Experimental and Numerical Investigation on Thrust Performance Improvement of Micro-Single-Nozzle Thrusters

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Experimental and numerical investigations on thrust performance of micro-single-nozzle thrusters with different area ratios were conducted to characterize and improve thrust performance of each nozzle. In the numerical simulation, the detailed mechanism of thrust improvement was investigated. From the experimental and numerical, studies, it was shown that for micro-single-nozzles with different throat sizes with identical exit height the thrust increased when the throat size was reduced. In the simulation, it was shown that pressure along the nozzle wall and static pressure at nozzle-exit plane became larger for smaller throat size nozzles. In this case, it turned out that contribution of the pressure thrust on the total thrust was more significant.

Key Words: Micro-Thruster, Micro-Single-Nozzle, Numerical Simulation, Direct Simulation Monte Carlo, Throat Size

1. 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 dreams1). 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. 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 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. 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 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 well. 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.

From our recent study, it was shown that variations of the background pressure in the vacuum chamber, in which
the thruster were tested, relatively affects on thrust performance. To overcome these issues, authors have been developing the micro-nozzle-arrays and testing their thrust characteristics. Scanning electron microscope (SEM) images of the micro-nozzles and microscopic side view of the nozzle element are shown in Fig.1. To evaluate thrust characteristics of the nozzle-array, its thrust performance is 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. The 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\(^4\). 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. 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 characterize and improve thrust performance of each nozzle element, experimental and numerical investigations on thrust performance of micro-single-nozzles with different area ratios are conducted.

Moreover, in the numerical simulation, the detailed mechanism of thrust improvement is elucidated and discussed.

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

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

Fig. 3. Schematic of experimental set up

2. Cold-Gas Thrust Performance Measurement of Micro-Nozzle Thrusters

A sketch of an experimental setup are illustrated in Fig.3(a). In this study, effect of throat size of micro-single-nozzles on thrust performance was examined. The micro-nozzles of throat heights of \(d_1 = 35\mu m, 45\mu m, \) and \(70\mu m\) with identical exit height of \(500\mu m\) were machined and tested. Cold-gas thrusts with gaseous nitrogen propellant were measured and compared for
various cases. The thrust was measured with a quartz cantilever attached with a quartz thrust stand structure (Fig.3(b)). For the structure, quartz was chosen to minimize the thermal expansion to avoid displacement errors. The displacement of the cantilever was measured with a laser displacement sensor. As for the calibration of the thrust stand, a known mass was hung by a fine string through a pulley exerting a known force to the thrust stand, as shown in Fig.3(b). Then, correlations of the force and displacement of the lever were examined. Motion of the mass was controlled by a vertical-stage and the calibration was performed during each measurement in vacuum.

In this experiment, thrust performance during the cold-gas operation test was primarily investigated and discussed to estimate the pure nozzle performance induced through each nozzle flow.

Variations of measured thrust and specific impulse with propellant mass flow rate are plotted in Figs.4 and 5, respectively, for the cold-gas thrust performance test using various throat sizes of the micro-single-nozzles of $d_t = 35 \mu m$, $45 \mu m$, and $70 \mu m$. It can be seen that thrust increases linearly with increase of mass flow rate. On the other hand, specific impulse tends to approach a constant value in each case. The results of thrust and specific impulse for mass flow rate of 1.25 mg/sec are listed in Table 1. Form the table, thrust and specific impulse for $d_t = 35 \mu m$ are $T = 1.15 \text{mN}$ and $1sp = 94 \text{sec}$, for $d_t = 45 \mu m$, $T = 0.68 \text{mN}$, $1sp = 55 \text{sec}$, and for $d_t = 70 \mu m$, $T = 0.37 \text{mN}$, $1sp = 30 \text{sec}$. The thrust increases up to 84% when the nozzle throat size is reduced from $d_t = 70 \mu m$ to $d_t = 45 \mu m$. Moreover, the thrust is further increased up to 210% when the throat is further reduced down to $d_t = 35 \mu m$.

From these results, reduction of the throat size of the micro-nozzle is probably causing the increase of the pressure thrust component at the nozzle exit plane, since the increase of plenum pressure is also induced at the same time for identical mass flow case. The detailed mechanism of the thrust performance improvement is investigated and discussed through the numerical simulation in the following sections.

![Figure 4: Thrust vs mass flow rate for comparison of nozzle performance.](image)

![Figure 5: Specific impulse vs mass flow rate for comparison of nozzle performance.](image)

Table 1. Results of pressure, thrust and $1sp$ for mass flow of 1.25 mg/sec.

<table>
<thead>
<tr>
<th>Throat Size $d_t$ [(\mu m)]</th>
<th>Plenum Pressure [Pa]</th>
<th>Thrust [mN]</th>
<th>$1sp$ [sec]</th>
</tr>
</thead>
<tbody>
<tr>
<td>35</td>
<td>0.41</td>
<td>1.15</td>
<td>93.6</td>
</tr>
<tr>
<td>45</td>
<td>0.27</td>
<td>0.68</td>
<td>55.3</td>
</tr>
<tr>
<td>70</td>
<td>0.04</td>
<td>0.37</td>
<td>30.2</td>
</tr>
</tbody>
</table>

3. Numerical Simulation

3.1. 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 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-single-nozzles. Since rectangular micro-nozzles have been developed and tested in our experiment, two-dimensional numerical models are utilized.

3.2. Simulation Models

Geometry of a two-dimensional simulation model for a micro-single-nozzle is illustrated in Fig.6. As shown in this figure, only the upper half of a nozzle element is calculated in the simulation. Boundary conditions are assumed as random reflection for the centerline and walls.

Typical models consist of 80 grids in horizontal direction (50 grids inside the nozzle) and 100 grids in vertical direction (50 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 a room temperature, 300 K. A typical Knudsen number is 0.004 at the nozzle throat. The calculation condition is listed in Table 2.

3.3. Results of Numerical Simulation

The simulation assumed micro-single-nozzles with throat sizes of \( d_t = 35 \mu m, 45 \mu m, \) and \( 70 \mu m \). In the simulation, various quantities at nozzle exit were calculated, and some of the examples of pressures and horizontal component velocity distributions for mass flow rate of 1.25 mg/sec are shown in Fig.7, showing (a) pressure distribution along the nozzle wall, (b) static pressure distribution at nozzle-exit plane, and (c) horizontal velocity distribution at exit plane. In the vertical axis, the cell number of 0 to 50 corresponds to an internal flow region, and that of 51 to 100 is showing the quantity along and on the nozzle wall in the simulation model. As shown in this figure, higher values of the pressure of the nozzle wall and static pressure at nozzle-exit plane are obtained when the nozzle throat size becomes smaller. In particular, each pressure becomes remarkably low for the largest throat size of \( d_t = 70 \mu m \). In addition, horizontal velocity component also increases when the throat size becomes smaller.

As for the next, calculation of theoretical thrust and specific impulse, estimated from these various quantities, was conducted. The theoretical thrust was calculated by integrating local momentum thrust estimated as a product of local density, area element, and square of horizontal velocity component, and local pressure thrust estimated as a product of static pressure and area element at each grid point at the exit plane. The calculated values of thrust and specific impulse for each throat size are plotted in Figs.8 and 9, respectively. As shown in this figure, the thrust is increasing proportionally with increase of mass flow rate. On the other hand, the specific impulse in each case is showing almost constant values. As for the influence caused by the difference in throat size on thrust performance, higher performance can be obtained with smaller throat sizes. The typical thrust and specific impulse for mass flow rate of 1.25 mg/sec are listed in Table 3. As shown in this table, thrust and specific impulse for the nozzle with \( d_t = 35 \mu m \) are 0.92 mN and 75 sec, for \( d_t = 45 \mu m \), they are 0.88 mN and 72 sec, and for \( d_t = 70 \mu m \), 0.54 mN and 44 sec, respectively.

The thrust increases up to 63% when the throat size is reduced from \( d_t = 70 \mu m \) to \( d_t = 45 \mu m \). Moreover, it is further increased up to 70% when the throat size is further reduced down to \( d_t = 35 \mu m \). It is shown that the thrust performance is improved when the throat size becomes smaller. As nozzle-wall pressure and static pressure become larger for smaller throat size nozzle, shown in Fig.7, it turns out that contribution of the pressure thrust in the theoretical thrust calculated in nozzle exit plane is becoming more significant.

The differences of the experimental and calculated values are 20% in a mutual error for \( d_t = 35 \mu m \) nozzle, 29% for \( d_t = 45 \mu m \) nozzle, and 46% for \( d_t = 70 \mu m \) nozzle. The primary cause of these errors is due to the two-dimensional calculation for an actual three-dimensional rectangular nozzle flow. Furthermore, some errors must be included in measured plenum pressure, temperature, and throat size, and it is found in our calculation that small differences of these quantities can cause a significant influence on calculation of the pressure thrust. This should be further discussed in our next study.

![Fig. 6. Simulation model for numerical simulation.](image-url)
Fig. 8. Thrust vs mass flow rate for comparison of nozzle performance from simulation.

Fig. 9. Isp vs mass flow rate for comparison of nozzle performance from simulation.

Table 3. Results of pressure, thrust, and Isp from simulation.

<table>
<thead>
<tr>
<th>Throat Size</th>
<th>Throat Pressure</th>
<th>Thrust</th>
<th>Isp</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[μm]</td>
<td>[Pa]</td>
<td>[mN]</td>
</tr>
<tr>
<td>35</td>
<td>0.092</td>
<td>0.92</td>
<td>74.7</td>
</tr>
<tr>
<td>45</td>
<td>0.059</td>
<td>0.88</td>
<td>71.5</td>
</tr>
<tr>
<td>70</td>
<td>0.008</td>
<td>0.54</td>
<td>44.1</td>
</tr>
</tbody>
</table>

4. Conclusion

Experimental and numerical investigations on thrust performance of micro-single-nozzles with different area ratios were conducted to characterize and improve thrust performance of each nozzle element. Moreover, in the numerical simulation, the detailed mechanism of thrust improvement was investigated.

From the experiment it was shown that for different throat sizes and identical exit height of micro-single-nozzles, the thrust was increased when the nozzle throat size was reduced.
From the numerical simulation, it was also shown that
the thrust performance was improved when the throat size
became smaller. As nozzle-wall pressure and static
pressure became larger for smaller throat size nozzles, it
turned out that contribution of the pressure thrust in the
theoretical thrust calculated in nozzle exit plane was
becoming more significant. In addition, it was found in
our calculation that small differences of these quantities
could cause a significant influence on calculation of the
pressure thrust. This will be further discussed in our next
study.

References

Small Spacecraft, Progress in Astronautics and Aeronautics,
2) Horisawa, H., and Kimura, I.: Influence of Constrictor Size on
Thrust Performance of a Very Low Power Arcjet, AIAA Paper
Sizes in Low Power Arcjet Thrusters, AIAA Paper 97-3202,
(1997).
4) Horisawa, 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
Characteristics of a Very Low-Power Arcjet, Proceedings of
the 28th International Electric Propulsion Conference, IEPC
03-0078, (2003).
Performances of a Very Low-Power Micro-Arcjet, Proc. Asian
Joint Conf. on Propulsion and Power 2004, (2004),
pp.358-363.