Thrust Performance of a Micro-Multi-Plasmajet-Array Thruster

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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. Stable discharge and operational conditions were confirmed for the 3x3 micro-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. 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 thrust efficiency averaged per nozzle element of the micro-plasmajet array thruster operated at 6.2 W with 1.46 mg/sec of propellant mass flow per nozzle element were 1.13 mN, 79 sec, and 24%, respectively. In addition, observation of the micro-nozzle discharges 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, 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

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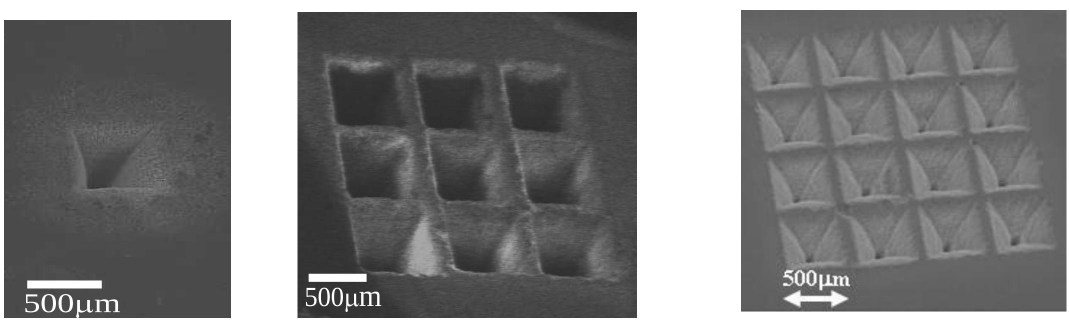
multi-nozzle jet array was additionally investigated.[5,7,8)] In the investigation, thrust characteristics of the 3x3 micro-multi-nozzle array were compared with those of a single-nozzle with identical elemental size. To compare the thrust performance between the arrayed thruster and single-nozzle thruster, 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. Experimantal

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.



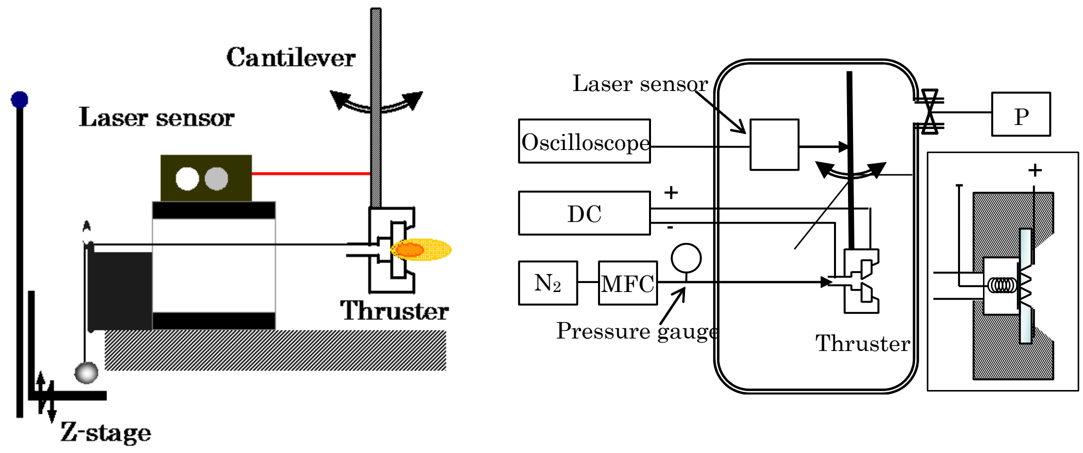
(a) Single-nozzle. **(b) 3 x 3 nozzle array.** **(b) 4 x 4 nozzle array.**

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.



(a) Experimental setup. **(b) Cantilever-type thrust stand.**

Figure 2. Schematics of experimental setups.

III. Results and Discussion

A. Comparison of Thrust Performance for Micro Single Plasmajet and Micro Multi-Plasmajet Array

Average thrust and specific impulse of 3x3 micro-plasmajet array thruster are shown in Figs.3 and 4. Values of the average thrust are those averaged per nozzle element, or total thrust divided by number of nozzles, which in these cases are nine. In these figures, values of mass flow rates of propellant (nitrogen) are also averaged values per nozzle element. In each case, the thrust linearly increases with mass flow rate. On the other hand, the specific impulse gradually increases with mass flow in each case.

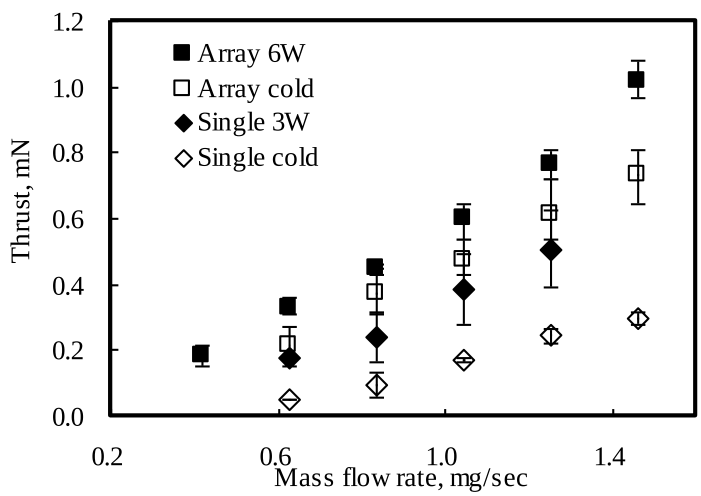


Figure 3. Thrust vs mass flow rate for MSPJ (Single) and MMPJ (Array).

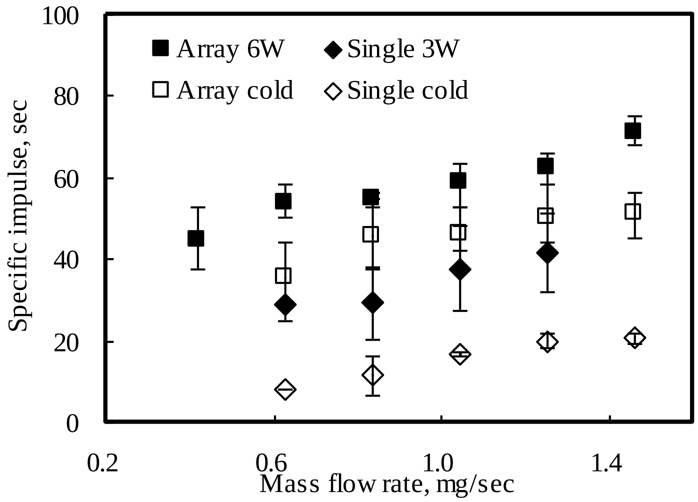


Figure 4. Specific impulse vs mass flow rate for MSPJ (Single) and MMPJ (Array).

Comparing the thrust and specific impulse between micro single plasmajet (MSPJ) and micro multi-plasmajet array (MMPJ) thrusters, significantly high thrust performances were obtained for the array thruster cases. In our previous study[5)], it was shown that the use of the multi-nozzle array was 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. Moreover, it was also expected that this effect of the increase of the static pressure at the nozzle exit will be transferred to an internal core flow in divergent nozzle section through a subsonic boundary layer of the internal flow, and will probably suppress and smooth a large pressure drop inside the nozzle, reducing the boundary layer thickness. Therefore, it can be expected that this multi-jet effect will reduce the boundary layer thickness and namely improve nozzle efficiencies.

Typical values of the averaged thrust and specific impulse at mass flow of 1.25 mg/sec per nozzle were 0.51 mN and 41 sec, respectively, for MSPJ at a total input power of 2.9 W. On the other hand, for MMPJ, the averaged thrust and specific impulse at the same mass flow per nozzle element were 0.77 mN and 62 sec, respectively, at a total input poweer of 6.5 W. From these results, it can be seen that with the arrayed nozzle structure the thrust and specific impulse were significantly improved, which were over 50% higher than the MSPJ cases.

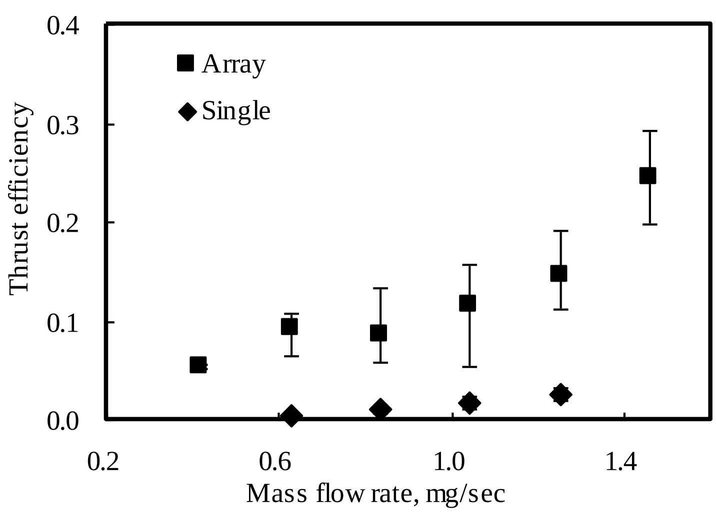


Figure 5. Thrust efficiency vs mass flow rate for MSPJ (Single) and MMPJ (Array).

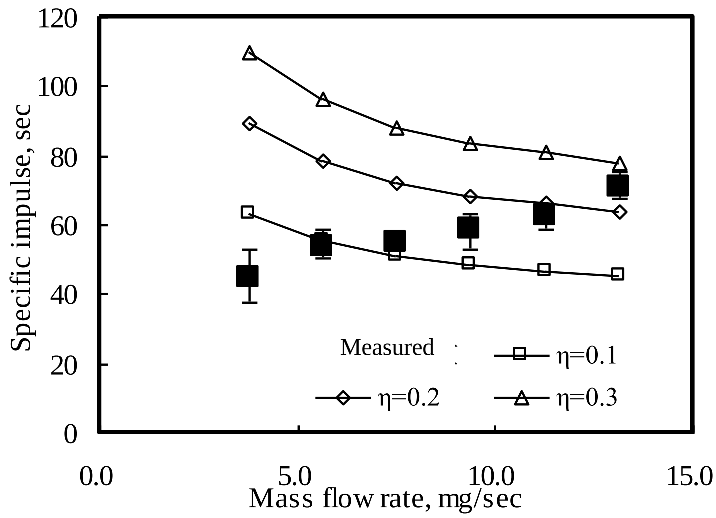


Figure 6. Comparison of theoretical and measured values of specific impulse for MMPJ, where values of thrust efficiencies are assumed η = 0.1 ~ 0.3.

Plots of thrust efficiency versus mass flow for MSPJ and MMPJ are shown in Fig.5, where the thrust efficiency is defined as a ratio of an increase of kinetic power of the exhaust gas to an electrical input power. The increase of kinetic power is obtained by the subtraction of the kinetic power of the cold gas thrust from a total kinetic power of the plasma flow thrust. Since the contribution of the cold gas thrust in the total thrust is relatively high and not negligible, the increment of the kinetic energy through the electrical dischcarge was used to estimate the thrust efficiency. From the figure, thrust efficiency was also improved siginificantly in multi-plasmajet cases. Typical values at mass flow of 1.25 mg/sec are 0.03 and 0.15 for MSPJ and MMPJ, respectively. From the results, a possibility to overcome one of the disadvantages of the micro-thrusters, i.e., low efficiency because of the viscous loss, was demonstrated with the arrayed plasmajet thruster.

Comparison theoretical and measured values of specific impulse for MMPJ cases are shown in Fig.6. In this figure, plots of the mass flow rate are the total mass flows for every nozzle element. The theoretical values are estimated from a simple quasi-one-dimensional flow analysis, where an expantion ratio of the nozzle is taken into account, and thrust efficiencies are assumed η = 0.1 to 0.3, using measured values. It can be seen that there are good agreement between theoretical and measured values at higher mass flow rate with η = 0.2 to 0.3 and at lower mass flow with η = 0.1, assuming the variation of the thrust efficiency along with the change of the measured values shown in Fig.5.

In electro-thermal thrusters, in general, where the aerodymanic acceleration of the gas is the primary mechanism of thrust generation, a theoretical specific impulse depends on a gas temperature inside the plenum. Under a constant input power condition for the thruster, the specific impulse decreases with mass flow. On the other hand, in our experiment, measured specific impulse decreases with decreasing mass flow. This is due to the decrease of thrust efficiency because of the decrease of Reynolds number and namely the increase of viscous loss inside the nozzles.

B. Discharge Characteristics of Micro Multi-Plasmajet Array Thruster

Discharge current-voltage characteristics of the MMPJ thruster are shown in Fig.7. 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.8. 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.

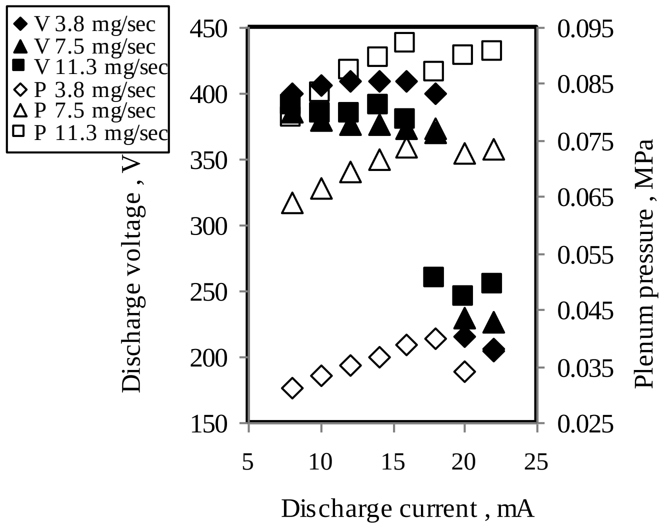
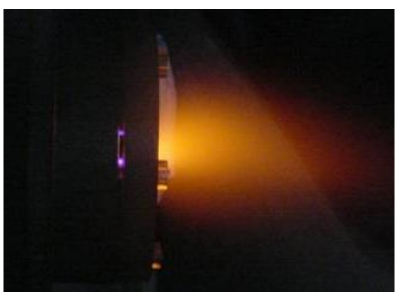


Figure 7. Discharge voltage and discharge plenum pressure vs discharge current.



(a) 10 mA

(b) 20 mA

Figure 8. Photos of stable plasma plumes operated under different discharge currents.

C. Influence of Throat Size of Each Nozzle Element on Thrust Performance

Influence of throat height of each nozzle element of 3x3 MMPJ was examined. Fig 9 to 11 show variation of thrust, specific impulse, and thrust efficiency for throat heights of dt = 60 μm and dt = 90 μm at input power of about 5 to 6 W. In these figures, plots of the mass flow rate are the total mass flows for every nozzle element. From the figures, higher thrust performances can be obtained with smaller throat nozzle cases. Typical thrusts at total mass flow of 11.25 mg/sec at input power of 5.4 W are 8.6 mN and 6.9 mN for *d*t = 60 μm and *d*t = 90 μm, respectively. In addition, typical specific impulses at total mass flow of 11.25 mg/sec at input power of 5.4 W are 78 sec and 62 sec for *d*t = 60 μm and *d*t = 90 μm, respectively. Moreover, thrust efficiencies are 0.15 and 0.22 for *d*t = 60 μm and *d*t = 90 μm, respectively. With the reduction of throat size, thrust performance increased up to 26%.

Although not shown in the figure, typical plenum pressures at total mass flow of 11.25 mg/sec are 0.28 MPa and 0.13 MPa for *d*t = 60 μm and *d*t = 90 μm, respectively. With the reduction of throat size, the plenum pressure increased twice as much. At larger mass flow and smaller throat conditions, or higher plenum pressure conditions, thrust performance could be improved. However, the discharge tended to turn unstable.

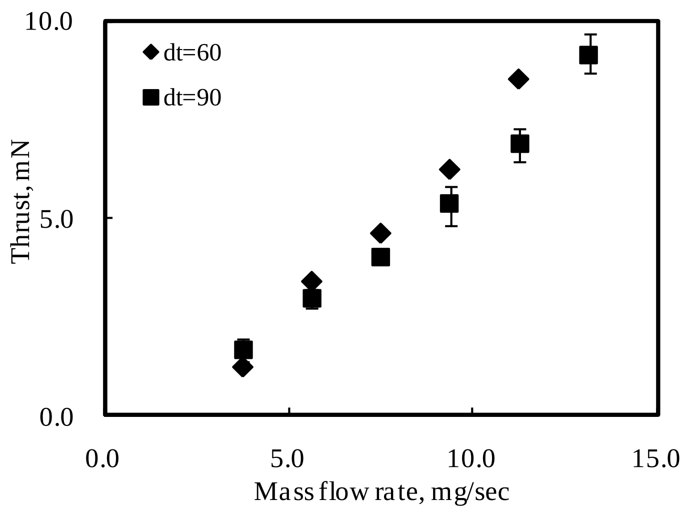


Figure 9. Thrust vs mass flow rate for different throat cases.

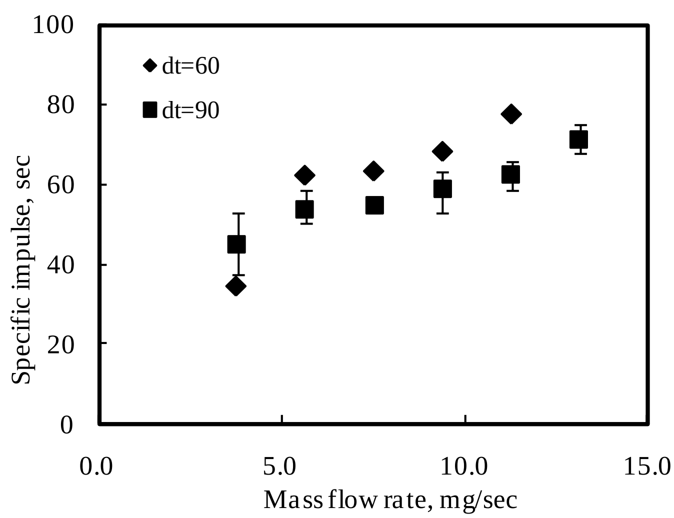


Figure 10. Specific impulse vs mass flow rate for different throat cases.

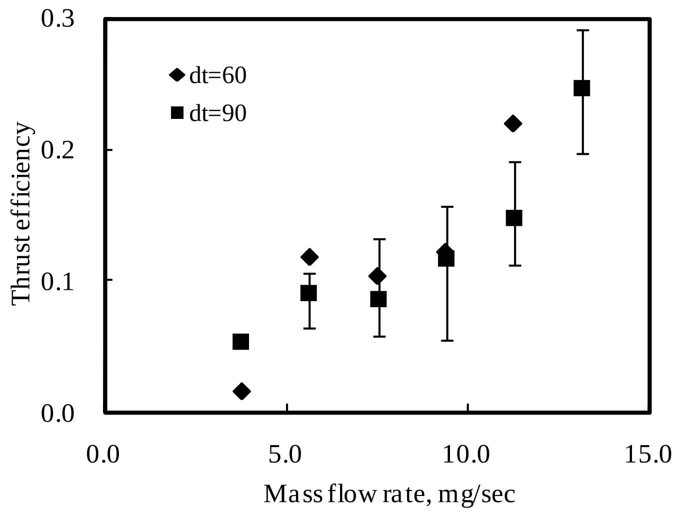


Figure 11. Thrust efficiency vs mass flow rate for different throat cases.

D. 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) For nozzles with different throat sizes and identical exit height of the 3x3 micro multi-plasmajet array thruster, the thrust performance increases when the throat size becomes smaller.
3) The typical values of the thrust, specific impulse and thrust efficiency of the micro-plasmajet array thruster operated at 5.4 W with 11.3 mg/sec of propellant mass flow were 8.6 mN, 78 sec, and 0.22, respectively.

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