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Micro-multi-plasmajet array thruster for space propulsion applications

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ABSTRACT

In this study, the characteristics of a 6 × 6 micro-multi-plasmajet array thruster were examined in vacuum. The discharge and thrust characteristics were examined experimentally. For the discharge operation, a stable and uniform plume from each nozzle element across an arrayed nozzle was observed at total nitrogen propellant mass flow rates ranging from 2.1 to 37.5 mg/s and total discharge currents ranging from 20 to 40 mA. Typical values of thrust, specific impulse, and thrust efficiency at a mass flow rate of 37.5 mg/s and an input power of 27 W were 39 mN, 107 s, and 0.33, respectively. Moreover, thrust performance of the 6 × 6 micro-multi-plasmajet array thruster was compared with a conventional 3 × 3 micro-multi-plasmajet array and micro single plasmajet thrusters. It was shown that the average thrusts per nozzle element of the 3 × 3 and 6 × 6 micro-multi-plasmajet array thrusters were two and three times higher, respectively, than the micro-single plasmajet thruster.

1. Introduction

It is becoming increasingly evident that microspacecraft will require efficient propulsion systems to enable many of the missions currently being investigated [1–4]. Although in the past, most of the small spacecraft have lacked propulsion systems altogether, future microspacecraft will require significant propulsion capability in order to provide a high degree of maneuverability. The benefit of using electric propulsion for the reduction of spacecraft mass will likely be even more significant for microspacecraft missions, where reducing the mass is a primary concern. Feasibility studies of microspacecraft are currently under development for masses less than 100 kg with an available power level for propulsion of less than 100 W.

Because of its system simplicity, arcjet thrusters with input power levels in the kilowatt range have been practically used in orbit such as in north–south station keeping (NSSK) of geosynchronous satellites, etc. It has been reported in previous studies that a thermal loss in electrodes and a frozen flow loss are the primary loss mechanisms of the arcjet thrusters [5–7]. It has been confirmed that the thermal loss can be reduced at high-voltage mode discharge operation cases. In addition, the frozen flow loss can be reduced at a lower specific power operation, or at a lower plasma temperature, although the specific impulse will decrease to some extent. In addition, it has been reported that the endurance of an arcjet is primarily determined by a degree of cathode erosion. From these facts, a significant suppression of these losses and cathode erosion can be expected with the use of the very low-power operation of the arcjet. In previous studies, for the reduction of arcjet input power, the operation of the throttle ability from 100 to 300 W was demonstrated, in which steady operation was achieved down to 40 W, but considerable voltage fluctuations were observed [8–11].

Horisawa et al. conducted investigations on small-sized very low-power arcjets, or plasmajets, of less than 10 W for discharge characteristics, thermal characteristics of discharging plasmas, and correlations of these characteristics with thrust performance [12–14]. Microfabrication of micro-arcjets with ultra-violet lasers, and the development of rectangular DC micro-arcjets of various sizes operated at less than 5 W have also been undertaken [15–17]. The geometry and dimensions in these experiments were of critical importance for efficient operation. In the previously mentioned

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studies, the rectangular micro-nozzle was machined in a 1.2-mm thick quartz plate. Sizes of the nozzle were 0.44 mm in exit height and 0.1 mm in constrictor height. The anode was a thin Au film (approximately 100 nm thick) coated by physical vapor deposition in vacuum on a divergent part of the nozzle. The cathode was also an Au film coated on an inner wall surface. In operational tests, a stable discharge was observed for a mass flow of 0.4 mg/s and input power of 4 W. In addition, thrust performance tests were conducted for various nozzles with different exit heights (0.4–0.8 mm), or area ratios, for a fixed length and various lengths of the divergent part [18]. From the results, nozzles with larger exit height and a longer divergent part showed higher thrusts and specific impulses. It was also shown that variations of the background pressure in the vacuum chamber, in which the thruster was tested, had a significant effect on thrust performance as much as the nozzle sizes owing to the enhanced under-expansion of the exhaust jet. To reduce the expansion of the exhaust jet, the effect of multi-jet interaction exhausted from the multi-nozzle jet array was additionally investigated [19–21]. In the investigation, the thrust characteristics of the 3 × 3 micro-multi-nozzle array were compared with those of a single-nozzle with identical elemental size. To compare the thrust performances between the arrayed thruster and single-nozzle thruster, the thrusts and mass flows per nozzle, or the average values of each nozzle element, of the array were estimated by dividing each of the measured values of thrust and mass flow by the number of nozzle elements of the array. From the results, it was shown that the thrust and specific impulse of each nozzle element with the nozzle array were significantly higher than those of the single-nozzle [19–21].

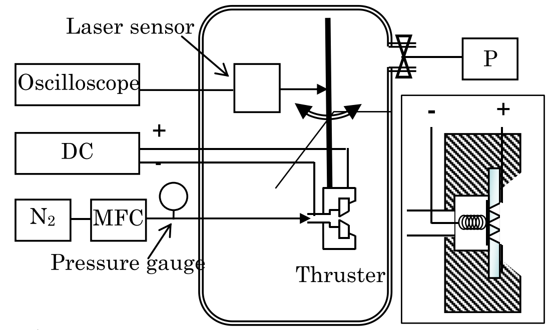
In this study, an investigation of discharge and thrust characteristics of a micro-multi plasmajet array thruster with a larger number of nozzle elements, i.e. 6 × 6, was conducted. Moreover, thrust performance of the 6 × 6 micro-multi plasmajet array thruster was compared with that of our previously developed 3 × 3 micro-multi-plasmajet array thruster and a micro-single plasmajet thruster.

2. Experimental analysis

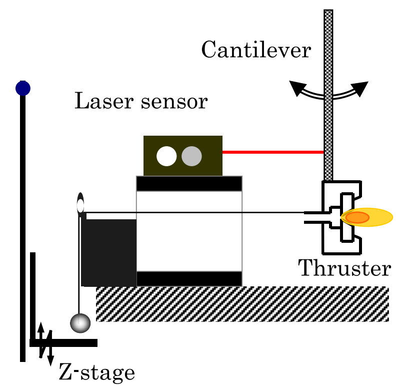
A schematic of the experimental setup is shown in Fig. 1(a). Thrust performance tests were conducted in vacuum to elucidate effects of various operational conditions on the discharge and thrust characteristics of a micro-multi-plasmajet array thruster. Nitrogen gas was employed as the propellant for the thruster, and its mass flow rate was controlled with a mass flow controller for various mass flow rates ranging from 2.1 to 37.5 mg/s. The thrust generated by the thruster was measured with a cantilever-type thrust stand consisting of a cantilever and structural members made of quartz glass to minimize the influence of the thermal expansion of the structure (Fig. 1(b)) [15]. A displacement of the cantilever was monitored by a laser displacement sensor. The background pressure throughout the experiments was under 3 Pa.

First, thrust tests were performed for cold-gas conditions to evaluate substantial thrusts induced owing to the aerodynamic acceleration of propellant flows through the nozzles of a micro-multi-plasmajet array thruster, in which the propellant supplied to the plenum was not heated by any electrical means, but kept in a room temperature (293 K). Second, for hot-gas conditions, an investigation of discharge characteristics and thrust performance of the micro-multi-plasmajet array thruster was also conducted for input powers of up to 27 W.

Figs. 2 and 3 show a schematic diagram and an image of the micro-multi-plasmajet array thruster with an array of plasmajets with 6 × 6 (36) elements. This thruster consists of a stainless steel anode with 6 × 6 plasmajet elements and 6 × 6 tungsten cathodes each having a ballast resistor. An alumina cathode holder and an alumina insulator (body) were employed for insulation of the cathodes and anode. To improve thrust performance and to achieve a uniform discharge over all electrode elements as compared to our previously tested thrusters [19–21], the new thruster with



(a) Experimental setup.



(b) Cantilever-type thrust stand.

Fig. 1. Schematics of experimental setups.

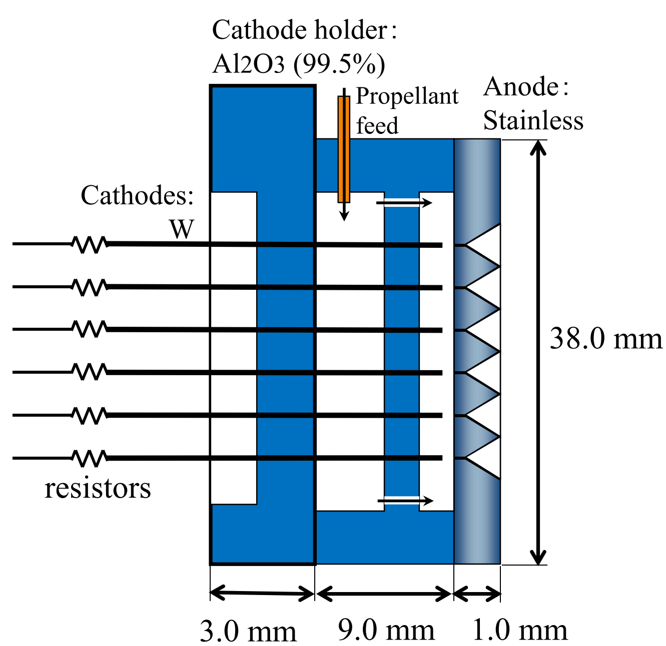


Fig. 2. Schematic of a micro-multi-plasmajet array thruster with 6 × 6 (36) nozzle elements.