

Vacuum test of a micro-solid propellant rocket array thruster

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Abstract: A $\phi 0.8$ mm micro-solid propellant rocket array thruster for simple attitude control of a 10 kg class micro-spacecraft was tested in vacuum. The micro-thruster uses boron/potassium nitrate propellant (NAB), because NAB has ignition temperature as low as 500°C, and easily start to burn in vacuum. For a half of the rockets, an ignition aid (RK) was also loaded. Ignition was succeeded in vacuum with NAB + RK and NAB. The maximum impulse thrust of 4.6×10^{-4} Ns, which is approximately a half of our requirement, was obtained with NAB. Compared to NAB, NAB + RK generated lower impulse thrust. The success rate of ignition was as low as 30%, although RK was used. These results suggest that RK has no benefit for the ignition of NAB, and other kinds of ignition aid should be found.

Keywords: micro-propulsion, micro-thruster, solid propellant, impulse thrust, ignition aid, MEMS.

Classification: Micro-electromechanical systems

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1 Introduction

The launch of heavy spacecrafts is performed using massive rockets, and costs colossally. The miniaturization of spacecrafts has distinguished advantages in 1) decreasing launch cost, 2) shortening development time, 3) increasing mission reliability by the redundancy of spacecrafts, and 4) networking the spacecrafts for cooperation working. In order to miniaturize spacecrafts and open up a new area in space technology, micro-electromechanical system (MEMS) technology plays a key role. In 1995, the National Astronautics and Space Administration (NASA) of the U.S.A. implemented “New Millennium Program [1]” to dramatically miniaturize spacecrafts. The goals of this program include the development of a micro-spacecraft with weight of about 10 kg or less. This can be achieved by the miniaturization of its components.

Recently, several micro-solid propellant rocket array thrusters composed of many one-shot solid propellant micro-rockets arrayed on a substrate are developed for the attitude control of micro-spacecrafts [2]–[7]. These micro-solid propellant rocket array thrusters have following advantages: 1) The system is completed on a substrate and compact. 2) Solid propellant has no anxiousness of leakage, unlike gas or liquid propellants. 3) The thruster has no moving parts. 4) The system is highly redundant. 5) The thrust is controlled digitally by adjusting the numbers of micro-rockets ignited.

We have developed the micro-solid propellant rocket array thruster for simple attitude control of a 10 kg micro-spacecraft. In the previous study, we prototyped it and confirmed its basic operation in air [5]. In this study, we report the test to measure impulse thrust in vacuum.

2 Structure

The prototyped micro-thruster has solid propellant micro-rockets ($\phi 0.8 \text{ mm} \times 1 \text{ mm}$) arrayed 10×10 at a pitch of 1.2 mm on a $22 \times 22 \text{ mm}$ substrate. Fig. 1 shows the cross-sectional structure of the micro-thruster. It consists of three layers. The first silicon layer has nozzles and ignition heaters on diaphragms. The nozzles are fabricated by EPW (ethylene diamine/pyrocatechol/water) etching of a (100) silicon substrate. The ignition heaters ($400 \mu\text{m} \times 400 \mu\text{m}$) are made of sputtered Pt/Ti, and have resistance of 400–600 Ω . The p^{++} silicon diaphragm, which bursts away after ignition, thermally insulates the ignition heater, and also seals a solid propellant. The second glass layer contains the solid propellants, and the third one covers them. The first and second layers are anodically bonded, and then, the solid propellants are inserted from the second layer. Finally, the second and third layers are bonded using epoxy adhesive.

In this study, we selected boron/potassium nitrate propellant (NAB, Nichiyu Giken Kogyo), because NAB has ignition temperature as low as 500°C , and easily start to burn in vacuum compared to other propellants such as HTPB/AP (hydroxyl-terminated polybutadiene/ammonium perchlorate) [7], GAP (glycidyle azide polymer) [6] and ZPP (zirconium perchlorate potassium) [6]. $\phi 0.7 \times 0.9 \text{ mm}$ NAB pellets shaped using a punch and dice are inserted to the propellant cylinders. Lead rhodanide/potassium chlorate (RK, Nichiyu Giken Kogyo), whose ignition temperature is about 200°C , is put between the ignition heater and the NAB pellet to facilitate ignition.

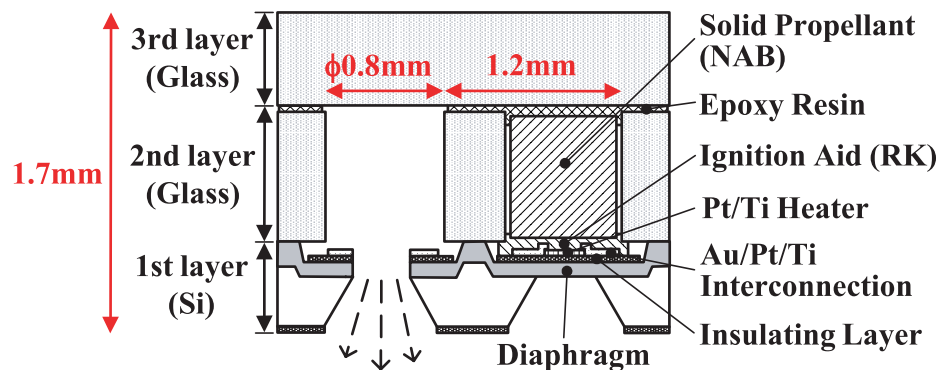


Fig. 1. Cross-sectional structure of the micro-solid propellant rocket array thruster.

3 Thrust measurement in vacuum

We performed the vacuum tests of the micro-solid propellant rocket array thruster. Fig. 2(a) shows the experimental setup. The micro-thruster mounted on a printed circuit board ($54 \text{ mm} \times 54 \text{ mm}$) is fixed at the lower end of a 260 mm long balsa pendulum, and the pendulum is hung from the testing stand. Ignition signals are supplied using $\phi 60 \mu\text{m}$ copper wires led from the upper end of the pendulum. The motion of the micro-thruster is

measured using a laser displacement meter (Z4M-W40, OMRON). The light from the combusting solid propellant is detected using a photodiode. Also, a digital video camera is installed to record the action of the thruster. We used an IC chip (S-4612A, Seiko Instruments) mounted on the printed circuit board for ignition control. The setup is installed in a vacuum chamber ($\phi 1.85 \text{ m} \times 4 \text{ m}$), which is pumped to 2 Pa.

We tested 20 rockets with NAB + RK and other 20 rockets with NAB. 6 rockets were successfully ignited in each case. Combustion scenes with NAB + RK and NAB are shown in Fig. 2 (b) and (c), respectively. Compared to NAB, NAB + RK generated smaller and darker flame, which indicates little NAB was burned. This would be because the short combustion of RK could not ignite NAB before the diaphragm was burst away. These results suggest that RK has no benefit for the ignition of NAB.

Impulse thrust ranged from $3.3 \times 10^{-5} \text{ Ns}$ to $2.0 \times 10^{-4} \text{ Ns}$ with NAB + RK, and the maximum impulse of $4.6 \times 10^{-4} \text{ Ns}$, which is approximately a half of our requirement [5], was obtained with NAB. Due to the problem of the experimental setup, only one impulse was successfully measured with NAB. Input energy for ignition was 5–49 mJ with NAB+RK, and 106 mJ

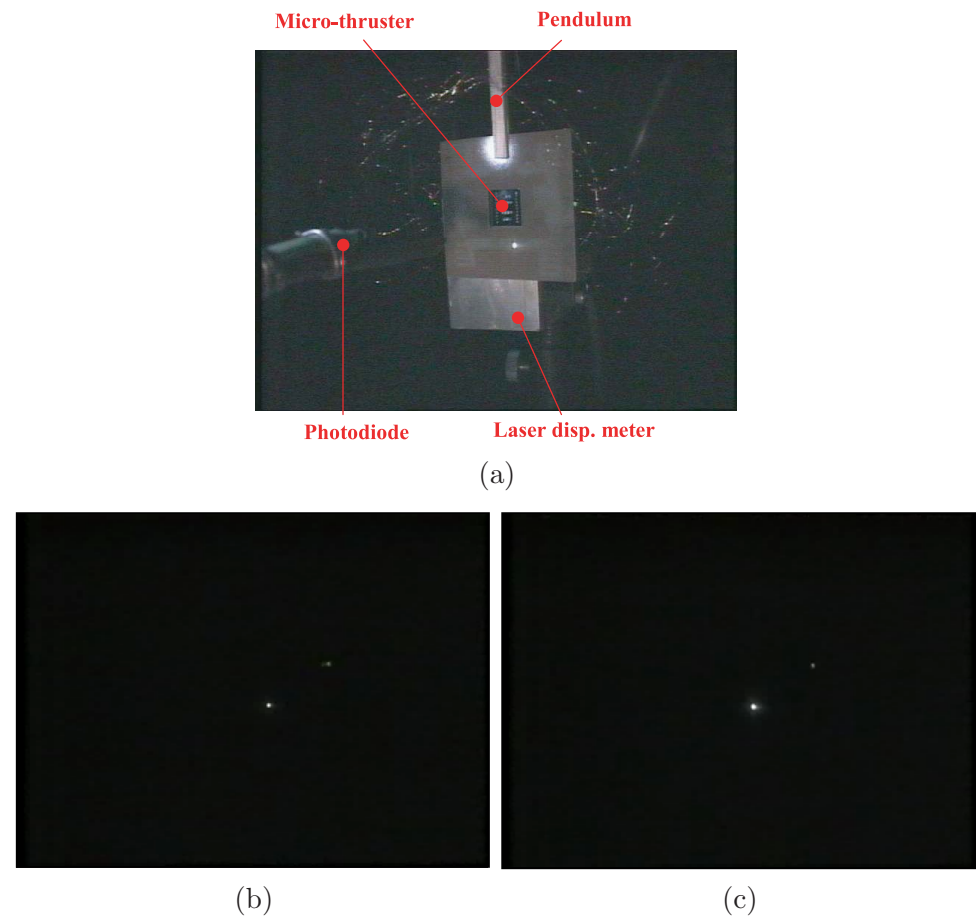


Fig. 2. Experimental setup (a), combustion scene with NAB+RK (b) (Movie file attached), and combustion scene with NAB (c) (Movie file attached) of the micro-solid propellant rocket array thruster.

with NAB. Ignition delay was 3–30 ms with NAB + RK, and 36 ms with NAB. After each combustion with and without RK, solid propellant (mainly NAB) still remained inside the propellant cylinder, probably because the propellant cylinder was rapidly depressurized after the diaphragm was burst away. To increase impulse thrust, it would be effective to tune the initial pressure and rate of the depressurization by changing the size and thickness of the diaphragm.

The success rate of ignition was not improved, although the ignition aid, RK, was used. We infer that this is due to the unstable contact between the ignition heater and RK. In propellant loading, RK powder dispersed in acetone was first inserted in the propellant cylinders, and then a NAB pellet was inserted on the RK. We thought that this propellant loading method was problematic, and observed the state of RK in propellant cylinders drilled in a transparent plastic plate. Figure 3 is an optical micrograph taken from the bottom of the propellant cylinder. We expected that RK was spread over the bottom of the propellant cylinder, but in fact, RK made uneven clusters. This suggests that cavities were formed on the ignition heaters, making ignition fail in some probability. From the same reason, ignition energy ranged widely. To improve the success rate of ignition, we should try other kinds of ignition aid.

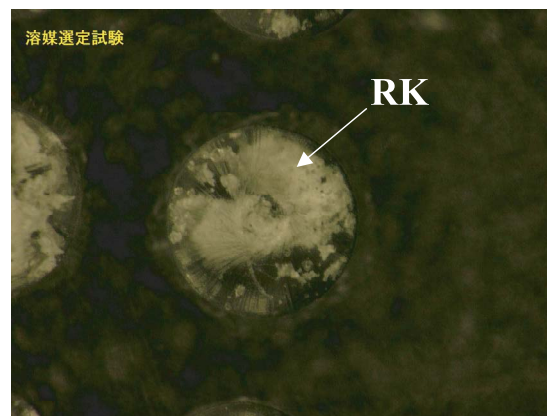


Fig. 3. Optical micrograph of RK observed from the bottom of the propellant cylinder.

We met another problem, the destruction of the micro-thruster. The first and second layers separated from each other, and this can sometimes triggered sympathetic detonation, which resulted in the destruction of the micro-thruster. The estimation of the mechanical strength of the diaphragm is quite complicated, as it depends on various factors such as shape, thickness and material properties. Cees van Rijn *et al.* [8] derived an equation that can be used to estimate the maximum tolerable transmembrane pressure of the brittle diaphragm:

$$P_{break} = 0.577 \times \frac{h\sigma_{max}^{3/2}}{lE^{1/2}}, \quad (1)$$

where h is the thickness, l is the length, σ_{\max} is the fracture stress, and E is the Young's modulus. From Eq. (1), the maximum tolerable transmembrane pressure of the diaphragm is found to reach anodic bonding strength, if anodic bonding is not strong. In the next prototyping, the bonding area should be increased to improve the anodic bonding strength.

4 Conclusion

A $\phi 0.8$ mm micro-solid propellant rocket array thruster for simple attitude control of a 10 kg class micro-spacecraft was tested in vacuum. The micro-thruster uses boron/potassium nitrate propellant (NAB, Nichiyu Giken Kogyo), because NAB has ignition temperature as low as 500°C, and easily start to burn in vacuum compared to other propellants. For a half of the rockets, an ignition aid (RK, Nichiyu Giken Kogyo) was also loaded.

Ignition was succeeded in vacuum with NAB + RK and NAB. The maximum impulse thrust of 4.6×10^{-4} Ns, which is approximately a half of our requirement, was obtained with NAB. After each combustion, solid propellant (mainly NAB) still remained inside the propellant cylinder, probably because the propellant cylinder was rapidly depressurized after the diaphragm was burst away. Compared to NAB, NAB + RK generated lower impulse thrust. This would be because the short combustion of RK could not ignite NAB before the diaphragm was burst away. These results suggest that RK has no benefit for the ignition of NAB.

The success rate was as low as 30%, although RK was used. From observation using transparent propellant cylinders, we revealed that the low success rate of ignition of RK was due to the unstable contact between the ignition heater and RK. Another problem which we met was that the first and second layer were separated by the pressure of burned propellant, because the bonding force was not enough.

In this study, we successfully demonstrated the combustion of the rockets in vacuum, and also revealed the problems to be solved. To increase impulse thrust, it would be effective to tune the initial pressure and rate of the depressurization by changing the size and thickness of the diaphragm. To improve the success rate of ignition, other kinds of ignition aid should be tried. Finally, the destruction of the micro-thruster will be solved by increasing the bonding area.

Acknowledgments

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