

Development of a Micro-Multi-Plasmajet-Array Thruster

IEPC-2011-295

*Presented at the 32nd International Electric Propulsion Conference,
Wiesbaden • Germany
September 11 – 15, 2011*

Naoto Kobayashi¹, Ryosuke Hitomi², Kazuki Asanuma³ and Hideyuki Horisawa⁴,
Dept. Aeronautics and Astronautics, Tokai University, Hiratsuka, Kanagawa, 259-1292 Japan

and

Ikkoh Funaki⁵
*Japan Aerospace Exploration Agency
Sagamihara, Kanagawa, 252-5210 Japan*

Abstract: Microfabrication of a 3x3 micro-plasmajet array with ultra-violet lasers and their thrust performance tests were conducted for nozzle elements with exit height of 0.5 mm and length of 0.5 mm. To evaluate thrust characteristics of the 3x3 arrayed plasmajet, thrust characteristics of the thruster were compared with those of the micro-single-nozzle plasmajet. It was shown that the thrust and specific impulse of the micro-plasmajet array were higher than those of the micro-single-nozzle plasmajet due to the multi-jet effect. The typical values of the thrust, specific impulse and averaged per nozzle element of the 3x3 micro-plasmajet array thruster operated at 6.5W with 1.25 mg/sec of propellant mass flow per nozzle element were 0.77 mN, 62 sec, respectively. In addition, observation of the micro-nozzle discharges was conducted, and a new thruster with extended nozzle structure for which each electrode element was electrically isolated from nearby elements was developed. A preliminary DSMC computation on internal and exhaust nozzle-flow characteristics of micro-nozzles of multi-nozzle array was conducted.

I. Introduction

Authors have been conducting investigations on small-sized very low-power arcjets, or plasmajet, of less than 10 watts for discharge characteristics, thermal characteristics of discharging plasmas, and correlations of these characteristics with thrust performance.^{1-3,6} Moreover, authors have conducted microfabrication of micro-arcjets with ultra-violet lasers, and developed rectangular DC micro-arcjets of various sizes operated under 5 watts.^{4,5,7,8} The rectangular micro-nozzle was machined in a 1.2 mm thick quartz plate. Sizes of the nozzle exit were 0.44 mm in height and 0.1 mm in constrictor height. For an anode, a thin Au film (~ 100 nm thick) was coated by physical vapor deposition in vacuum on a divergent part of the nozzle. As for a cathode, an Au film was also coated on inner wall surface. In operational tests, a stable discharge was observed for mass flow of 0.4 mg/sec, input power of 4 watts, as shown in Fig.1. In addition, thrust performance tests were conducted for various nozzles with different exit heights (0.4 to 0.8 mm), or area ratios, for a fixed nozzle length and various lengths of divergent part.⁴ From the results,

¹ Graduate Student, Department of Aeronautics and Astronautics, 1bmjm011@mail.tokai-u.jp

² Graduate Student, Department of Aeronautics and Astronautics, 0bmjm021@mail.tokai-u.jp

³ Graduate Student, Department of Aeronautics and Astronautics, 1bmjm002@mail.tokai-u.jp

⁴ Professor, Department of Aeronautics and Astronautics, horisawa@keyaki.cc.u-tokai.ac.jp

⁵ Associate Professor, Japan Aerospace Exploration Agency, funaki@isas.jaxa.jp

nozzles with larger exit height and 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 were tested, relatively affected on thrust performance as much as nozzle sizes due to the enhanced under-expansion of the exhaust jet.⁴ To suppress the expansion of the exhaust jet, the effect of multi-jet interaction exhausted from the multi-nozzle jet array was additionally investigated.^{5,7,8} In the investigation, thrust characteristics of the 3x3 micro-multi-nozzle array were compared with those of a single-nozzle with identical elemental size. To compare the thrust performance between the arrayed thruster and single-nozzle thruster, thrusts and mass flows per nozzle, or average values of each nozzle element, of the array were estimated by dividing each of measured values of thrust and mass flow by number of nozzle elements of the array. From the results, it was shown that the thrust and specific impulse of the each nozzle element with the nozzle array were significantly higher than those of the single-nozzle.^{5,7,8}

In this study, thrust characteristics of the micro-nozzle arrays with different geometries were investigated. Moreover, after fabricating the electrodes in the micro-nozzle arrays, investigation of the discharge characteristics and preliminary propulsive characteristics were also conducted.

II. Experimental

A. Microfabrication of Micro-nozzles

Authors have developed and been using a laser micromachining system for machining of micro-nozzles.^{4,5,7,8} In order to minimize and localize thermal influences and to achieve accurate geometries, a short-pulse ultra-violet laser system was utilized. For the UV laser oscillator, a fifth harmonic generation wave of an Nd:YAG laser beam (Fifth-HG, wavelength 213 nm, NEWWAVE RESEARCH, Tempest-10, repetition rate 10 Hz) was utilized. With this technique, 3x3 and 4x4 micro-nozzle-arrays were machined. The SEM images of the micro-nozzles are shown in Fig.1. In this study, a single nozzle (a), 3x3 and 4x4 nozzle arrays, (b) and (c), consisting of identical nozzle elements with (a), were machined and tested. Sizes of the nozzle element, or single nozzle, are 0.5 mm in total length, 100 μm in throat height and length, 500 μm in exit height.

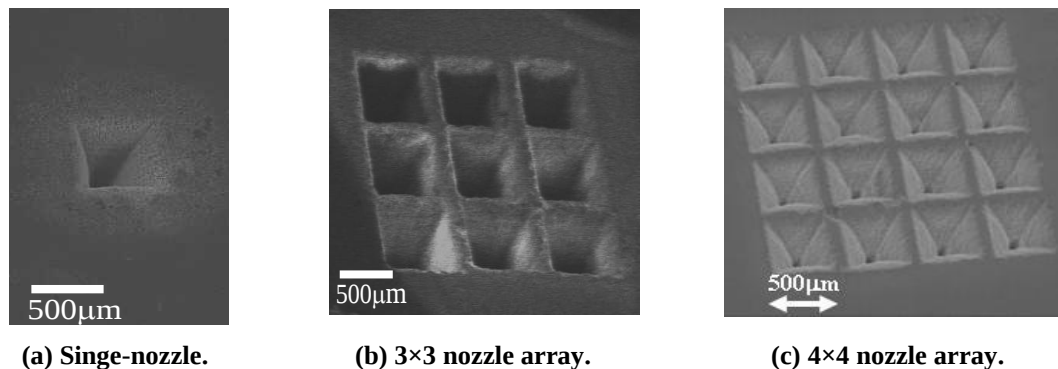


Figure 1. Scanning electron microscope images of micro nozzles.

B. Thrust Measurement

A sketch of an experimental setup is illustrated in Fig.2(a). Thrust performance tests were conducted to elucidate effects of nozzle configuration on thrust characteristics for the micro single-nozzle and the novel nozzle array thrusters. For various mass flow rate conditions of nitrogen gas propellant thrusts were measured for both types of the thrusters, and then thrust characteristics were compared. The thrust was monitored with a cantilever-type thrust stand consisting of a cantilever and structural members made of quartz glass to minimize influences of thermal expansion of the structure (Fig.2(b)). To evaluate the substantial thrust induced from aerodynamic acceleration of the propellant flow through the nozzle, the propellant supplied to the plenum is not heated by any electrical means but kept in a room temperature. Namely, the thrust tests are performed for the cold-gas operation.

In addition, after depositing film electrode made of gold on both plenum side (cathode) and divergent-nozzle side (anode), shown in Fig.2(a), investigation of the discharge characteristics and preliminary thrust performance tests were conducted for the micro-multi-plasmajet array thruster.

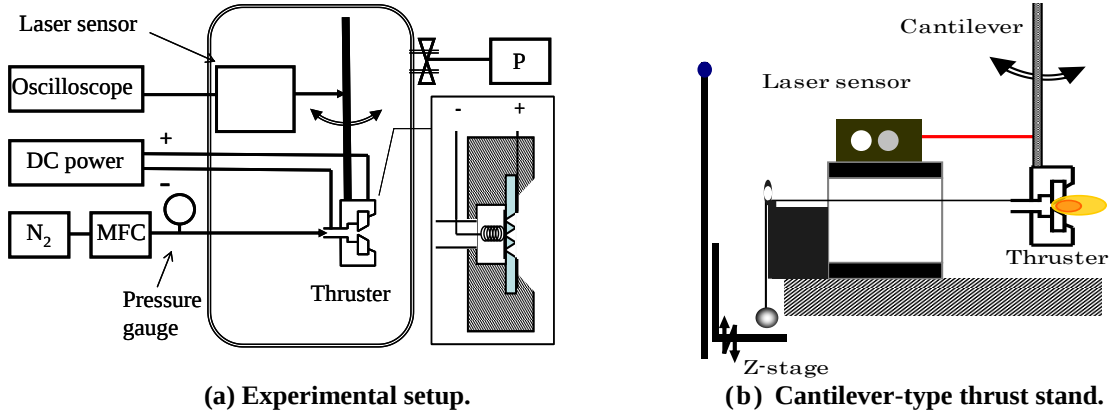


Figure 2. Schematics of experimental setups.

III. Thrust Performance Experiment of Micro-Nozzle-Array

A. Electrode Structure of Micro-Multi-Plasmajet-Array Thruster

Figs.3 and 4 show schematics of electrode structure of micro-multi-plasmajet thruster. In Fig.3, the anode is made of a gold film coated on divergent (exhaust) side and the cathodes are made of tungsten needles of 0.1 mm in diameter. Each pair of anode and cathode consists of a typical electrode structure of conventional arcjet thrusters. A cathode holder is made of Inconel® alloy which has 9 holes with each depth and diameter of 1 mm and 0.1 mm, respectively. Inserted into each hole, 9 tungsten needles can work as a cathode. In discharging operations, it is observed that the heat of cathode tips is not easily transferred into the holder and nozzles ensuring possibilities of long operation time.

On the other hand in Fig.4, the cathode is made of tungsten filament attached with film cathode coated on inner (convergent) side. Difference of discharge operational characteristics was compared with each electrode structure.

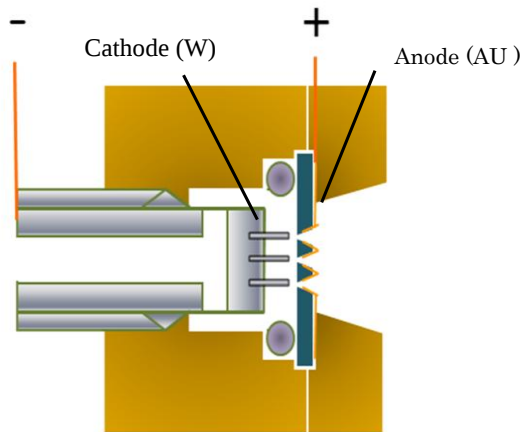


Figure 3. Schematic of micro-multi-plasmajet thruster with needle cathodes.

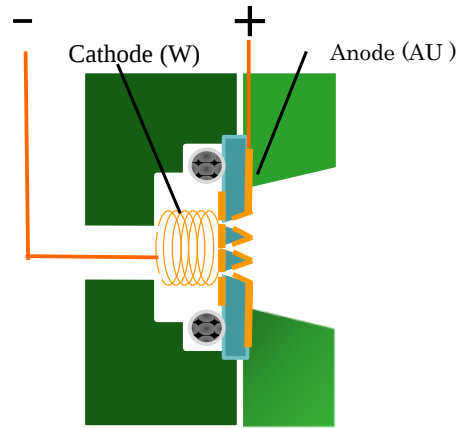


Figure 4. Schematic of micro-multi-plasmajet-array thruster with tungsten filament.

B. Typical Thrust Characteristics of Micro-Multi Plasmajet Array Thruster

To evaluate thrust characteristics of the nozzle-array, its thrust performance was compared with the single-nozzle. The thrusts and mass flows per nozzle, or each nozzle element, of the array-nozzle were estimated by dividing each of measured values of thrust and mass flow by number of nozzle elements of the array-nozzle. Typical results of specific impulse are plotted in Fig.5. The typical values of the specific impulse of the 3x3 array and single micro-plasmajets operated with 1.25 mg/sec of propellant mass flow were 62sec and 41sec, respectively.

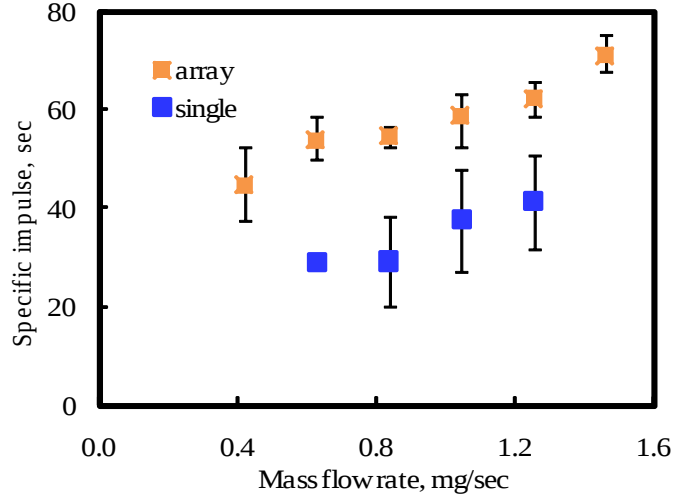


Figure 5. Comparison of specific impulse for various mass flow for 3x3 micro nozzle-array- and single-nozzle- thrusters operated.

C. Discharge Characteristics of Micro Multi-Plasmajet Array Thruster

Discharge current-voltage characteristics of the micro-multi-plasmajet-array thruster are shown in Fig.6. In the figure, variation of plenum pressure inside the discharging thruster is also plotted. From the current-voltage characteristics, abrupt drops of discharge voltages, which are roughly from 360 V to 240 V, are observed at discharge currents between 18 mA and 20 mA for various mass flow cases. Although further investigation should be needed, from the negative current-voltage characteristics the discharge partly has an aspect of arc discharge characteristics. On the other hand, the plenum pressure increases with mass flow and discharge current.

Photos of plasma plumes at discharge currents of 10 mA and 20 mA are shown in Fig.7. As shown in these figures, a stable and uniform plasma plume exhausted from the 3x3 micro-plasmajet array thruster can be observed. Through the side face of the quartz plate, several discharging columns at each throat of the micro multi-plasmajet can be observed in the 10 mA condition. While in the 20 mA condition, emission from the each throat is so strong that each emission cannot be separately identified.

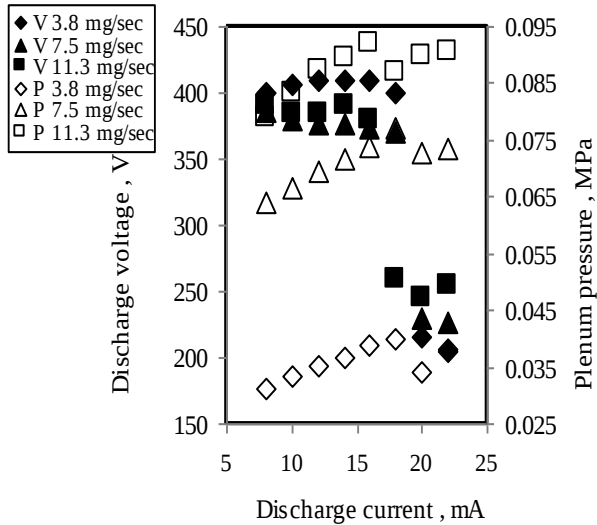
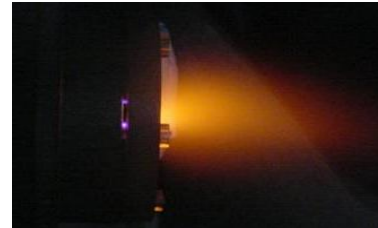


Figure 6. Discharge voltage and discharge plenum pressure vs discharge current.



(a) 10 mA.



(b) 20 mA.

Figure 7. Photos of stable plasma plumes operated under different discharge currents.

D. Discharge behaviors of 3x3 Micro-Multi Plasmajet Array

Front (backward) view images of plasma plumes exhausted from the 3x3 micro-multi plasmajet array in discharging operation employing different electrode structures were shown in Figs.8 and 9. These images were taken by the CCD video camera (30 frames/sec) through an ND filter, a band-pass filter and a convex lens to obtain a magnification by 30 times.

Three typical characteristics of the plasma plume behaviors can be obtained with the increase of discharge current.

Firstly under low current cases, translation of positions of the discharging spots is observed with the increase of the current. Secondly, the brightest spot, or an ununiform discharging emission spot, is observed in the center of Figs.8 (b) and the upper left of 9 (b) with other electrodes showing much darker emissions.

In the last, the brightest spots of are not always occurring at the same position (electrode) in each discharging operation.

These phenomena may cause not only decreasing thermal efficiency of the thruster, but also increasing possibility of taper off the cathode tips as well.

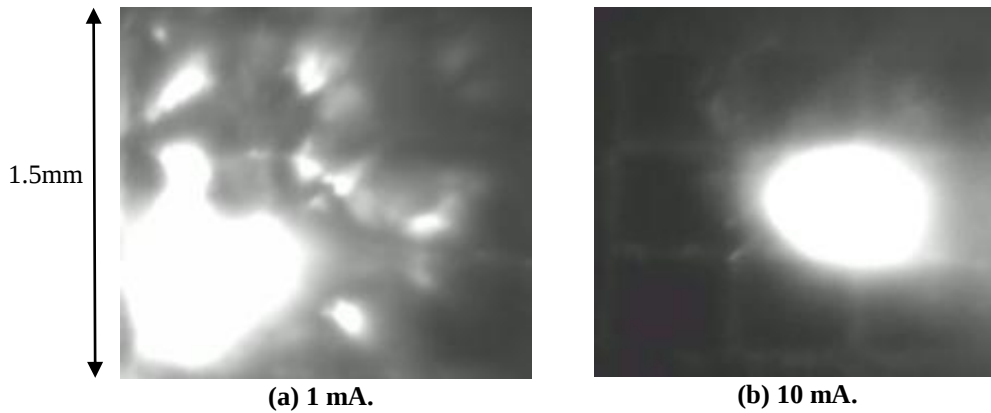


Figure 8. Photos of 3x3 nozzles in discharge experiment(W-filament cathode).

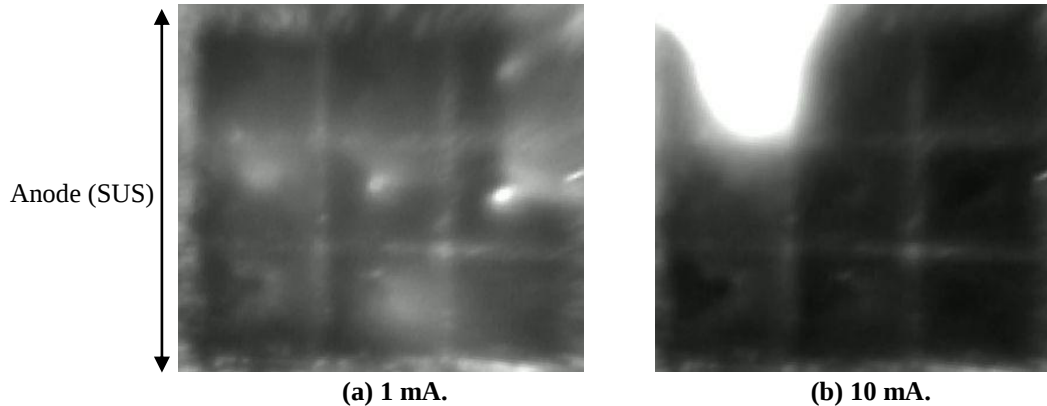


Figure 9. Photos of 3x3 nozzles in discharge experiment(W-needle cathodes).

Therefore, to improve thrust performances and to achieve uniform discharges over all electrode elements, a new thruster with extended nozzle structure for which each electrode element was electrically isolated from nearby elements was developed. Figs.10 and 11 depict a schematic of the new thruster and that nozzle array with 36 nozzle elements. And, Fig.12 shows a microscopic image one nozzle element. Increase of the number of nozzle elements is expected to lead improvement of thrust performances through multi-jet effect of interacting gas jets⁸.

This thruster consists of a stainless steel anode with 6x6 nozzle elements and 6x6 needle cathodes made of tungsten wires each having a ballast resistor. With these resistors, uniform discharge over electrodes can be expected. In addition, control of the each discharge current can be done by controlling each resistance.

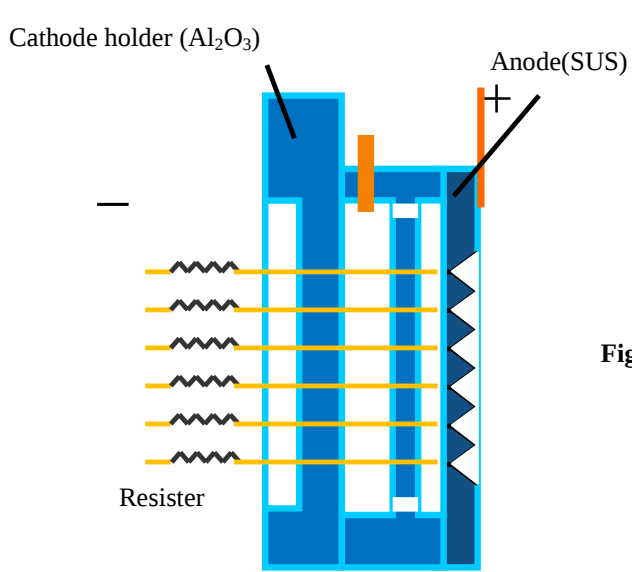


Figure 10. Schematic of multi-nozzle array thruster with 36 nozzle elements.

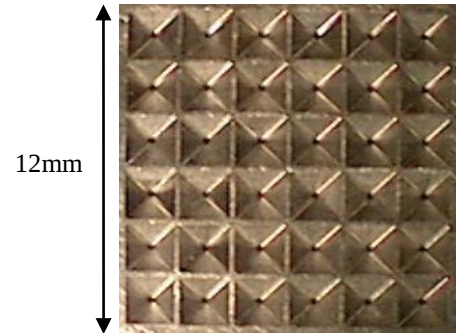


Figure 11. Photos of nozzle array with 36 nozzle elements.

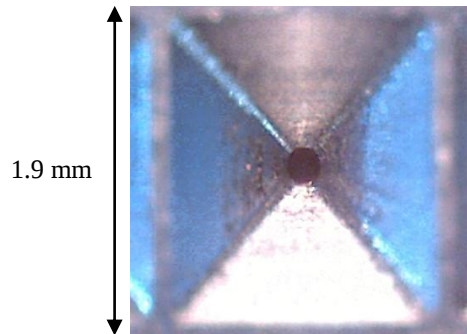


Figure 12. Microscope image of one nozzle element.

In Figs.13 and 14, thrust characteristics of the new thruster in cold gas experiments were shown.

Variation of thrust with mass flow rate is shown in Fig.13. It is shown that the thrust linearly changes with mass flow rate.

Variation of specific impulse is plotted in Fig.14. With lower mass flow conditions under 7 mg/sec, measured specific impulse is very low, i.e. under 40 sec.

The typical values of the thrust and specific impulse of the multi-nozzle array thruster with 36 nozzle elements operated with 11 mg/sec of propellant mass flow were 6 mN and 60 sec, respectively

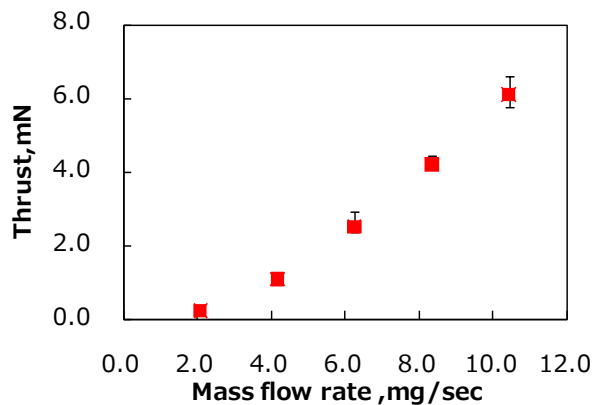


Figure 13. Thrust vs mass flow rate of nozzle performance.

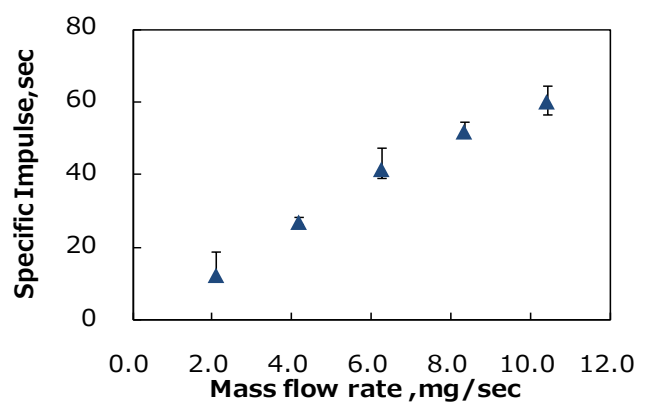


Figure 14. Specific impulse vs mass flow rate of nozzle performance.

IV. NUMERICAL SIMULATION

A. DSMC Method

In designing an optimum micro-nozzle configuration, it is significantly important to consider the factors such as area ratio, pressure ratio, micromachining accuracies (geometrical accuracy, surface flatness, surface roughness), boundary layer thickness on inner nozzle wall, etc. Traditional continuum-based computational techniques employing the Navier-Stokes equation for the simulation of micro-nozzle flows can often provide erroneous or misleading results. These inaccuracies generally result during the computation of molecular transport effects. The macroscopic properties of any fluid flow may be identified with average values of the appropriate molecular quantities at any location within the flow. When this condition is not satisfied, there is a limit imposed on the range of validity of these continuum equations. This limit occurs when gradients of the macroscopic variables become so steep that the scale length is of the same order as the mean free path of the gas⁹.

Because the flows through very small throat diameter sizes even at large stagnation pressures result in relatively small Reynolds numbers, the predicted results obtained from Navier-Stokes solutions may be inaccurate. In the micro-nozzle flow predictions, it has been indicated that the Direct Simulation Monte Carlo (DSMC) method gives more accurate results for macroscopic performance characteristics⁹. The DSMC method provides means to simulate the flow of a general rarefied gas at the molecular level.

Therefore in this study, the DSMC method is employed to investigate flowfield of micro-nozzles. Since rectangular micro-nozzles have been developed and tested in our experiment, two-dimensional numerical models are utilized.

B. Simulation Models

Geometries of two-dimensional simulation models for micro nozzle-array are illustrated in Fig.15. As shown in these figures, only upper half of a nozzle element is calculated for a nozzle-array. A lower half of an upper nozzle element combined with an upper half of a lower nozzle element along the centerline. Boundary conditions are assumed as random reflection for the centerline and walls. Length and width of the nozzle element are identical to those used in our experiments, given in Fig.15. Typical models consist of 70 grids in horizontal direction (50 grids inside the nozzle) and 200 grids in vertical direction (100 grids inside the nozzle).

Conditions at stagnation point are taken from our experimental data for cold-gas flow of gaseous nitrogen propellant in which the stagnation temperature is assumed as room temperature, 300 K. A typical Knudsen number is 0.01 at nozzle throat.

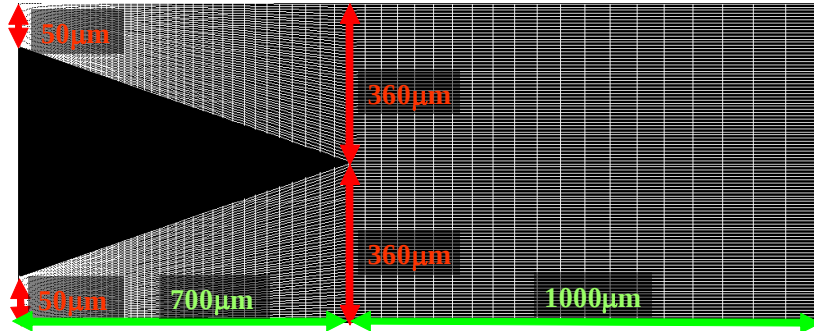


Figure 15. Simulation model of DSMC for successive internal nozzle flow and exhaust multi-jets.

C. Micro Nozzle-Array

Typical results for a micro nozzle-array are shown in Fig.16, showing pressure and Mach number distributions. It can be seen that pressure at the nozzle exit is increased through interaction of the exhaust-jet boundaries. This effect of the increase of the static pressure at the nozzle exit may be transferred to an internal core flow in divergent nozzle section through a subsonic boundary layer of the internal flow, and suppress and smooth a large pressure drop inside the nozzle, leading reduction of the boundary layer thickness.

In addition, it can be seen that Mach numbers drop between the jet-boundaries, and then the exhaust-jets are not expanded at the nozzle exit, or rather confined. These effects will reduce losses derived from viscous losses of the internal nozzle flow and under-expanding flow of the exhaust jet. Further simulation will be conducted to elucidate these mechanisms.

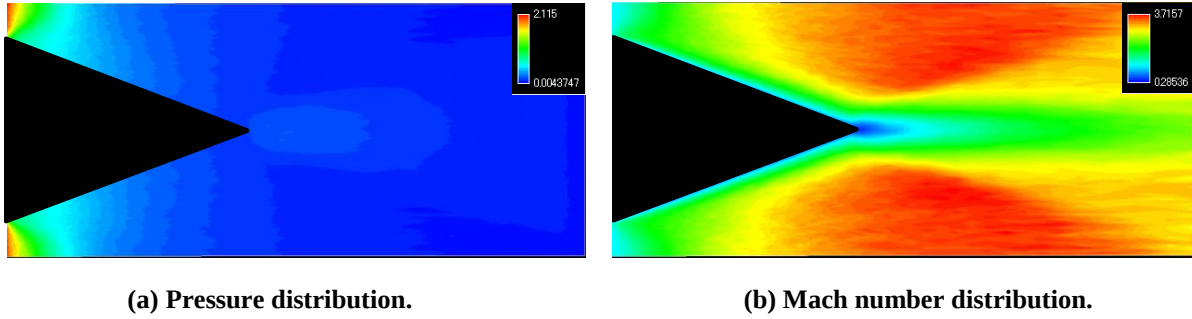


Figure 16. Results of DSMC computation of successive internal nozzle flow and exhaust multi-jets.

D. Interaction of Exhaust Multi-Jets from Micro Array-Nozzle

An investigation on an interaction of exhaust multi-jets of the micro-nozzle array was also conducted using a DSMC computation code. Since our primary concern in this simulation was on the influences of interactions between under-expanded exhaust jet boundaries, or multi-jet effect, a sonic condition was employed to each exhaust jet without calculating internal nozzle flows for simplicity.

Typical results of pressure distributions for two-dimensional quintuple nozzle cases for different nozzle-separations, i.e., (a) 100 μm , (b) 50 μm , (c) 25 μm , and (d) 0 μm are shown in Fig.17, in which each exit height of each nozzle element is 400 μm . As shown in these figures, pressure drops between the nozzles, or at separating points, at the exit tend to become less significant as the nozzle-separation decreases. Moreover in the smaller separation case, a higher pressure region tends to extend further in axial direction and also in normal direction perpendicular to a nozzle axis. It can be seen that the tendency of the extension of the high pressure region is more exaggerated especially in the center nozzle element.

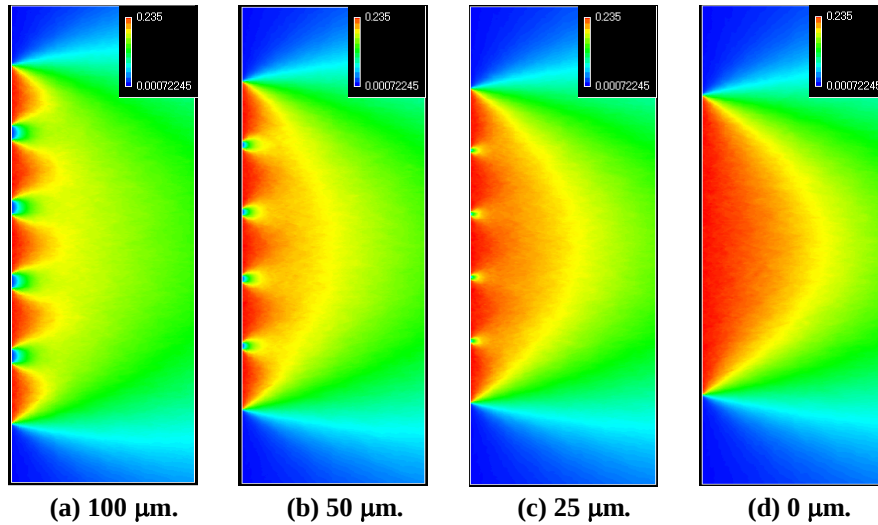


Figure 17. Typical results of pressure distributions for two-dimensional quintuple nozzle cases for different nozzle-separations, (a) 100 μm , (b) 50 μm , (c) 25 μm , and (d) 0 μm .

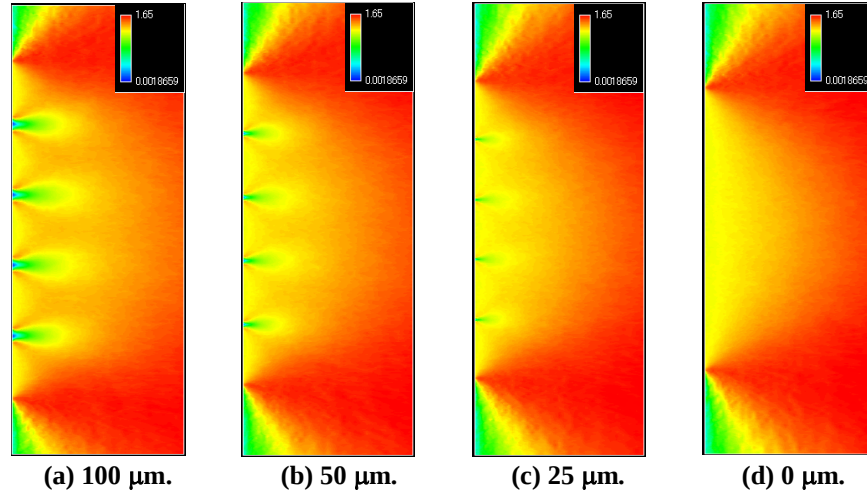


Figure 18. Typical results of Mach number distributions for two-dimensional quintuple nozzle cases for different nozzle-separations, (a) 100 μm , (b) 50 μm , (c) 25 μm , and (d) 0 μm .

Results of distributions of Mach numbers are shown in Fig.18. As can be seen in these figures, flows expanding between the nozzles, or to separating regions, at the exit tend to become significantly small as the nozzle-separation decreases. Namely, it is confirmed that the expansion of each expanding nozzle jet tends to become suppressed and axial velocity components and Mach number being augmented through the interactions of the jet boundaries.

Therefore, from these results, it is shown that the use of the multi-nozzle array is effective in suppressing expansion of each under-expanding jet, and in inducing more axially confined jets, through the interactions of the jet boundaries and the increase of the background pressure between the nozzles.

The reduction of each nozzle-separation will result in the nozzle exhaust flow to be equivalent to that of a single nozzle which has the identical total-exit-height. Although the total-exit-height is identical, the multi-nozzle-array has the advantage in that its nozzle length can still be kept small, or thin, compared with the single nozzle, in which its length has to be at least twice as large as its height. This point can be one of the most significant advantages of the multi-nozzle-array.

V. Conclusion

Microfabrication of a 3x3 micro multi-plasmajet array with ultra-violet lasers and its thrust performance tests were conducted for nozzle elements with exit height of 0.5 mm and lengths 0.5 mm. Stable discharge and operational conditions were confirmed for the 3x3 micro multi-plasmajet array thruster. To evaluate thrust characteristics of the arrayed plasmajet, thrust characteristics of the thruster were compared with those of the micro-single-nozzle plasmajet. The thrust was measured by a calibrated cantilever-type thrust stand in vacuum. Following results were obtained.

- 1) It was shown that the thrust and specific impulse of with the micro-plasmajet array were higher than those of the micro-single-nozzle plasmajet due to the multi-jet effect.
- 2) To improve thrust performances and to achieve uniform discharges over all electrode elements, a new thruster with extended nozzle structure for which each electrode element was electrically isolated from nearby elements was developed.
- 3) The typical values of the thrust and specific impulse of the multi-nozzle array thruster with 36 nozzle elements operated with 11 mg/sec of propellant mass flow were 6 mN and 60 sec, respectively.
- 4) From the DSMC computation, it was shown that the use of the micro nozzle-array was effective in suppressing expansion of each under-expanding jet, and in inducing axially confined jets, through the interactions of the jet boundaries, or multi-jet effects.
- 5) It was also shown from the simulation that pressure at the nozzle exit increased through interaction of the exhaust-jet boundaries. This effect must increase a pressure thrust component and static pressures of boundary

layers in internal nozzle flows. These effects will reduce losses derived from viscous losses of internal nozzle flow and under-expanding flow of exhaust jet.

References

- ¹Horisawa, H., and Kimura, I., "Influence of Constrictor Size on Thrust Performance of a Very Low Power Arcjet," AIAA Paper 98-3633, July 1998.
- ²Horisawa, H., and Kimura, I., "Optimization of Arc Constrictor Sizes in Low Power Arcjet Thrusters," AIAA Paper 97-3202, July 1997.
- ³Horisawa, H., Ashiya, H. and Kimura, I.: Discharge Characteristics of a Very Low-Power Arcjet, IEPC 03-0078, 2003.
- ⁴Horisawa, H., Onodera, K., Tsuyoshi, N. and Kimura, I.: "Multi-Jet Effects of Micro-Nozzle Array in Very Low-Power DC Micro-Arcjets," AIAA Paper 06-4496, July 2006.
- ⁵Sawada, F., Kosiyama, A., Hagiwara, S., Horisawa, H. and Funaki, I.: "Effects of Nozzle Geometries on Thrust Performance Improvement of Micro-Multi-Nozzle-Array Thrusters," ISTS 2008-b-16, 26th International Symposium on Space Technology and Science, 2008.
- ⁶Horisawa, H., and Kimura, I.: Studies of Very Low Power Arcjets, Chap.6 in Micropropulsion for Small Spacecraft (Micci, M.M., and Ketsdever, A.D. eds.), *Progress in Astronautics and Aeronautics* Vol.187, pp.185-197, American Institute of Aeronautics and Astronautics, 2000.
- ⁷Koshiyama, A., Onodera, K., Sawada, F., Horisawa, H. and Funaki, I.: "Micro-Plasmajet Array: Multi-Jet-Effect for Thrust Performance Improvement," IEPC-2007-201, *Proceedings of the 30th International Electric Propulsion Conference, 2007*.
- ⁸Horisawa, H., Sawada, F., Onodera, K., and Funaki, I.: "Numerical simulation of micro-nozzle and micro-nozzle-array flowfield characteristics," *Vacuum*, 83 (2008), pp.52-56.
- ⁹Ketsdever, A. D.; System Consideration and Design Options for Microspacecraft Propulsion System, *Progress in Astronautics and Aeronautics*, Vol.187, 2000, pp.139-163.