Experimental Study of a Nitrous Oxide/Ethanol Propulsion System: Technology Demonstration with a BBM

Shinichiro TOKUDOME[1], Tsuyoshi YAGISHITA[1], Ken GOTO[1], Hiroto HABU[1],
Naohiro SUZUKI[1], Fuyuko FUKUYOSHI[1], Yasuhiro DAIMOH[2], and Fumio OKUNO[3]

[1] Institute of Aeronautics and Astronautical Science, Japan Aerospace Exploration Agency
3-1-1 Yoshinodai, Chuo-ku, Sagamihara-shi, Kanagawa 252-5210, JAPAN.
[2] IHI Aerospace Engineering Co., Ltd.
900 Fujiki, Tomioka-shi, Gunma 370-2307, JAPAN.
[3] School of Physical Sciences, Space and Astronautical Science,
The Graduate University for Advanced Studies
3-1-1 Yoshinodai, Chuo-ku, Sagamihara-shi, Kanagawa 252-5210, Japan.

Introduction

A nitrous oxide (N_2O) / ethanol propulsion system has been studied in ISAS/JAXA since 2003[1), 2)]. It is distinguished as the liquid propulsion with non-toxic, user-friendly, and storable bipropellant, since N_2O and ethanol are generally used as the inhalation anesthetic and the food additive. The current target of the present study is to build a safe and responsive propulsion system applicable to an upper-stage propulsion system for JAXA's next-generation solid launcher under study. The application to spacecraft propulsions has been also considered because the propellant has adaptability to low temperature environment and potential as energy media. So far, four series of ground static firing tests were performed with a breadboard-model (BBM) for technology demonstrations of 2kN thrust class propulsion system. In these tests, the capabilities of three prototypes of a like-doublet impingement injector and the durability of a combustion chamber made of a heat resistant fiber-reinforced ceramic composite (SiC/SiC) were evaluated. From the viewpoint of the engine system design, a relationship between the wall heat flux determined with the water cooling chamber and the estimated local mixture ratio adjacent to the chamber inner-wall was studied from the test results. Findings and issues to be associated with the injector design and the engine operation were also obtained in the present study.

Figure 1. Appearance of propulsion system BBM equipped with N_2O/ethanol engine burning.

Non-Toxic and User-Friendly Storable Propellant

We have been seeking a propulsion system in which excels operational readiness, maneuverability, user-friendly, and application range broad enough to be the material for practical engineering educations. Its propellant selection was done on the basis of the following priority; (1) good operability (property non-toxic and storable at room temperature), (2) ready availability and cost (commercial-off-the-shelf and delivery system currently used), and (3) performance and originality (space application and the world's first study).

As a result, we selected nitrous oxide (N_2O) and ethanol as the only propellant combination being almost non-toxic to human body. The main factor was their toxicity extremely low enough to improve system operability. Performance comparison with typical propellant combination currently used under a specific condition is shown in table 1. The vacuum specific impulse of N_2O/ethanol propellant is slightly lower than that of solid propulsion, and the density specific impulse can be improved by using N_2O near freezing point. The density at -80 degrees C is 50 percent higher than that at 20 degrees C, and then, the density specific impulse improvement evaluated is 38 percent under constant C* efficiency condition. The value is slightly higher than the LOX/Methane propulsion's.

Combustion and propulsive performance of the N_2O/ethanol propulsion as a function of mixture ratio is shown in figure 2. The vacuum specific impulse reaches its peak at the stoichiometric ratio of 5.74. We selected nominal operation point at a fuel rich mixture ratio of 4.5 since an excess fuel is needed as a coolant for film cooling to prevent an ablative cooling chamber made of silica FRP or a radiation cooling chamber of heat-resistant SiC/SiC composite from high temperature combustion gas.

Table 1. Propulsive performance comparison with typical propulsion system currently used.

Propellant	Vac. Specific Impulse*1 (s)	Mean Density*2 (g/cm³)	Density Specific Impulse*3 (g/cm³·s)
LOX / LH_2	442	0.38	168
LOX / RP-1	353	1.02	360
LOX / Ethanol	336	1.00	336
LOX / Methane	361	0.84	303
Aluminized Solid*4	301	1.80	541
NTO / Hydrazine	331	1.20	398
NTO / MMH	331	1.19	394
Hydrazine (Mono)	227	1.01	229
Low Temp. N_2O / Ethanol*5	290	1.10	319
Room Temp. N_2O / Ethanol*6	294	0.79	232

*1,*2,*3 Combustion Pressure of 2 MPa, Nozzle expansion ratio of 100, Specific impulse efficiency of 95 % (Assuming shifting equilibrium composition, mixture ratio of stoichiometric proportion of 0.8);
*4 Aluminum content of 20 %;
*5 Low temperature N_2O of -80 deg.C, *6 Room temperature N_2O of 20 deg.C.

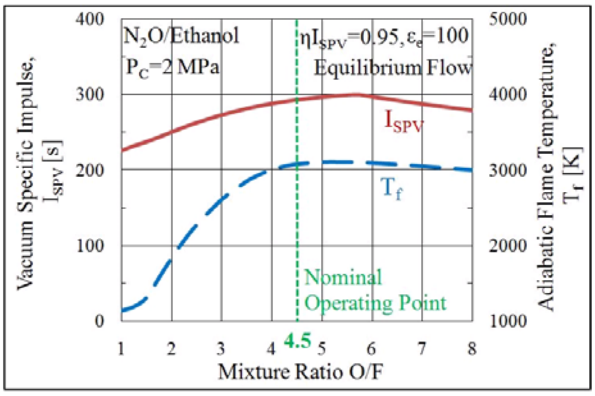

Figure 2. Combustion and propulsive performance of nitrous oxide / ethanol propulsion.

Propulsion System BBM for Technology Demonstration

As a result of system consideration of the application to the JAXA's new small solid launcher, the primary specifications of the small liquid propulsion system had determined. And then, we built a breadboard-model (BBM) for demonstrating the technologies of the main propulsion system and its components. Figure 3 shows an external appearance of the BBM. We targeted a 2 kN as the vacuum thrust level of a practical flight model and set up to 30 seconds of enough burning duration of the BBM since we employed the radiation cooling chamber made of the heat-resistant ceramic composite material (SiC/SiC) and we preliminarily estimated it reached thermal equilibrium within 15 seconds in the test conditions evaluated. A nominal operating condition set was 4.5 in mixture ratio, 2 MPa in combustion chamber pressure, and less than 30 s in total burning duration. A prototype engine combined with the SiC/SiC combustion chamber is schematically shown in figure 4. We employed a like-doublet impingement injector with 26 injection elements based on the results of preliminary experimental study[1).

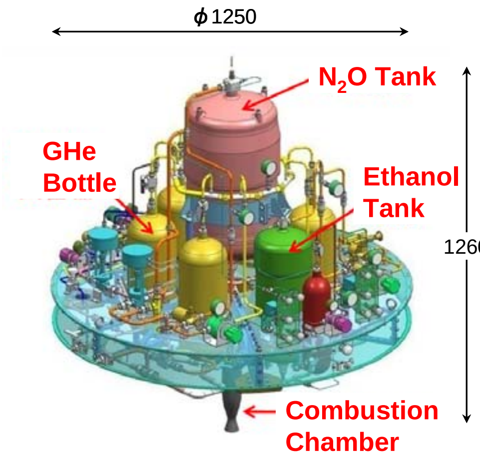

Figure 3. External appearance of BBM.

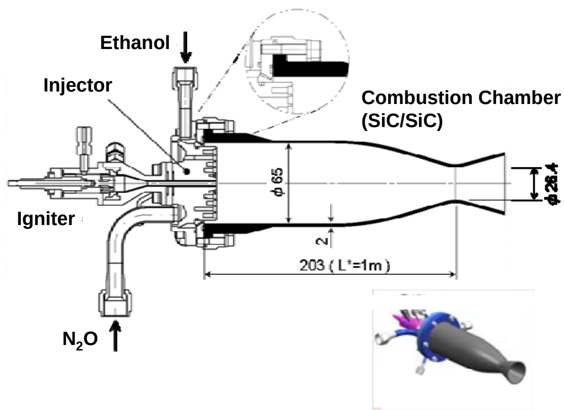

Figure 4. Schematic of prototype engine.

Primary Results of Demonstration Tests

The primary technical challenges in the present study are the design of the like-doublet impingement injector to achieve the high efficiency and stability of combustion within the limitation of upper temperature limit of the SiC/SiC, and the durability evaluation for the radiation cooling chamber in a real thermal environment. We have conducted four series of firing tests under sea-level static condition, so far.

As the result of the tests with water-cooling combustion chamber, we found that the inner wall temperature estimated at nozzle throat location under the nominal operating condition could be about 200 K higher than the upper temperature limit of chamber material. For this reason, we conducted a test of long burning duration for evaluating the durability of the chamber under a lower mixture ratio condition to control the inner wall temperature. Thus we successfully demonstrated a thirty seconds firing with the SiC/SiC chamber. Figure 5 shows time histories of a combustion chamber pressure and an outer wall temperature of the chamber measured at nozzle throat location with thermography.

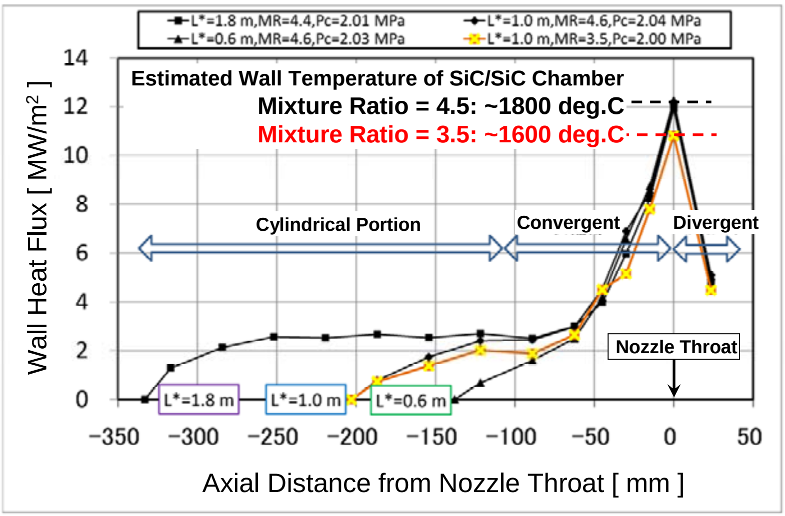

Figure 5. Axial distributions of wall heat flux from chamber inner surface, which obtained in the tests using water cooling chamber, with various chamber length and propellant mixture ratio.

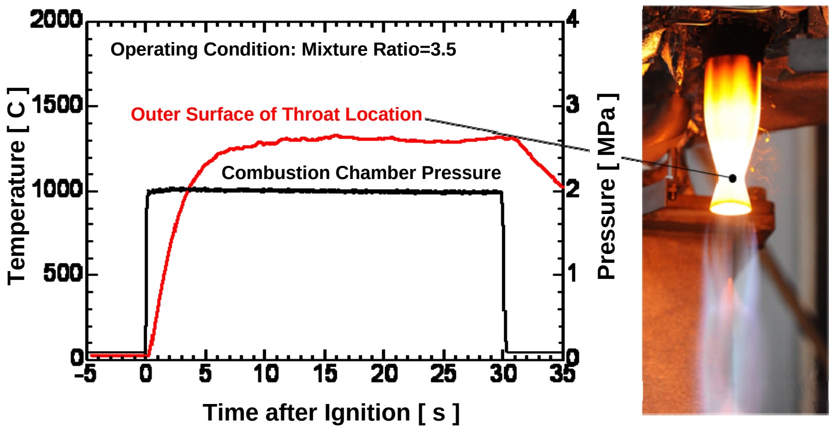

Figure 6. Result of endurance test for SiC/SiC combustion chamber.

References

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