Micro-Plasmajet Array: Numerical Simulation on Thrust Improvement of Multi-Jet Effect

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Abstract: The flowfields of a cold-gas jet from a micro-fabricated nozzle and a micro-nozzle-array for a micro plasmajet array were numerically investigated using the Direct Simulation Monte Carlo (DSMC) method. As for the micro nozzle-array simulation, much higher exit pressure than that of the single array thruster was observed at the downstream of the nozzle element and also at jet boundaries. It was shown that the use of the multi-nozzle array was effective in suppressing expansion of each under-expanded 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 at the nozzle exit.

KEYWORDS: Direct Simulation Monte Carlo Method, Micro Plasma Jet, Micro Arcjet, Micro Nozzle-Array, Multi Jet Interaction

I. Introduction

The progress of micromachining techniques such as micro-mechanical machining systems and micro-electromechanical systems (MEMS) has brought space engineering fields another good chance to challenge new innovative dreams.[1] One of the examples is that these techniques have enabled fabrication of various elements and parts of high-functional microspacecraft systems. Currently it has become possible for a combined fleet of the microspacecrafts orbiting the earth to perform critical and highly complex tasks with various high-functional electronic- and mechanical- devices.[1-4] Capable micro-spacecrafts with distributed functionality are envisioned to take over the tasks of more massive and expensive platforms with increased survivability and flexibility. It is becoming increasingly evident that these microspacecrafts will require efficient propulsion systems to enable various kinds of the missions currently being investigated. Although in the

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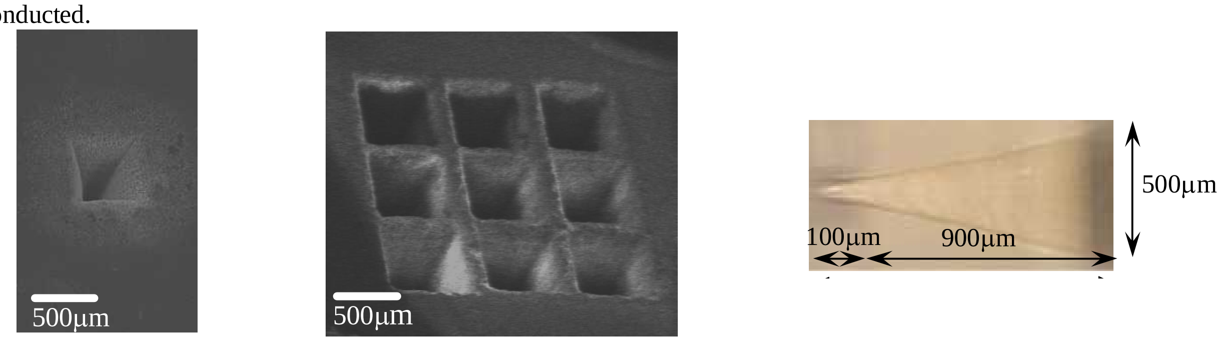
past, most of small spacecrafts have lacked propulsion systems altogether, future microspacecrafts will require significant propulsion capability in order to provide a high degree of maneuverability and capability. The system constraints on mass, power, maximum voltage, and volume with which microspacecrafts will undoubtedly have to contend will pose several challenges to overcome.

Feasibility studies of microspacecrafts are currently under development for the mass less than 100 kg with an available power level for propulsion of less than 100 watts.[1-4] Various potential propulsion systems for microspacecraft applications, such as ion thrusters, field emission thrusters, PPT, vaporizing liquid thrusters, resistojets, microwave arcjets, pulsed arcjets, etc., have been proposed and are under significant development for primary and attitude control applications. Because of its system simplicity the arcjet thruster must be appropriate for the small-sized spacecrafts. Many of thrusters of this type with input power level of kilo-watts have been practically used in orbit such as north-south stationkeeping (NSSK) on geosynchronous satellites, etc. It has been reported in previous studies that a thermal loss to electrodes and a frozen flow loss are the primary loss mechanisms of the arcjet thrusters. It has been confirmed that the thermal loss can be reduced at high-voltage mode discharge operation cases. Also, the frozen flow loss can be reduced at a lower specific power input, or at lower plasma temperature operation, although the specific impulse in a lower-power arcjet will be decreased to some extent compared with middle- and high- power arcjets. In addition, it has been reported that an endurance of the arcjet is primarily determined by a degree of cathode erosion. From these facts, a significant suppression of those losses and cathode erosion can be expected with the use of the very low-power operation of the arcjet.

Authors have been focusing on the study of DC arcjets or plasmajet operational at very low-power levels, i.e., less than 10 watts, for microspacecraft propulsion devices, relating not only to the thrust performance but to the fundamental physical issues of the very low power DC discharges as wel.l.[5-6] In addition, fabrication of micro-arcjet nozzles with fifth-harmonic Nd:YAG pulses (wavelength 213 nm) and their DC discharge tests were also conducted, and stable operation with satisfying performance was shown[7-15].

Scanning electron microscope (SEM) images of the micro-nozzles and a microscopic side view of the nozzle element are shown in Fig.1[15]. As for the micro single-nozzles, thrust performance tests were conducted for various nozzles with different exit heights, or area ratios, for various lengths of divergent part.[14-15] 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 affects on thrust performance rather than nozzle sizes. To overcome these issues, authors have been developing the micro-nozzle-arrays and testing their thrust characteristics. From the thrust performance tests, significant improvement of the performances of each nozzle element with mass flow were obtained with the nozzle-arrays than those of only using a single-nozzle .[14-15] In the test, 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. An example of calculated values of the specific impulse of each nozzle element for the nozzle-array, compared to those of the single nozzle, are plotted in Fig.2 for a background pressure of 4 Pa[15]. From the figures, it can be seen that significant increases of the specific impulse with increasing mass flow can be seen in the nozzle-array case. For a larger mass flow rate of 1.0 mg/sec, the specific impulse of the single-nozzle is 45 sec. While in the nozzle-array case, higher values of 73 sec can be obtained. This is probably due to the multi-jet interaction between the nozzle elements suppressing under-expansion and confining each jet into axial direction.

In this study, to elucidate the mechanism of the thrust improvement, and to optimize nozzle geometries, such as sizes, separation between nozzle-elements, etc., numerical simulation of internal and external flowfield of the nozzle was conducted.



(a) Micro single-nozzle **(b) Micro nozzle-array** **(c) Side view of nozzle element**

Figure.1 Micro single nozzle and nozzle array used in experiment.

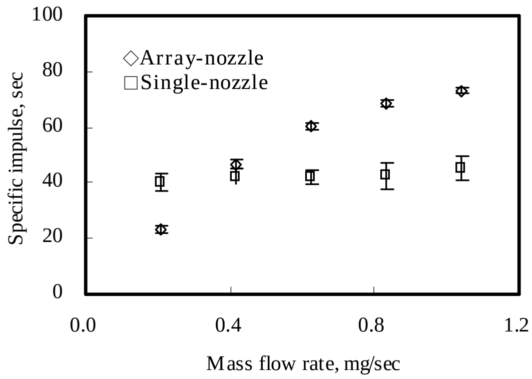


Figure.2 Comparison of specific impulse for various mass flow for 3x3 micro nozzle-array- and single-nozzle-thrusters operated in a background pressure of 4 Pa.

Table.1 Calculation condition.

temperature	300 K	
Knudsen number	0.01 (nozzle throat)	
propellant	nitrogen	
number of grids	horizontal direction	70
	vertical direction	100
number of molecules	3000	

II. 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[16]. 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 gas.

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 characteristics. 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. Simulstion Models

Geometries of two-dimensional simulation models for a micro single-nozzle and micro nozzle-array are illustrated in Figs.3 (a) and (b), respectively. As shown in these figures, only the upper half of a nozzle element is calculated for a single-nozzle is used in the simulation, and for a nozzle-array the lower half of an upper nozzle element is combined with an upper half of the 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.1. Typical models consist of 70 grids in horizontal direction (50 grids inside the nozzle) and 100 grids in vertical direction (50 grids inside the nozzle).

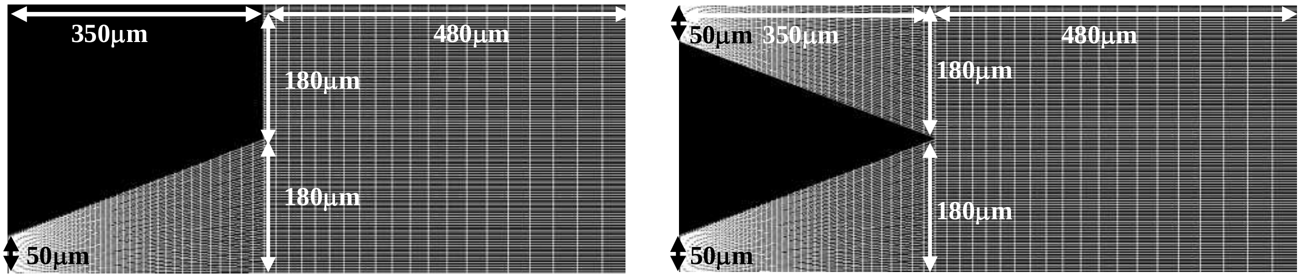
Conditions at stagnation point is taken from our experimental data for cold-gas flow of gaseous nitrogen propellant in which the stagnation temperature is assumed as a room temperature, 300 K. A typical Knudsen number is 0.01 at nozzle throat.

III. Results and Discussion

A. Micro Single-Nozzle

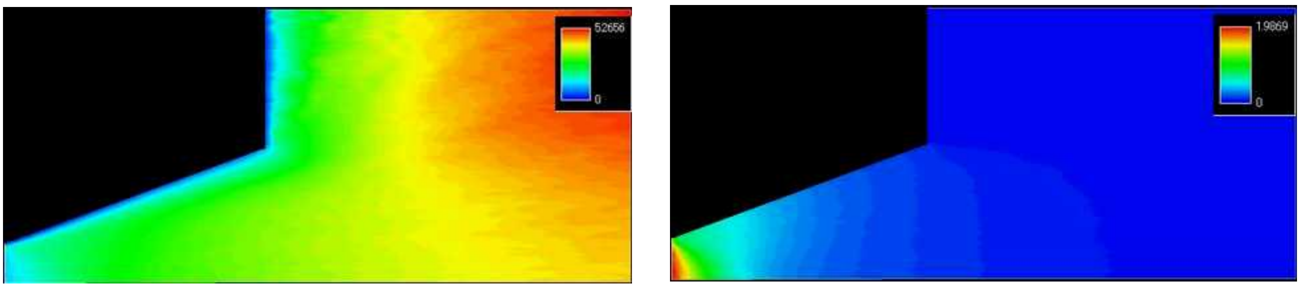
Examples of typical pressure and Mach number distributions obtained for a micro single-nozzle are shown in Fig.4. Since the Knudsen number at nozzle exit is lager than unity, apparent shocks and expansion fins are not visible. It can also be seen in Fig.4 (b) that thick viscous boundary layers being developed, indicating poor nozzle efficiencies.

Theoretical thrusts are obtained by integrating local momentum changes (momentum thrust) and local pressure distribution (pressure thrust) over across the nozzle exit plane. The calculated results are compared with our experimental data. Plots of specific impulse for various mass flow rates obtained from experiments under different background pressures, and from the simulation are shown in Fig.5. As can be seen, the simulated results (in which the background pressure is set to 0 Pa) fairly agree with the experimental data (0.03 Torr). The poor performance probably arises from the adverse interaction of the subsonic boundary layer with the core of supersonic flow causing the flow not to expand fully in the divergent nozzle section.



(a) micro single-nozzle **(b) micro nozzle-array**

Figure.3 Geometries of two-dimensional simulation models.



(a) Pressure distribution **(b) Mach number distribution**

Figure.4 Non-dimensinal Pressure and Mach number distributions obtained from numerical simulation using DSMC method for micro single-nozzle.

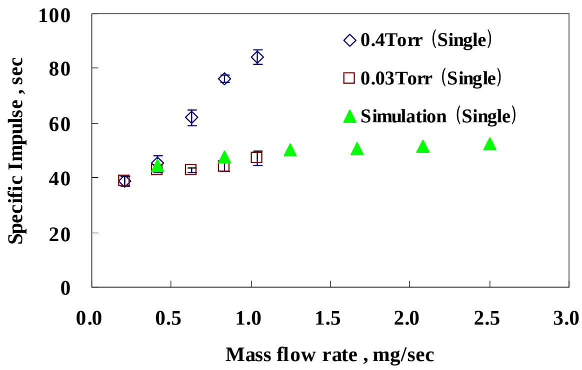
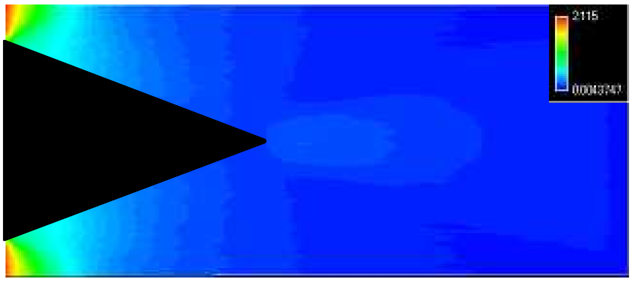
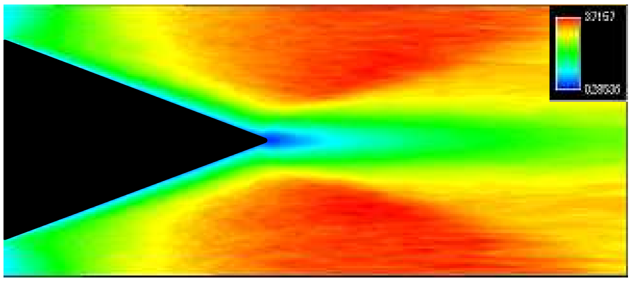


Figure.5 Plots of specific impulse for various mass flow rates obtained from experiments under different background pressures, and from the simulation.





(a) Pressure distribution **(b) Mach number distribution**

Figure.6 Pressure and Mach number distributions obtained from numerical simulation using DSMC method for micro nozzle-array.

B. Micro Nozzle-Array

Typical results for a micro nozzle-array are depicted in Fig.6, showing the pressure and the Mach number distributions. It can be seen that the pressure at the nozzle exit is increased in comparison with the single-nozzle case (Fig.5) because of the interaction between the exhaust-jet boundaries. 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.

An increase in the static pressure at the exit of the nozzle array may be transferred to an internal core flow in divergent nozzle section through a subsonic boundary layer of the internal flow; then the suppressed and smoothed pressure drop inside the nozzle leads to the reduction of the boundary layer thickness. This is the reason because the nozzle-array configuration shows a better thrust performance than the single-nozzle configuration.

C. Interaction of Exhausted Multi-Jets for Micro Nozzle-Array

To elucidate the interaction of exhaust multi-jets for each jet, simulations on sonic multi-jets are conducted. Since our primary concern in this simulation is on the influences of interactions between under-expanded exhaust jet boundaries, or multi-jet effect, a sonic condition is employed to each exhaust jet without calculating internal nozzle flows for simplicity. Geometries of two-dimensional simulation models are illustrated in Fig.7.

Typical results of pressure distributions for two-dimensional triple nozzle cases for different nozzle-separations, i.e., (a) 100 μm, (b) 25 μm, and (c) 0 μm are shown in Fig.8, in which each exit height of each nozzle element is 400 μm. As shown in these figures, the low pressure region downstream the nozzle end, or at the separating points, tend to dissapiear as the nozzle-separation decreases. Moreover in the smaller separation case, a higher pressure region tends to extend further in the horizontal (flow) direction and also in the vertical direction. It can be seen that this tendency of the extended high pressure region is more exaggerated especially in the central nozzle element.

Results of Mach number distributions are shown in Fig.9. As can be seen in these figures, the size of the flow region expanding between the nozzles, or to the separating regions, 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. The reduction of the nozzle-separation region 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.

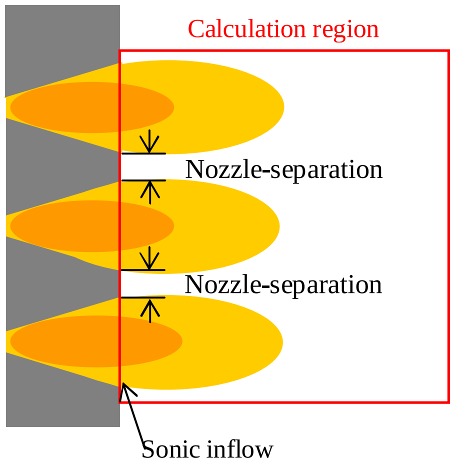
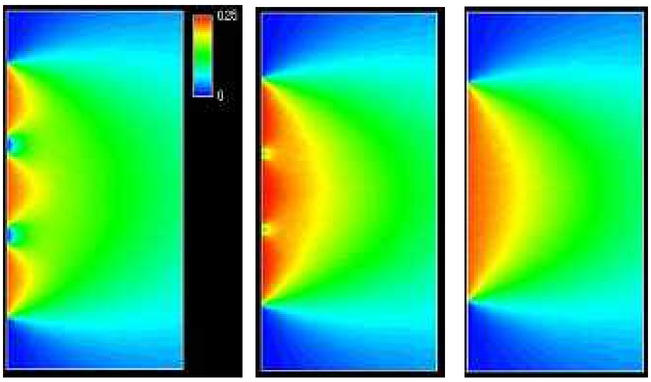
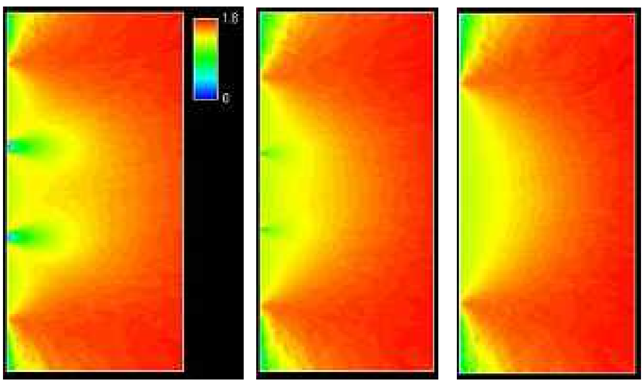


Figure.7 Geometries of two-dimensional triple nozzle simulation models.



(a) 100 μm (b) 25 μm (c) 0 μm.

Figure.8 Typical results of pressure distributions for two-dimensional triple nozzle for different nozzle-separations.



(a) 100 μm (b) 25 μm (c) 0 μm.

Figure.9 Mach number distributions for two-dimensional triple nozzle for different nozzle-separation.

IV. Conclusion

Preliminary numerical simulation using the Direct Simulation Monte Carlo (DSMC) method was conducted to elucidate mechanisms of interaction of exhaust multi-jets from micro-nozzles resulting in thrust performance improvement of a micro nozzle-array. As results, it was shown that, for micro single-nozzles, the numerically simulated specific impulses for various conditions agreed well with our experimental data.

As for the micro nozzle-array simulation, much higher exit pressure than that of the single array thruster was observed at the downstream of the nozzle element and also at jet boundaries. As a result, each under-expanding jet from each nozzle can be converted to more axially confined jets, through the interactions of the jet boundaries or multi-jet effect. Also, the pressure increase must increase static pressure of the boundary layer in internal nozzle flows. In the case of multi-nozzle-array, these effects will contribute to obtain higher thrust comparing with the single array configuration by reducing losses derived from under-expanding exhaust-jet and viscous losses of internal micro-nozzle flow.

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