Response of the Arc Plasma Source to Combustion Chamber Pressure Fluctuation of the Small Size Thruster Using Plasma Support Combustion

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This paper deals with the influence of variation in combustion-chamber pressure on an arcjet plasma source for an arcjet-assisted thruster. Arcjets have been applied to chemical thrusters in order to promote combustion and augment performance. Some groups reported that combustion of solid propellant and monopropellant such as SHP163 was successfully sustained with arcjet. Arc discharge is, however, negatively influenced by variation in combustion-chamber pressure. Hence, we propose to apply active control to arcjet-assisted chemical thruster in order to stabilize combustion. The controller design requires the response of arcjets to variation in combustion-chamber pressure. In this study, we investigated the influence of step-like pressure change on arcjet exit using a combustion chamber simulator. In the simulator, pressure was suddenly increased from 0.1 to 0.35 MPa using a nitrogen-filled buffer with a burst diaphragm. At a pressure rise of 0.15 MPa with a time constant of 0.2 s, arc discharge was interrupted immediately after sudden rise in pressure of the combustion chamber simulator. From the results, arcjet was negatively affected by the combustion-chamber pressure.

Key Words: Arcjet, Plasma, Chemical Propulsion

Nomenclature

\( p \) : Pressure in combustion chamber simulator

\( Ps \) : Probability at which arc discharge was sustained even after sudden rise in pressure was induced in combustion-chamber pressure

\( \Delta p \) : Pressure increment in combustion chamber simulator

\( V \) : Discharge voltage

\( \Delta V \) : Discharge voltage increment owing to sudden rise in combustion chamber simulator

1. Introduction

An arcjet is applied to liquid and solid propellant thrusters to promote combustion and enhance performance.1-3) Figure 1 shows a schematic of an arcjet-assisted liquid propellant thruster. The arcjet, which is a high enthalpy flow, is fed to a combustion chamber in order that combustion is immediately completed in a small combustion chamber. This design possibly improves performance and downsizes combustion chambers.

Figure 2 depicts an arcjet and working-fluid flow. Arc discharge is induced between a cathode and nozzle anode. Working gas is converted into an arc plasma, and heated by the Joule heating. Arc plasma jet is expelled from the nozzle.

Arc discharge is, however, affected by pressure variation of the combustion chamber. Thrusters with arcjet-assisted combustion are possibly destabilized by pressure change in combustion chamber. Hence, we propose to apply active control to arcjet-assisted thruster in order to stabilize combustion. A computer measures pressures in plenum and combustion chambers, and adjusts arc discharge current and mass flow rate so that the thruster yields stable thrust with relatively high performance. The controller design requires the response of arcjet to variation in combustion-chamber pressure.

In this study, we prototyped a combustion chamber simulator that gave sudden change in combustion-chamber pressure to arcjets. The simulator induced pressure variation ranging from 0.05 to 0.25 MPa.

Fig. 1. A schematic of a liquid thruster with arcjet-assisted combustion.
2. Prototyped Arcjet

2.1 Radiatively-cooled arcjet

Figure 3 shows a schematic of a prototyped radiatively-cooled arcjet. The cathode was a 2-mm-diam thoriated tungsten rod to reduce the electrode erosion. The anode was made of copper tungsten which had a relatively high melting point of 1338 K and better machinability than tungsten. To prevent irregular electric discharge, a ceramic insulator tube was inserted between the body and cathode. Because supersonic jet was not necessary for promoting combustion, the arcjet had no divergent section. The diameter and length of constrictor are 1 mm.

2.2 Water-cooled arcjet

A prototyped water-cooled arcjet is shown in Fig. 4. An anode was made of copper, which has relatively high heat conductivity among metals, was cooled with water flow. A water-cooled arcjet generally produces a stable arc discharge owing to the thermal pinch effect. When an arc column is cooled by the surrounding gas, it usually shrinks and enlarges current density. This increases arc plasma temperature and pressure, and accordingly stabilizes arc discharge. Then, the arc plasma was expelled through the nozzle that had a convergent section, and a constrictor of 1 mm and 12.4 mm in diameter and length.

3. Experimental Apparatus

Figure 5 shows a schematic of experimental apparatus. Argon, which was used as a working fluid for arcjet because it is readily ionized, was stored in a vessel, and supplied to arcjet through a mass flow controller. Arc discharge current was supplied with a regulated current power supply through a ballast resistor to the arcjet. For ignition, a train of 5000-V-peak pulses of 60 Hz in repetitive frequency were supplied by an ignition transformer.

3.1 Combustion chamber simulator

Figure 6 shows the combustion chamber simulator for providing sudden change in pressure to the nozzle exit of the arcjets. A buffer with a burst diaphragm was connected to the combustion chamber simulator to raise pressure rapidly. Values of $\Delta p$ were varied by adjusting an exhaust valve and initial nitrogen pressure in the buffer. Ballast resistors were inserted between the cathode and power supply. This is because arcjet generally presents negative resistance, which usually destabilizes arc discharge. Ballast resistors of 1 $\Omega$ and 2 $\Omega$ were used since the arcjet presented 1 $\Omega$ class resistance.

3.2 Buffer

Figure 7 illustrates a schematic diagram of the buffer with a burst diaphragm for giving sudden pressure increment to the arcjet. The buffer, which was initially filled with compressed nitrogen, rapidly increased pressure in the combustion chamber simulator at a time constant of 0.2 s after an electromagnetic actuator breaks the diaphragm.

3.3 Experimental procedure

Table 1 summarizes experimental condition. Discharge current and mass flow rate of argon were 15 A and 60 mg/s, respectively. Target values of $\Delta p$ was varied 0.05 to 0.25 MPa.
with an increment of 0.05 MPa.

Initially, the buffer was filled with nitrogen at pressures from 0.18 to 0.74 MPa, and the exhaust valve was adjusted so as to increase the pressure in the simulator by $\Delta p$. After, starting to feed argon, arc discharge was ignited by producing sparks between the electrodes at 60 Hz. When arc discharge was stabilized, nitrogen was supplied from the buffer to the combustion chamber simulator by breaking a diaphragm of the buffer. The response of plenum-chamber pressure, and discharge voltage were recorded with a computer.

Table 1. Experimental condition.

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<tr>
<td>Open end voltage, V</td>
<td>120</td>
<td></td>
</tr>
<tr>
<td>Discharge current, A</td>
<td>15</td>
<td></td>
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<td>Working gas for arcjet</td>
<td>Ar</td>
<td></td>
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<tr>
<td>Mass flow rate of argon, mg/s</td>
<td>60</td>
<td></td>
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<tr>
<td>$\Delta p$, MPa</td>
<td>0.05, 0.1, 0.15, 0.2, 0.25</td>
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<td>Ballast resistor, $\Omega$</td>
<td>1, 2</td>
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4. Results and Discussion

4.1. Time history of discharge voltage, pressure of plenum chamber and mass flow rate of argon

Figure 8 shows time history at $\Delta p = 0.15$ MPa for the water-cooled arcjet with a ballast resistor of 1 $\Omega$. As illustrated in Fig. 8, a sudden pressure change in combustion chamber simulator increased plenum-chamber pressure, and then, intermitted arc discharge. Simultaneously, discharge voltage was increased to 120 V, which was an open end voltage. In same tests, arc discharge was intermitted by pressure increment in combustion chamber simulator.

In the other case, an arc discharge was sustained despite sudden variation in pressure. Figure 9 shows the time history at $\Delta p = 0.20$ MPa for the water-cooled arcjet. Arc discharge voltage was increased by 6 V by pressure rise in combustion chamber simulator, and then returned to an initial value of 13 V. From these results, arcjets was sometimes interrupted by pressure increment in combustion chamber simulator.

The reason pressure increment $\Delta p$ interrupted arc discharge and increased discharge voltage is that the nozzle was not choked. From the configuration of the nozzle, and pressure ratio of plenum chamber pressure to the combustion chamber simulator, the nozzle is never choked, and hence the nozzle flow is subsonic. Then, the pressure variation $\Delta p$ is transmitted to the plenum chamber. Because sustaining plasma becomes more difficult in higher pressure, arc discharge was autonomously interrupted by pressure rise.

Pressure increment $\Delta p$ induced temporary increment in discharge voltage. Because discharge current is regulated,
electric resistance of plasma would be momentarily augmented by $\Delta p$. Increase in electric resistance is would be caused by rise in plasma density. Plasma density is increased by $\Delta p$ because neutral density is enlarged. Generally, growing plasma density enlarges electric resistance because ions and electrons collide more frequent. Through the process, $\Delta p$ induced $\Delta V$.

4.2. The effect of pressure rise $\Delta p$

Figure 10 shows the dependence of $P_s$ on $\Delta p$. From this result, increasing $\Delta p$ interrupted arc discharge at higher probability.

Figure 11 shows the correlation $\Delta V/V$ and $\Delta p$. No data is present at $\Delta p=0.15, 0.2, 0.25$ MPa for radiatively-cooled arcjet, and at $\Delta p=0.2, 0.25$ MPa for water-cooled arcjet because arc discharge was interrupted by pressure rise in the simulator. From the results, $\Delta V/V$ is almost monotonically increased with increasing $\Delta p$.

The increase in $\Delta V/V$ due to $\Delta p$ can destabilize thrust production. Rise in $\Delta V/V$ enlarges arc-discharge power because discharge current was regulated. Augmentation in arc-discharge power possibly enhance combustion, and resultantly expands the pressure. This is a positive feedback, and hence the system would be destabilized. Hence, from these results, active control system is necessary to stabilize thruster by suppressing the voltage increment.

As shown in Fig. 10, both water- and radiatively-cooled arcjets presented the similar dependence of $P_s$ on $\Delta p$ whereas water-cooled arcjets usually exhibit stable plasma compared with radiatively-cooled arcjets owing to the thermal pinch effect. Hence, we had expected that the water-cooled arcjet would yield higher $P_s$ than the radiatively-cooled type. This discrepancy between our expectation and the experimental results would be attributable to the flow direction induced by pressure increment $\Delta p$. In the tests, the gas flow which is induced by $\Delta p$ forced the arc spot to detach from the anode because the flow goes along the arc discharge current path toward the cathode tip. Then, the arc plasma was blown off by the gas from the combustion chamber simulator.

As shown in Fig. 11, $\Delta V/V$ is monotonically increased with $\Delta p$. As mentioned previously, electric resistance is generally increased by enlarging pressure, and hence $\Delta V$ is induced by $\Delta p$ because of increased electric resistance.

4.3. Effect of ballast resistor

Ballast resistor affected $P_s$, as shown in Fig. 10. The ballast resistor of 1 $\Omega$ shows lower $P_s$ than 2 $\Omega$. This is attributable to negative resistance of arc discharge. In general, arc discharge voltage decreases with increasing arc discharge current. This is referred as negative resistance, which would yield a positive feedback in electric circuits. Because the ballast resistor reduces the effect of negative resistance, they are sometimes applied to arcjet. Hence, interruption of arc discharge due to $\Delta p$ may be partially related to the stability of electric circuit.

![Fig. 8. (a) Time history with water-cooled arcjets at a discharge current of 15 A, ballast resistor of 1 $\Omega$, $\Delta p$ of 0.15 MPa. (b) Time history of discharge voltage and current after breaking the diaphragm.](image-url)
Fig. 9. (a) Time history with water-cooled arcjets at a discharge current of 15 A, ballast resistor of 1 Ω, Δp of 0.2 MPa. (b) Time history of discharge voltage and current after breaking the diaphragm.

Fig. 10. Dependence of $P_s$ on Δp.

Fig. 11. Dependence of $\Delta V/V$ on Δp.
5. Summary

We investigated the influence of variation in combustion chamber pressure on arcjets for an arcjet-assisted thruster to design active control system for stabilize arcjet-assisted combustion and to enhancing performance. The following are the summary of this study.

- We propose to apply active control to arcjet-assisted thruster in order to stabilize combustion in arcjet assisted chemical thrusters.
- The controller design requires the response of arcjets to variation in combustion-chamber pressure.
- Radiatively and water-cooled arcjets were prototyped, and tested to evaluate the influence of exit pressure change in arcjet exit using a combustion chamber simulator. In the combustion chamber simulator, pressure was rapidly increased by 0.1 to 0.35 MPa using a nitrogen-filled buffer with a burst diaphragm.
- Increasing $\Delta p$ reduces $Ps$ for both arcjets.
- Discharge voltage was increased by the sudden pressure increment in combustion chamber. Hence, active control system suppress the variation in arcjet power.
- Ballast resistor of 2 $\Omega$ showed higher $Ps$ than 1 $\Omega$. From this result, ballast resistor made a contribution to robustness against sudden change in combustion-chamber pressure.

References