Influence of Injector for Performance of N₂O/DME Bipropellant Thruster

By Takamasa ASAKURA,¹⁾ Shouta HAYASHI,¹⁾ Yasuyuki YANO,²⁾ and Akira KAKAMI²⁾

¹⁾ *Department of Mechanical Design Systems Engineering, University of Miyazaki, Miyazaki, Japan*

²⁾ *Technical Center, University of Miyazaki, Miyazaki, Japan*

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This paper describes the performance of a proposed bipropellant thruster using nitrous oxide (N₂O) and dimethyl ether (DME). Conventionally, nitrogen tetroxide and hydrazine are used in thrusters for spacecraft, but requires gas treatment systems in the ground tests due to toxicity and reactivity to materials. Hence, we proposed to apply N₂O and DME to a bipropellant thruster in order to develop a compact and eco-friendly bipropellant thruster. N₂O and DME, which are liquefied gas, are neither toxic nor reactive to materials, and require no gas treatment system in the ground tests. Furthermore, the combustion chamber can be downsized because gaseous injection can eliminate the evaporation time. The application vapor pressures of 6.4 MPa (N₂O) and 0.6 MPa (DME) at 25 °C to self-pressurization would eliminate the necessity of pressurant to simplify the feeding systems. In this study, a 0.4-N class N₂O/DME bipropellant thruster with two types of injector was prototyped, and tested in a vacuum chamber to clarify the dependence of injector design on characteristic velocity (C^*) efficiency. Using an injector consisting of showerhead and subsequent 15-mm orifice, the thruster yields combustion chamber pressure of 0.27 MPa, with corresponding C^* efficiency of 68.3 % at O/F = 3.5.

Key Words: Bipropellant Thruster, Vacuum, Eco-friendly, Injector

1. Introduction

Today, microsatellites are attracted because of lower cost and shorter period for development, and hence, universities and companies develop microsatellites, some of which have been sent to the earth orbit. To realize more complex mission by microsatellites, microthrusters are necessary for the attitude control and orbit maintenance. However, most of the microsatellites have no thruster because of the limitation in volume and power supply.

Conventionally, nitrogen tetroxide (NTO)/hydrazine (N₂H₄) bipropellant thrusters have been generally used in spacecraft. Owing to hypergolicity, combustion is readily initiated by the propellant impingement, and hence, neither igniter nor its electric circuit is necessary. However, the propellant requires gas treatment systems in the ground tests due to toxicity and reactivity to materials. Pressurant and temperature management devices are also needed because NTO and N₂H₄ have vapor pressures of 96, and 1.92 kPa, and relatively high freezing points of 261 and 274.3 K, respectively.

Our groups purposed a new eco-friendly microthruster using nitrous oxide (N₂O) and dimethyl ether (DME). In this study, a 0.4-N class N₂O/DME bipropellant thruster was prototyped and tested in a vacuum chamber to clarify the dependence of injector design on characteristic velocity (C^*) efficiency.

2. N₂O/DME Bipropellant Thruster

The proposed bipropellant thruster possibly has the following features: N₂O and DME, which are liquefied gas, are neither toxic nor reactive to materials, and then, require no gas

treatment system in ground tests. Vapor pressure of 6.4 MPa (N₂O) and 0.6 MPa (DME) at 25 °C allows the propellant to be stored in a liquid form, and fed in a gaseous form simply by managing temperature and pressure. Gaseous injection would downsize the combustion chamber by nulling evaporation time and reducing mixing time in the combustion chamber, and self-pressurization using the vapor pressures would eliminate the necessity of pressurant to simplify the propellant feeding system. Tanks are also possibly downsized due to higher specific gravity than that of NTO and N₂H₄. With regard to theoretical I_{sp} , N₂O/DME bipropellant has 290 s whereas NTO/N₂H₄ bipropellant has 318 s¹⁻³⁾ for a nozzle ratio of 50, and combustion chamber pressure of 0.4 MPa, under frozen flow condition. Nevertheless, in terms of safety and simplicity, the proposed thruster is suitable for microsatellites developed by universities.

3. Experimental Apparatus

3.1. Prototype thruster

Table 1 and Fig. 1 show the configuration and schematic of the 0.4-N class prototype thruster, respectively. N₂O and DME are separately supplied to the combustion chamber by an injector through the buffers that were used to suppress pressure spikes at ignition. Combustion were initiated with a spark plug, and combustion products were expelled through a nozzle 0.785 mm² in throat cross section and 1.3 in expansion ratio. The expansion ratio was selected such that the thruster exhibited the optimum expansion at the atmospheric back pressure.

Two types of injectors, which had an orifice and showerhead, were prototyped, as shown in Fig. 2. The injector (A) was

Fig. 1. Schematic illustration of the prototyped thruster.

Table 1. Prototyped thruster configuration.

Target thrust	[N]	0.4
combustion chamber pressure	[MPa]	0.4
Theoretical vacuum specific impulse	[s]	208(O/F=3.5) 198(O/F=5.7) 186(O/F=8.0)
L^*	[m]	32.7 67.6 102($L^*=32.7$) 136($L^*=67.6$)
Thruster length	[mm]	60(max) 49(min)
Thruster outer diameter	[mm]	34
Combustion chamber diameter	[mm]	34
Throat area	[mm ²]	0.785
Nozzle area ratio (designed so that the thruster presents optimum expansion at the atmospheric back pressure)		1.3

Fig. 2. Schematic illustration of the injector.

comprised of a showerhead with 26 ϕ 1-mm holes, and a subsequent orifice with a ϕ 15-mm hole to promote mixing by bending the propellant flow passing through the showerhead.

The injector (B) had a showerhead with 26 ϕ 1-mm holes and subsequent orifice with two ϕ 10-mm holes. The hole position of the showerhead was rotationally shifted from those of the orifice at an angle 90° to effectively mix the propellant.

3.2. Experimental apparatus

Figure 3 shows a schematic diagram of the experimental apparatus. The prototype thruster was placed on a thrust stand in the vacuum chamber. The flow rates of N_2O and DME were regulated by mass flow controllers (MFCs), and the supply was started and intermitted with solenoid valves. For safety, check valves were inserted between the MFCs and thruster. The vacuum chamber was evacuated with a rotary pump. During thruster firing, nitrogen was supplied to the vacuum chamber to dilute exhausted gas. Despite increase in ambient pressure to 40 kPa, dilution was necessary because without dilution, unburned mixture of N_2O and DME could be filled in the vacuum chamber and subsequently evacuated with the rotary pump, which repetitively confined the evacuated gas to oil-submerged small chambers. Furthermore, combustion produced other flammable gas such as carbon monoxide gas could be filled in the rotary pump. Hence, nitrogen was fed to prevent spontaneous ignition inside the vacuum chamber and rotary pump.

3.3. Experimental condition

Table 2 summarizes propellant flow rates in the firing tests. The prototype was tested at oxidizer to fuel ratio (O/F) of 3.5, 5.7 and 8.0; CEA⁴⁾ which is chemical equilibrium computation program shows that the bipropellant theoretically yields the maximum I_{sp} at O/F = 3.5 and stoichiometric combustion at O/F of 5.7. Mass flow rate was determined such that the thruster produces 0.4 N. Two spark-plug positions was tested because numerical simulation in our previous study showed that flow in the combustion chamber would be asymmetric, and relative position to the injector influenced on local O/F and flow velocity.⁵⁾ Then, we focused on azimuth, which significantly affected the velocity and local O/F, and hence, the spark plug was set at the point adjacent to the showerhead outlet of N_2O or DME. For simplicity, spark plug position was referred as N_2O side or DME side: DME side shows that the ignitor was adjacent to the DME outlet of the showerhead as in Fig. 1.

Fig. 3. Schematic diagram of the experimental apparatus.

Table 2. Mass flow rate.

Oxidizer fuel ratio (O/F)	Mass flow rate, mg/s	Theoretical vacuum I_{sp} at expansion ratio of 1.3, s
3.5 (maximum theoretical I_{sp})	208	208
5.7 (Stoichiometric mixture ratio)	218	198
8.0 (oxidizer rich)	232	186

4. Experimental Result and Discussion

4.1. Time history for injector

Figure 4 shows a time history of combustion chamber pressure; the injector (A) was placed on the N_2O side at $O/F=8.0$ and $L^*=32.7$ m. For the first 2 s after the spark plug started firing, combustion was repeatedly started and intermitted. Subsequently, combustion remained stable without spark-plug firing until the propellant supply was interrupted. The corresponding combustion chamber pressure was 0.33 MPa, and C^* efficiency was 81.6 %.

By contrast, under certain O/F and spark plug position, combustion remained unstable although the spark plug kept firing for 60 s. Figure 5 depicts a typical time history; the thruster with injector (B) was fired at $O/F=5.7$ and $L^*=67.6$ m for the N_2O side. Combustion was repetitively start and intermitted during 60-Hz repetitive spark-plug firing. When the spark plug firing was intermitted, combustion was interrupted. The unstable combustion deteriorated performance; the corresponding average combustion chamber pressure was 0.09 MPa and C^* efficiency was 22.4 %.

4.2. Combustion and stability

Table 3 presents the dependence of combustion stability on the thruster configuration. For the injector (A), under certain condition, the thruster yielded stable combustion, whereas the thruster with the injector (B) showed unstable combustion in all the tests.

It seems to that the cause of the DME mass ratio and velocity between the spark plug electrodes. Then, cold propellant flow was simulated using Flow Simulation of SolidWorks. Flow Simulation is a CFD software that uses the finite volume method. Figure 6 shows simulation result for using injector (B). Average DME mass ratio and velocity between the electrodes are 0.212 and 0.030 m/s, respectively. Ref.5 has been reported that the tendency of the ignition stability, which if average DME mass ratio is 0.2 class and average velocity is higher between the electrodes, the thruster is stable operation. Therefore, when using injector(B), the velocity between the spark plug electrodes required for the stable combustion is insufficient.

4.3. Dependence C^* efficiency

Figure 7 shows the dependence of C^* efficiency on O/F . In the case that the thruster produced unstable combustion, C^* efficiency was less than 40 %, whereas C^* efficiency was more than 60 % in the case of stable combustion. At $O/F=3.5$, the thruster yielded the maximum C^* efficiency of 68.3 % at $L^*=32.7$ m using the injector (A).

The spark plug position slightly affected C^* efficiency, whereas having influence on combustion stability, as shown in table 3. With regard to the injector (A), L^* affected C^* efficiency

Fig. 4. Time history of combustion chamber pressure for injector(A), $O/F=8.0$, $L^*=32.7$ m, igniter was placed N_2O side

Fig. 5. Time history of combustion chamber pressure for injector(B), $O/F=5.7$, $L^*=67.6$ m, igniter was placed N_2O side

Table 3. Dependence of combustion stability on thruster configuration.

Injector	L^* , m	Spark-plug position					
		N_2O side			DME side		
		O/F	O/F	O/F	O/F	O/F	O/F
Injector (A)	32.7	3.5	5.7	8.0	3.5	5.7	8.0
Injector (A)	67.6	3.5	5.7	8.0	3.5	5.7	8.0
Injector (B)	67.6	3.5	5.7	8.0	3.5	5.7	8.0

○:stable Δ:unstable

among the tests where the thruster yield stable combustion; the thruster produced the highest C^* efficiency at $L^*=32.7$ m among the tests with injector (A). This suggests that heat loss in the combustion chamber would deteriorate C^* efficiency, and hence, decreasing L^* would enhance performance.

C^* efficiency increase as O/F increases. This is considered to be due to the fact that the fuel is not burned but only the oxidizer is burning.

In the future work, we will clarify the actual combustion reaction from the radical distribution in the combustion flame using spectroscopy.

Fig. 6. Result of Flow Simulation for using injector (B)

Fig. 7. Dependence of C^* efficiency.

5. Summary

The following is the summary of this study

- We proposed an N₂O/DME bipropellant thruster in order to develop an eco-friendly bipropellant thruster.
- A 0.4-N class N₂O/DME bipropellant thruster was prototyped, and tested in a vacuum chamber
- In order to clarify the dependence of injector design, two types of injector were designed; the injector (A) was comprised of a showerhead and a subsequent orifice with a $\phi 15$ -mm hole, and showerhead with a subsequent two $\phi 10$ -mm orifices.
- The injector (B) had a showerhead with 26 $\phi 1$ -mm holes and subsequent orifice with two $\phi 10$ -mm holes. The hole position of the showerhead was rotationally shifted from those of the orifice at an angle 90° to effectively mix the propellant.
- For the injector (A), under certain condition, the thruster yielded stable combustion, whereas the thruster with the injector (B) showed unstable combustion in all the tests.
- The spark-plug position slightly affected C^* efficiency, whereas having influence on combustion stability.
- With regard to the injector (A), L^* affected C^* efficiency among the tests where the thruster yield stable combustion; the thruster produced the highest C^* efficiency at $L^* = 32.7$ m among the tests with injector (A). At O/F = 3.5 and 8.0, the thruster yielded the maximum C^* efficiency of 68.3 % and 81.6 %, respectively.
- Heat loss in the combustion chamber would deteriorate C^* efficiency, and hence, lowering L^* would enhance performance.

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