Design and Test of Impingement Type of N_2O/DME Bipropellant Thruster

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This paper describes the design and test of impingement-type bipropellant thruster using nitrous oxide (N_2O) and dimethyl ether (DME). Conventionally, nitrogen tetroxide (NTO) and hydrazine (H_2N_4) are used in thrusters for spacecraft, but they require temperature management for storage and gas treatment systems in the ground tests due to toxicity and reactivity to materials. Hence, we proposed to apply N_2O and DME to a new eco-friendly bipropellant thruster. An N_2O/DME bipropellant thruster was tested to develop onboard propulsion systems for small satellites. Non-toxic liquefied gas storage and gaseous-propellant feed reduce tank volume and null evaporation time in thrust chambers. In a 0.4-N prototype thruster, an impingement-type injector was applied owing to structural simplicity and effective-mixing capabilities. In this study, momentum fluxes of N_2O and DME streams were focused on effectively to mix the bipropellant. Using an angle of 30° impingement-type injector, a test was estimated the inner wall temperature of the thrust chamber at stable combustion, and the prototype yields a C^* efficiency of 68.4% at a mass flow rate 232 mg/s.

Key Words: Green propellant, Bipropellant thruster, N_2O/DME Impingement, Eco-friendly

1. Introduction

The development of space engineering has increased the opportunities for Earth observations, remote sensing, and international high-speed communication. Today, microsatellites are also attracted because of lower cost and shorter development periods, and hence, universities and startup companies develop microsatellites, some of which have been sent to the Earth orbit. Bipropellant thrusters have been used for a diverse range of spacecraft: geostationary satellites, space probes, and orbit transfer vehicles.

Conventionally, nitrogen tetroxide (NTO)/hydrazine (N_2H_4) bipropellant thrusters have been generally used as onboard propulsion systems. Because of hypergolicity, combustion is readily initiated by oxidizer-fuel impingement, and hence, neither igniter nor its electric circuit is necessary. However, the bipropellant requires temperature management for storage and gas treatment systems in the ground tests due to toxicity and reactivity to materials. Pressurant and heater are needed because the NTO and N_2H_4 have the vapor pressure of 96, and 1.92 kPa, and relatively high freezing points of 261 and 274.3 K, respectively.

Hence, we proposed a new eco-friendly bipropellant thruster using nitrous oxide (N_2O) and dimethyl ether (DME). A 0.4-N class N_2O/DME bipropellant thruster was prototyped and tested to develop onboard propulsion systems for small satellites. In this study, the momentum flux of N_2O and DME streams were focused on effectively to mix the bipropellant.

2. Impingement type of N_2O/DME Bipropellant Thruster

Both N_2O and DME are non-toxic liquefied gases, and then, feeding gaseous propellant nulls the evaporation time in the combustion chamber. The liquefied bipropellant is allowable at the vapor pressures of 5.66 MPa (N_2O) and 0.53 MPa (DME) to supply in a gaseous form, which could be simply by managing temperature and pressure.[1,2] Moreover, a pressurant is not necessary for the gaseous bipropellant for feeding because self-pressurization enables supply by themselves.

With regard to the theoretical specific impulse (I_{sp}) for the frozen flow with an expansion ratio of 50, N_2O/DME bipropellant has 290 s whereas NTO/N_2H_4 bipropellant has 318 s.[3] Despite the lower I_{sp}, the proposed impingement-type N_2O/DME bipropellant thruster has features: safeness, simplicity, non-toxicity, and non-reactivity.

3. Prototype Thruster

3.1. Prototype thruster

Figure 1 and Table 1 show a schematic and configuration of the 0.4-N class prototype thruster. The gaseous N_2O and DME were separately fed to the combustion chamber through the impingement injector. The combustion chamber had an inner diameter of 38.7 mm and a thruster length of 65 mm. Combustion was initiated with a spark plug, and combustion products were expelled through the nozzle that was designed such that the optimum expansion is obtained at atmospheric ambient pressure. Expansive-graphite gaskets were used for sealant between the parts.

3.2. Impingement-type N_2O/DME injector

Figure 2 shows a schematic of the impingement-type N_2O/DME injector. The N_2O and DME streams were provided with five injection holes of ϕ1.9-mm and ϕ1-mm, respectively. The impingement angle of the thruster injector was fixed at 30°. The diameter and number of holes were determined so that momentum flux densities were equal for N_2O and DME.

3.3. Nozzle

Table 1 provides the throat area and the expansion ratio, which was determined such that the prototype produced 0.4-N thrust with the target combustion chamber pressure of 0.4 MPa. Here, the nozzle had sonic velocity at a ϕ1-mm throat, and the theoretical specific impulse (I_{sp}) was calculated using NASA-Chemical Equilibrium with Application so that the thruster exhibited the optimum expansion at the atmospheric back pressure. [4)]

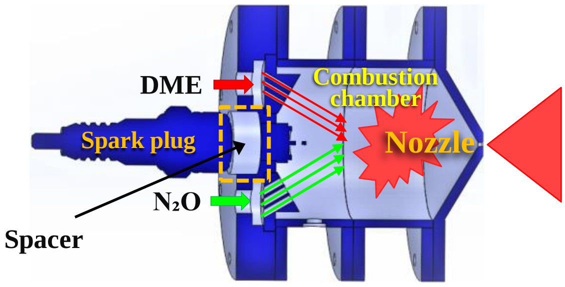

Fig. 1. Schematic of the prototype thruster

Table 1. Prototyped thruster configuration.

Impingement angle		30°		
Target thrust	[N]	0.4		
Combustion chamber pressure	[MPa]	0.4		
Mass flow rate	[mg/s]	208	218	232
Theoretical vacuum specific impulse I_{sp}	[s]	208(O/F=3.5) 198(O/F=5.7) 186(O/F=8.0)		
Characteristic length L^*	[m]	67.6		
Thruster length	[mm]	65		
Thruster outer diameter	[mm]	42.7		
Combustion chamber diameter	[mm]	38.7		
Nozzle area ratio		1.3		
Throat area, A_t	[mm^2]	0.785		
Nozzle area ratio (designed so that the thruster presents optimum expansion at the atmospheric back pressure)		1.3		

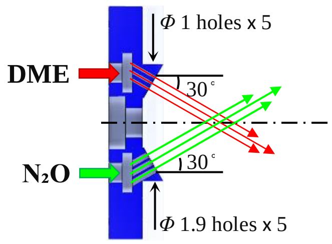

Fig. 2. Schematic of the impingement-type N_2O/DME injector.

4. Flow Simulation in Thrust Chamber

Figure 3 shows the simulation results for the propellant flow velocity and DME mass fraction in the thrust chamber. Since the ignition requires a certain flow velocity and DME mixture ratio in the spark-plug gap, N_2O and DME propellant flow were simulated at O/F=3.5 using Flow Simulation of SolidWorks. The flow simulation, which uses the finite volume method deals with viscosity and compressibility. As shown in Fig. 3, N_2O and DME streams collide at the impingement point, and go to the spark plug gap. The maximum flow velocity in the legends is limited to 5.0 m/s to clearly illustrate low-speed, whereas the simulation showed that the velocity near the nozzle throat reaches sonic or supersonic velocities.

Regarding mixture ratio, the mixture ratio in the spark-plug gap was 0.22, which is equal to that when N_2O and DME are completely mixed. Our previous study showed that ignition required DME mixture ratios in the spark-plug gap ranging from 0.20 to 0.30. From the simulation results, the prototype would be able to start combustion.

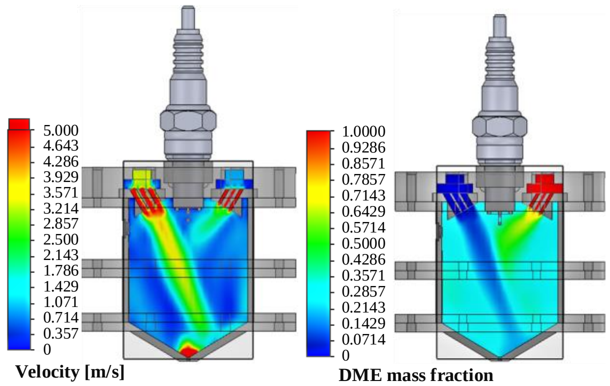

Fig. 3. Schematic of the flow simulation in the thrust chamber

5. Experimental Apparatus

5.1 Experimental apparatus

Figure 4 shows a schematic diagram of the experimental apparatus. The propellant was stored in high-pressure vessels. Because N_2O has an adequate vapor pressure for self-feeding at room temperature, no heater was used for N_2O, and the pressure was decreased using a pressure regulator. In contrast, DME was heated using a water-pool heater to keep at 30°C because 0.5-MPa vapor pressure was necessary for the supply using the self-pressurization. Then, N_2O and DME were fed through the solenoid valves, and flow rates were controlled by mass flow controllers (MFCs). The propellant was also supplied to the prototype thruster through tubes. For safety, check valves were inserted between the MFCs and prototype thruster. The spark plug was ignited with 5-kV peak voltage by an ignition transformer to produce small electric discharge.

The thruster was tested in a cubic vacuum chamber. The thruster was mounted on the thrust stand, which was fixed on the vacuum chamber of 400-mm in side. The vacuum chamber was evacuated with a vacuum pump through an exhaust port. For safety, during thruster firing, nitrogen was supplied to the vacuum chamber to dilute the exhausted gas because carbon monoxide and flammable gas could be stored in the rotary pump and vacuum chamber. Nitrogen purge increased ambient pressure up to 40 kPa. Despite the penalty due to the increase in ambient pressure, dilution was necessary because the unburned mixture of N_2O and DME was exhausted with the rotatory pump, which repetitively confined the evacuated gas to oil-submerged small chambers. Hence, nitrogen was fed to prevent spontaneous ignition. The thrust was measured using a pendulum-type thrust stand, and was calculated based on the pendulum displacement measured by a laser displacement sensor. During the test, the outer wall temperature of the thruster was measured with thermocouples. The thermocouple signals were transferred to a data logger.

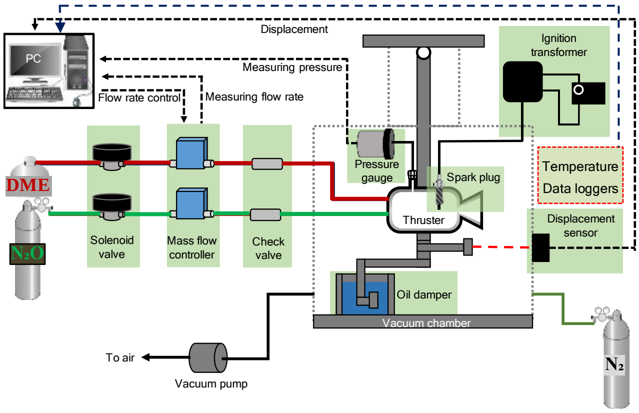

Fig. 4. Schematic diagram of the experiment apparatus

5.3. Detailed information on experimental apparatus

Figure 5 depicts the surge ranks and the flame arresters, which the N_2O and DME passed through. The flame arresters were installed to quench the combustion when the flames went upstream at ignition. Surge tanks were used to suppress pressure spikes at ignition. Thermocouples adhered to the combustion chamber walls for temperature monitoring.

Table 1 provides the propellant flow rates in the firing tests. CEA shows that the bipropellant theoretically yields the maximum I_{sp} at O/F=3.5, stoichiometric combustion at O/F of 5.7, and oxidizer rich at O/F of 8.0, respectively. Furthermore, tests were also conducted at 75%, 100% and 125% of the design flow rate.

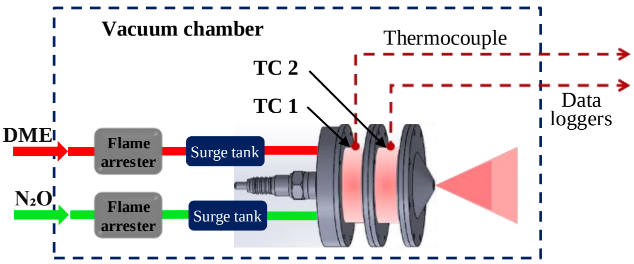

Fig. 5. Schematic of the detailed information of the experiment apparatus

6. Experimental results

6.1. Results in thruster firing

Figure 6 shows time histories of thrust and thrust chamber pressure at O/F=8.0 and mass flow rate of 232 mg/s. The combustion was repeatedly started and interrupted while the spark plug was repetitively fired. Without spark-plug firing, no combustion was sustained. In all the tests, the thruster showed such an intermittent combustion. Hence, in order to obtain stable combustion, we kept repetitive firing of the spark-plug until the stable combustion was included.

Figure 7 shows an experimental result in thruster firing when the period of spark-plug firing time was extended. At approximately 300 s after the start of the spark-plug firing, the thruster started stable combustion. The thrust and combustion chamber pressure was stable even after interrupting spark-plug firing and gradually increased with time. Combustion was terminated by interrupting propellant feeding. In the test, the thruster with impingement injector would yield the C^* efficiency and I_{sp} are 68.4% and 57 s, respectively.

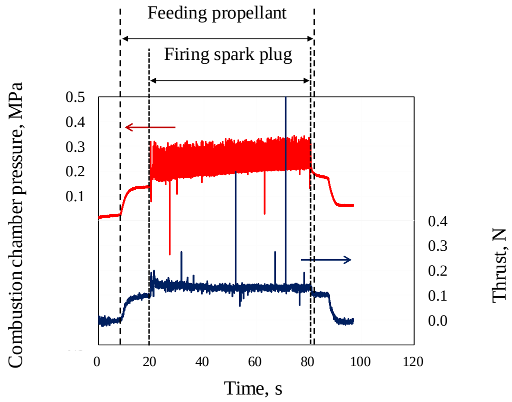

Fig. 6. Time history of combustion experiment: intermittent combustion

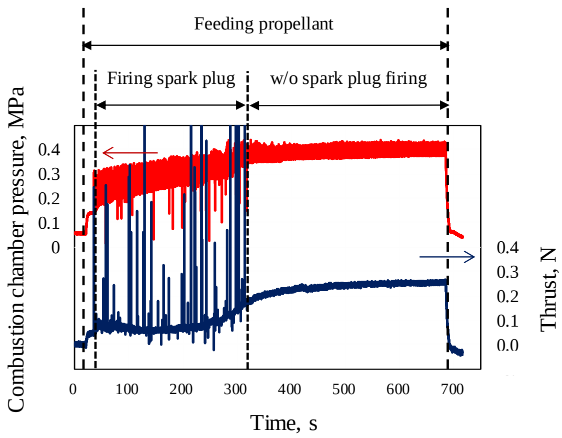

Fig. 7. Time history of firing spark plug with stable combustion

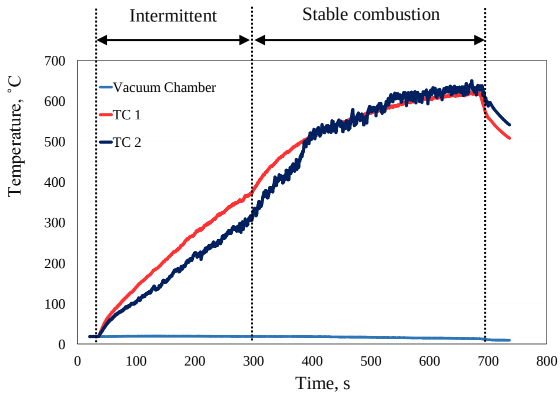

Fig. 8. Time histories of the outer surface temperature of the thrust chamber

6.2. Outer surface temperature of the combustion chamber

Figure 8 provides time histories of the outer surface temperature on the combustion chamber. Here, the temperatures are increased up to 320 and 370˚C for TC 1 and TC 2 when the stable combustion was obtained. After the start of the stable combustion, the outer wall temperature keeps increased until propellant supply was interrupted.

7. Discussion

From the experimental results, the stable combustion was possibly sustained after the thruster was heated. Hence, inserting heated surfaces into the combustion chamber could sustain stable combustion. To examine the temperature at which stable combustion is supported, the temperature of the inner wall of the combustion chamber was estimated.

For the estimation, a simple heat transfer model was introduced, as shown in Fig. 9. Assuming steady-state and the natural convective heat transfer, heat flux is balanced, so that $q_1 = q_2$. Then, the heat fluxes are expressed as

$$q_1 = h(T_O - T_a) \tag{1}$$

$$q_2 = \lambda / l\,(T_I - T_O) \tag{2}$$

The heat transfer coefficient h is generally dependent on the outer surface temperature. Then, the heat transfer coefficient h was evaluated by applying Churchill and Chu relation equation: [5)]

$$h = \frac{k}{D}\left(0.6 + \frac{0.387\,Ra^{1/6}}{\left\{1+\left(\frac{0.599}{Pr}\right)^{9/16}\right\}^{8/27}}\right)^2 \tag{3}$$

where, R_a is the Rayleigh number, and Pr is the Prandtl number. Then, T_I is calculated using Equations (1) to (3).

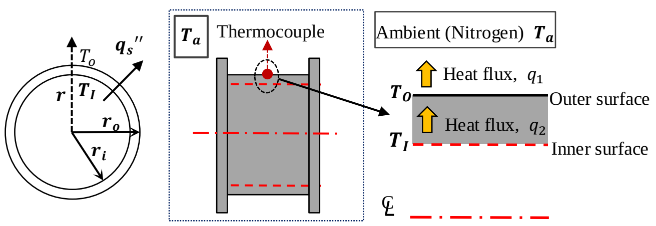

Fig. 9. Schematic of the upstream part of the thrust chamber

Figure 10 and Table 3 show the time histories of the estimated temperature on the inner wall, and the temperatures when the combustion became stable are 681˚C and 542˚C for TC 1 and TC 2, respectively. Hence, 500-700˚C class heated surfaces in the combustion chamber could assist in stable combustion. Therefore, some reasonable metal or ceramic could be applicable as the heated surface for stable combustion.

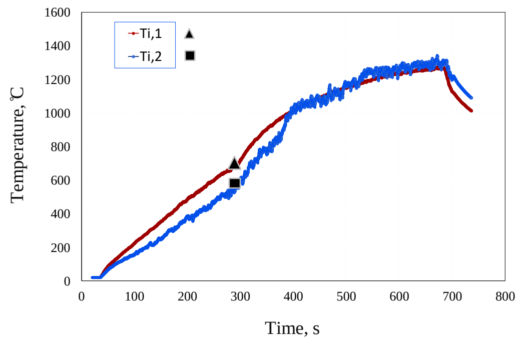

Fig. 10. Time histories of estimated temperature on the inner wall

Table 3. The estimated temperature at stable combustion

Thruster's inner wall temperature at T℃ point 1	681℃
Thruster's inner wall temperature at T℃ point 2	542℃

8. Summary

The following is the summary of this study

1. We focused on the impingement type N_2O/DME bipropellant thruster with 30˚ impingement type angle in order to develop an eco-friendly thruster.
2. Combustion was started by spark-plug firing but immediately quenched. Hence, combustion was intermittent by repetitive spark-plug firing.
3. Extending the firing period (300 s) yielded stable combustion.
4. Elevated temperature on the combustion wall possibly assisted stable combustion.
5. Heated surface would be necessary for stable combustion.

References

1) *"Thermophysical Properties of Nitrous Oxide"* (page 14 of PDF, page 10 of original document), ESDU.
2) Japan DME Association: *DME handbook*, Ohmsha, Japan, 2006 (in Japanese).
3) Kuroishi, R., Uraoka, T., Yano, Y. and Kakami, A.: Performance Evaluation of a Micro Thruster using N_2O/DME Bipropellant in Atmospheric Pressure and in Vacuum, *Proc. of space Transportation Symposium FY2013*, STCP-2013-065, Sagamihara, Japan, 2013 (in Japanese).
4) Gordon, S. and McBride, B. J.: Computer Program for Calculation of Complex Chemical Equilibrium Compositions and Applications, NASA Reference Publication 1311, 1996.
5) S.W. Churchill and H.H.S. Chu. Correlating equations for laminar and turbulent free convection from a horizontal cylinder. *Int. J. Heat Mass Transfer*, 18:1049-1053, 1975.