit, Monterey, CA, AIAA Paper 93-2223, June 1993.

[11] Butler, G. W., and Cassady, R. J., "Directions for Arcjet Technology Development," *Journal of Propulsion and Power*, Vol. 12, No. 6, Nov.–Dec. 1996.

[12] Zube, D., Lichon, P., Cohen, D., Lichtin, D., Bailey, J., and Chilleli, N., "Initial On-Orbit Performance of Hydrazine Arcjets on A2100™ Satellites," AIAA/SAE/ASME/ASEE 35th Joint Propulsion Conference and Exhibit, Los Angeles, CA, AIAA Paper 99-2272, June 1999.

[13] Hamley, J., and Sankovic, J., "A Soft-Start Circuit for Arcjet Ignition," AIAA/SAE/ASME/ASEE 29th Joint Propulsion Conference and Exhibit, Monterey, CA, AIAA Paper 93-2396, June 1993.

[14] Sankovic, J. M., and Curran, F. M., "A Low Erosion Starting Technique for High-Performance Arcjets," AIAA/ASME/SAE/ASEE 30th Joint Propulsion Conference, Indianapolis, IN, AIAA Paper 94-2867, June 1994.

[15] Hardy, T. L., and Curran, F. M., "Low Power DC Arcjet Operation with Hydrogen/Nitrogen/Ammonia Mixtures," AIAA/SAE/ASME/ASEE 23rd Joint Propulsion Conference, San Diego, CA, AIAA Paper 87-1948, 1987.

[16] Haag, T. W., and Curran, F. M., "Arcjet Starting Reliability: A Multistart Test on Hydrogen/Nitrogen Mixtures," 19th AIAA/DGLR/JSASS International Electric Propulsion Conference, Colorado Springs, CO, AIAA Paper 87-1061, May 1987.

[17] Cruciani, G., and Deininger, W. D., "A 300-Hour Endurance Test of an Arcjet Thruster at 1 kW," AIAA/SAE/ASME/ASEE 29th Joint Propulsion Conference and Exhibit, Monterey, CA, AIAA Paper 93-1900, June 1993.

[18] Mclean, C. H., Lichon, P. G., and Sankovic, J., "Life Demonstration of a 600-Second Mission Average Arcjet," 30th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Indianapolis, IN, AIAA Paper 94-2866, June 1994.

[19] Yoshikawa, T., Onoe, K., Yasui, M., and Morimoto, S., "A Low-Power Arcjet Thruster for Space Propulsion," AIAA/DGLR/JSASS 18th International Electric Propulsion Conference, Alexandria, VA, AIAA Paper 85-2032, 1985.

[20] Yoshikawa, T., Onoe, K., Ohba, T., Yoshida, H., Suzuki, H., and Morimoto, S., "Development of a Low Power Dc Arcjet for Space Propulsion," 19th AIAA/DGLR/JSASS International Electric Propulsion Conference, Colorado Springs, CO, AIAA Paper 87-1058, May 1987.

[21] Viertel, Y. E., Schmitz, H-D., Riehle, M., Kurtz, H. L., Auweter-Kurtz, M., "Development and Test of a 1 kW Hydrazine Arcjet system," 32nd AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Lake Buena Vista, FL, AIAA Paper 96-2960, July 1996.

[22] Das, A. K., Sreekumar, K. P., and Venkatramani, N., "DC Plasma Torch Voltage and Current Characteristics Through Heat Balance Measurements," *Plasma Sources Science and Technology*, Vol. 3, 1994, pp. 108–113.
doi:10.1088/0963-0252/3/1/013

[23] Ramasamy, R., and Selvarajan, V., "Current-Voltage Characteristics of a Non-Transferred Plasma Spray Torch," *European Physical Journal D: Atomic, Molecular and Optical*, Vol. 8, 2000, pp. 125–129.

[24] Tang, H., Liu, Y., and Dai, W., "Experiments and Numerical Simulations in Low Power Arcjets," 37th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Salt Lake City, UT, AIAA Paper 2001-3905, July 2001.

[25] Tang, H., Zhang, Z., Liu, Y., and Dai, W., "Experiment and Performance Analyses on Low Power Arcjet," *Journal of Propulsion Technology*, Vol. 22, No. 3, June 2001 (in Chinese).

J. Blandino
Associate Editor