Trans. JSASS Space Tech. Japan
Vol. 7, No. ists26, pp. Ta_19-Ta_25, 2009

Recent Advances in LOX / LH_2 Propulsion System for Reusable Vehicle Testing

By Shinichiro TOKUDOME[1)], Yoshihiro NARUO[1)], Tsuyoshi YAGISHITA[1)], Satoshi NONAKA[1)], Maki SHIDA[1)], Hatsuo MORI[2)], and Takeshi NAKAMURA[2)]

[1)]*The Institute of Space and Astronautical Science, JAXA, Sagamihara, Japan*
[2)]*IHI Corporation, Tokyo, Japan*

(Received May 2nd, 2008)

The third-generation vehicle RVT#3 equipped with a pressure-fed engine, which had upgraded in terms of durability enhancement and a LH_2 tank of composite material, successfully performed in repeated flight operation tests; and the vehicle reached its maximum flying altitude of 42m in October 2003. The next step for demonstrating entire sequence of full-scale operation is to put a turbopump-fed system into propulsion system. From a result of primary system analysis, we decided to build an expander-cycle engine by diverting a pair of turbopumps, which had built for another research program, to the present study. A combustion chamber with long cylindrical portion adapted to the engine cycle was also newly made. Two captive firing tests have been conducted with two different thrust control methods, following the component tests of combustor and turbopumps separately conducted. A considerable technical issues recognized in the tests were the robustness enhancement of shaft seal design, the adjustment of shaft stiffness, and start-up operation adapted to the specific engine system. Experimental study of GOX/GH_2 RCS thrusters have also been started as a part of a conceptual study of the integration of the propulsion system associated with simplification and reliability improvement of the vehicle system.

Key Words: Reusable rocket vehicle, Expander cycle engine, Quick turnaround, RCS thruster

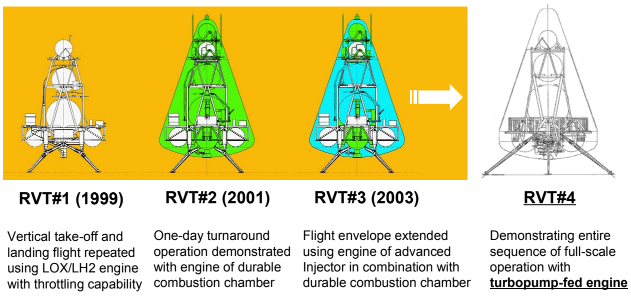
1. Introduction

For a flight test campaign with small reusable rocket vehicle, which was named reusable vehicle testing (RVT), small liquid oxygen (LOX) / liquid hydrogen (LH_2) engine of 8 kN class has been upgraded for four generation since 1998[1),2)]. The pressure-feed system was employed on the engine of the first three generation, because the vertical takeoff and landing vehicle needed a highly-responsive lightweight small engine system with continuous throttling capability. Three flight test campaign with the partially modified engine have been performed so far. Vertical-landing flights were first demonstrated in 1999, one-day turnaround operations were successfully conducted with the second-generation vehicle (RVT#2) in 2001. The third-generation vehicle (RVT#3) equipped with a LH_2 tank of composite material successfully performed in repeated flight operation tests and the RVT vehicle reached its maximum flying altitude of 42 m in 2003. For the meantime, injector and combustion chamber had been upgraded by introducing electroforming technique into their production processes in terms of durability enhancement.

The next step for demonstrating entire sequence of full-scale operation is to put a turbopump feed system into the propulsion system. An 8 kN class expander-cycle engine, which was built for another study[3)], was refurbished, so as to use it for the RVT within the realistic limit of the budget. The first series of captive firing tests of the propulsion system were performed in November 2006, following the component tests of combustor and turbopump separately conducted. After that, a fuel turbopump (FTP) was thoroughly redesigned to enhance robustness and then a new FTP was manufactured. A series of component tests of the new FTP was conducted in September 2007. Successive captive firing tests of a new engine have been performed in November 2007.

Experimental study of GOX/GH_2 RCS thrusters have been also conducted as a part of a conceptual study of integrated propulsion and power system that is a technical issue associated with simplification and reliability improvement of the vehicle system. So far, both a 140 N thruster with CMC chamber for yaw and pitch control and a 10 N class catalytic one for roll control have been demonstrated experimentally.

In this paper, some topics, which are associated with recent advances in the propulsion system prepared not only for RVT but also for future reusable vehicles, mentioned above are presented.



RVT#1 (1999) Vertical take-off and landing flight repeated using LOX/LH2 engine with throttling capability

RVT#2 (2001) One-day turnaround operation demonstrated with engine of durable combustion chamber

RVT#3 (2003) Flight envelope extended using engine of advanced Injector in combination with durable combustion chamber

RVT#4 Demonstrating entire sequence of full-scale operation with **turbopump-fed engine**

Fig. 1. Advancement of test vehicle in RVT campaign.

2. Pressure-Fed Engine for RVT#3

2.1. Propulsion system overview

Fig. 2. shows former pressure-fed main propulsion system built for RVT#3 campaign. It featured a combustion chamber with durable design components, quick re-ignition capability, and a composite cryogenic tank of filament wound CE-FRP with aluminum alloy liner. Engine thrust magnitude was controlled by directly throttling mass flow rate of both liquid propellant with thrust control valves (TCV-F and TCV-O).

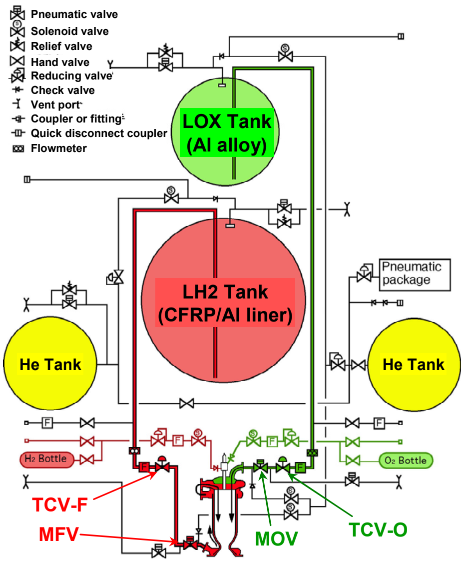


Fig. 2. Main propulsion system of RVT#3.

Table 1. RVT#3 engine specifications evaluated (rated).

	RVT#3
Thrust (@ sea level)	8.14 kN
Chamber Pressure	2.55 MPa
Propellant Mixture Ratio	5.4
Nozzle Expansion Ratio	3.5
LOX Mass Flow Rate	2.53 kg/s
LH_2 Mass Flow Rate	0.466 kg/s
Specific Impulse (@ sea level)	277 s
Thrust Control Range	3.25–8.14 kN (40 - 100%)

Volumes and operation pressures of both propellant tanks were 50 liter and 4.9 MPa for the LOX tank, and 141 liter and 4.5 MPa for the LH_2 tank, respectively. In spite of we had almost established a manufacturing technique of composite cryogenic tank, however, LOX tank was made of aluminum alloy because of insufficiently of budget and a period of preparation.

As an auxiliary propulsion system for attitude control, a nitrogen cold-gas-jet reaction control system, including four 100 N thrusters, four 10 N thrusters, and two 28 liter high pressure GN_2 composite tanks, was equipped with on the top of the vehicle.

The engine specifications of RVT#3 are listed in table 1. A low nozzle expansion ratio making deep throttling without nozzle flow separation possible and a nozzle exit contour with bell-shape designed for a previous engine with higher expansion ratio operated in space caused moderate propulsive performance. We had demonstrated that the engine had a capability of deep throttling down to 19 % of the rated thrust level.

2.2. Promising technologies employed

We had applied two technical originalities to the propulsion system through RVT#2 and RVT#3. One is composite cryogenic tank, which is detailed in the reference 4, for realizing considerable weight reduction of the system, the other is nickel (Ni) electroforming technique for making combustion chamber with high durability.

The combustion chamber partially made by the Ni electroforming technique had prepared as a part of the RVT#2 campaign. The outer casing was directly formed on the grooved outer surface of inner cylinder, which made of oxygen free copper, by the electroforming. In the RVT#3 one, we additionally tried to apply it to the annular injector element for enhancing its durability and accuracy and simplifying the manufacturing process. Fig. 3. shows the schematic of application of the technique to engine production processes.

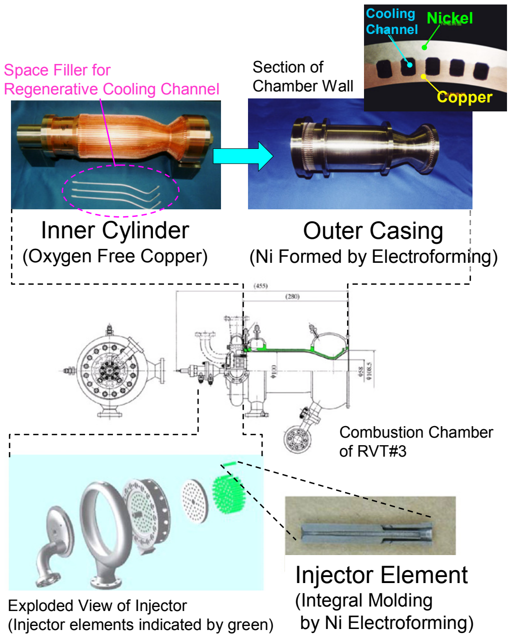


Fig. 3. Combustion chamber made by Ni electroforming.

Durability and accuracy enhancement are realized by reducing the welds and the places of brazing, so as to control thermal deformation and residual stress. Simplification of the manufacturing process is achieved by precision core-making method under the condition of low process temperature (about 60 degree C). All 60 injector elements with single-piece structure had been produced using integral molding by Ni electroforming. Space filler for regenerative cooling channel machined on the inner copper cylinder and multiple cores for making the injector element were made of pure aluminum. They were dissolved chemically with caustic soda (sodium hydroxide) following the electroforming processes. In addition we had successfully applied this technique to repair and refurbishment of the existing combustion chamber when we added processing to fit the new injector to it.

2.3. Results of engine operation

An operating life of the combustion chamber analytically evaluated in the metal fatigue due to thermal shock stress at a engine ignition was 1000 cycles at a safety factor of 4. The combustor have endured a total of 234s, nineteen cycles of starting and stop operation through the combustor component firing tests, the captive firing tests for propulsion system, and the vertical take-off and landing flight tests. Furthermore, static firing tests for evaluating durability of the single-piece injector element have been conducted using a small-size gas generator with three injector elements and almost the same combustor characteristic parameters as the engine. So far, the injector elements have endured in a total of 108 cycles of starting and stop firings[5]. We had also obtained dynamic response characteristics of the system. Frequency response up to 5 Hz, deep throttling capability down to 19 % of rated thrust without chugging, and combustion stability over the wide operating condition were demonstrated in the ground static firing tests. Fig. 4. shows time histories of thrust and chamber pressure in the chamber component static firing test. In the end, three vertical take-off and landing flights with RVT#3 vehicle were successfully conducted in October 2003, and the propulsion systems operated well. A typical result of vertical take-off and landing flight test is shown in Fig. 5.

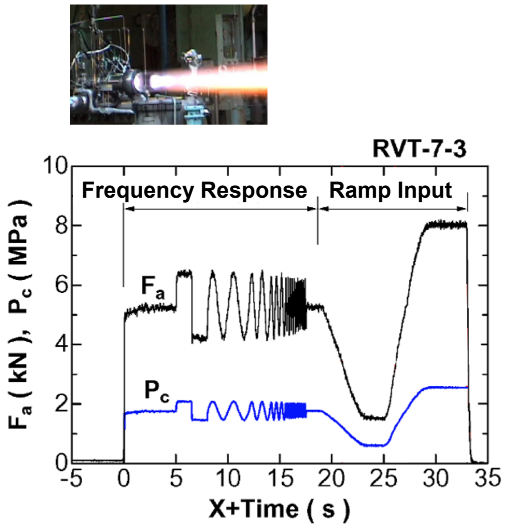


Fig. 4. Time histories of thrust F_a and chamber pressure P_c in chamber component static firing test.

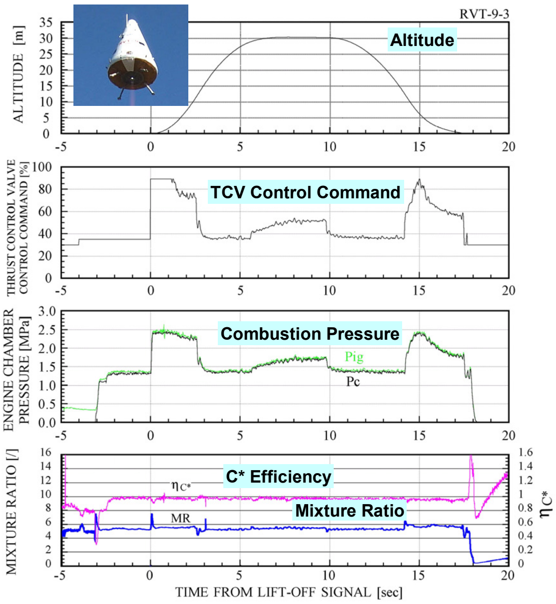


Fig. 5. Result of vertical take-off and landing flight test (RVT-9-3, Maximum Altitude = 30 m, Oct. 2003).

3. Turbopump-Fed Engine for RVT#4

3.1. Overview of 8 kN expander-cycle engine

Full-scale turbopump-fed engine have been prepared since 2003. There are three requirements for the main propulsion system of RVT#4 vehicle with turbopump-fed engine.

- Over 8 kN of rated thrust and wide range of throttling capability for demonstrating full-scale operation of reusable rocket vehicle.
- Dynamic response characteristics to meet vertical take-off and landing flight with a small test vehicle.
- Preparation and operation conducted within the resource for basic research.

We have decided to divert turbopumps, which had built for another research program[3], to the present activity so as to keep expenses for turbopump-feed system within the limits of the budget. The pumps had prepared for a prototype of 10 kN expander-cycle engine with high expansion ratio nozzle applicable to upper stage propulsion system. Although it has been believed that it was very difficult to built appropriate expander-cycle engine with separately developed component parts because the engine typically had strong interdependency among its component parts, we want to produce good results not only for the present application but also for the academic purposes by daring to build it and seeking the design approach.

Since the design points in propellant mass flow rate were about 30 % less than those of new RVT engine, we needed to partially refurbish them for adjustment. Meanwhile, we decided to make new combustion chamber with longer cylindrical regenerative cooling portion on the basis of an evaluation of the heat exchanger duty required to drive turbopumps. Furthermore, consumption reduction of coolant and seal gas was the most important issues needed to be solved to realize the flight test.

External appearance of new engine, which is currently under development, is shown in Fig. 6. It consists of eight main parts that are turbopumps, propellant valves, thrust control valves, and main combustion chamber. The present engine specifications estimated are listed in table 2. Specific impulse has been improved by the modified nozzle-exit contour adapting to ground level operation and the combustor with long cylindrical portion. The former improves nozzle efficiency and the latter elevates combustion efficiency.

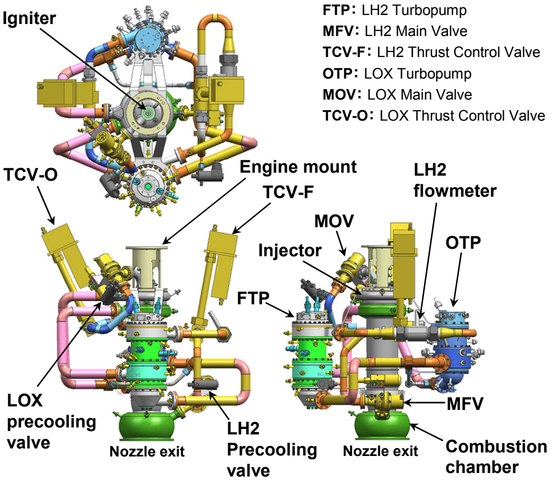


Fig. 6. Turbopump-fed engine under development.

Table 2. Turbopump-fed engine specifications planned.

	RVT#4 (reference)
Thrust	8.45 kN
Chamber Pressure	2.45 MPa
Propellant Mixture Ratio	5.26
Nozzle Expansion Ratio	3.5
Specific Impulse (@ sea level)	324 s
FTP rotational speed	91,400 rpm
FTP discharge pressure	7.95 MPa
LH_2 Mass Flow Rate	0.466 kg/s
OTP rotational speed	45,400 rpm
OTP discharge pressure	4.76 MPa
LOX Mass Flow Rate	2.53 kg/s

Details of turbopump refurbishment, combustor design, unit tests for them, simplified engine system, and captive firing tests of the propulsion system are described the following section.

3.2. Turbopump refurbishment

We modified the turbopumps in the following three points adapted to the increases in propellant mass flow:

- Enlarging the outlet width of the impellers of both turbopumps.
- Increasing the outlet angle of the impeller backward blades of FTP.
- Adjusting the turbine nozzle arrangement of FTP in a percentage of the partial admission and in a circumferential distribution of the nozzle openings.

From the aspect of propulsion system operation to reduce consumptions of helium gas and propellants, furthermore, we have devised configurations of both the feed lines for the helium seal gas and the drain systems.

From the results of two component test series of turbopumps, operation characteristics and entire sequence of operations were obtained and we verified to make their functions improved. Fig. 7. shows a schematic view of turbopumps refurbishment.

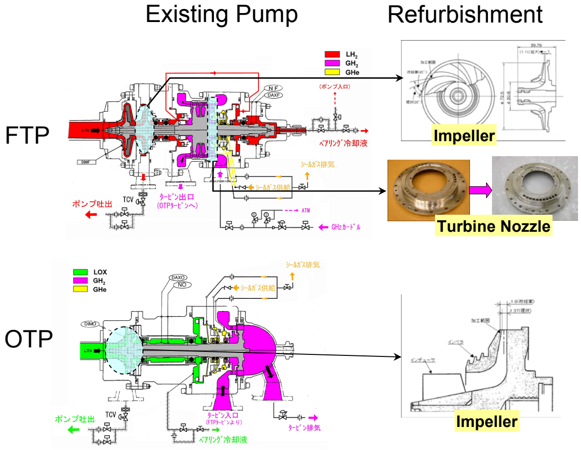


Fig. 7. Schematic view of turbopumps refurbishment.

3.3. Combustion chamber

The combustion chamber had newly made by the same Ni electroforming technique applied to the previous engine. Since the cylindrical portion became 200 mm longer than the previous one to meet expander-cycle engine, it was difficult to make aluminum single-piece space fillers previously applied to each regenerative cooling channels during the electroforming processes. So we newly applied aluminum spraying to fill in the cooling channels. A comparison of a new combustion chamber with the previous one is shown in Fig. 8.

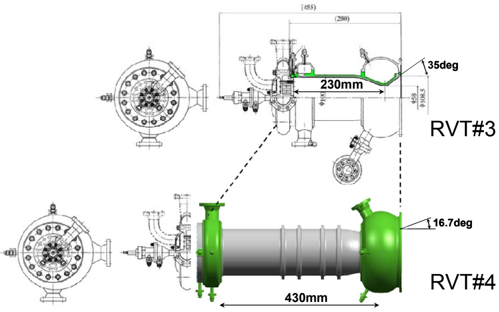


Fig. 8. Comparison of new chamber with previous one.

Component static firing tests with the combustion chamber in combination with the igniter and the injector inherited from the previous engine had been conducted at Kakuta Space Propulsion Center of JAXA (KSPC/JAXA) in the early part of 2006. We have evaluated combustion performance, thrust performance, and heat-exchange capability of the component from the test results. Both a C* efficiency (around 99 %) and a vacuum thrust coefficient efficiency (about 94 %) were significantly improved from the previous one. A heat-exchange capability was evaluated about 2.5 times as much as the previous shorter one over a wide range of operating condition, and this result demonstrated enough heat exchanger duty for accomplishment of our purpose. An transfer lag of overall heat exchanging system was estimated at about 0.4 s from the result. Fig. 9. shows a comparison of amount of heat exchanged as a function of the 0.8th power of the mass flux of combustion gas flow in chamber cylindrical portion. Open circles indicate the values evaluated under the conditions of steady operation.

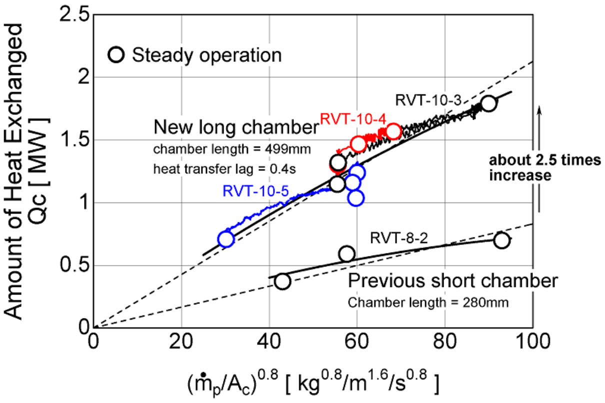


Fig. 9. Heat-exchange capability of combustion chamber.

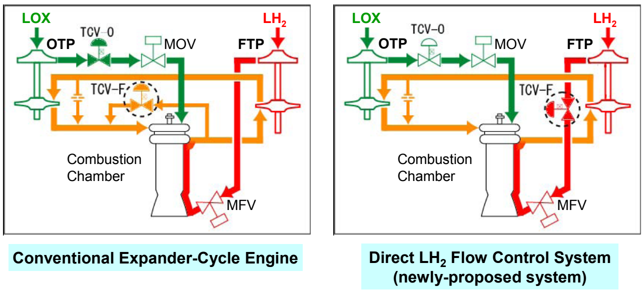
3.4. Thrust control system

An engine system was primarily required to have dynamic response high enough to make vertical take-off and landing flight possible. Furthermore, we had to make a robust and simple propulsion system for performing quick-turnaround operations with repeated flights within the limit of the resources. Therefore, we have decided to build up the engine system with minimum component parts. Minimization of number of components to the engine system results in improvement of an operation reliability.

On the basis of primary analytical study of closed expander-cycle engine system, we have figured out two thrust control systems described in Fig. 10. One was almost typical component formation of expander-cycle engine the other was newly-proposed system that LH_2 flow was directly controlled with the thrust control valve in the fuel-feeding line (TCV-F).

The former conventional one had applied to the first propulsion system built. We conducted the first captive firing test with the system. An advantage of this system is relatively low pressure difference existing in the FTP and a drawback is that the propellant mixture ratio changes with throttling: and it has relatively low dynamic response characteristics.

The latter newly-proposed one has applied to the propulsion system secondly built with a new FTP, which was newly-designed to adapt a shaft seal system to a higher pressure difference in the turbopump than that of the conventional one. A disadvantage of this system is that there is a high pressure difference through the part of shaft seal system. However, propellant mixture ratio, rotational speed, and discharge pressure of the turbopumps can be almost kept constant with throttling, and then the system has high dynamic response. We have thought that this important characteristic feature resulted in the improvement of the operation reliability in terms of avoidance of passing through critical speed during throttling.



Conventional Expander-Cycle Engine

Direct LH_2 Flow Control System (newly-proposed system)

Fig. 10. Schematic plan of thrust control systems.

3.5. Results of captive firing tests

The first series of captive firing tests were performed with the conventional expander-cycle system at Noshiro Testing Center of JAXA (NTC/JAXA) in November 2006, following the component tests of combustion chamber and turbopump separately conducted. Fig. 11. shows an appearance of the test. Propulsive and combustion performance, dynamic response characteristic, and an entire sequence of full-scale operation without detaching umbilical from the system of the expander-cycle engine, which was installed in air frame structure, were demonstrated in the tests. However, the test series had resulted in failure because of a problem with operating pressure set for pneumatic main fuel valve (MFV). An FTP built-in mechanical shaft seal was broken by large pressure difference across the seal itself, following the MFV had closed abruptly due to a shortage of the pneumatic pressure for operating MFV. Fig. 12. shows the last test result. The obtained data agreed well with simulation results. A considerable technical issue recognized in the tests was robustness improvement of shaft seal design of the FTP, since there was a large pressure difference across the seal part beyond allowable design limit under deep throttling condition.

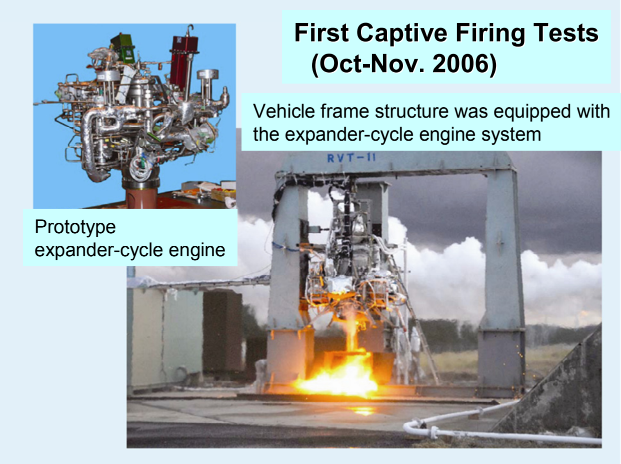


Fig. 11. Captive firing test of prototype expander-cycle engine for RVT#4 campaign.

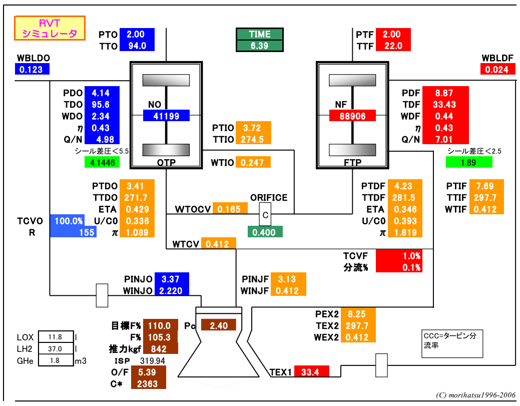


Image of engine simulation tool

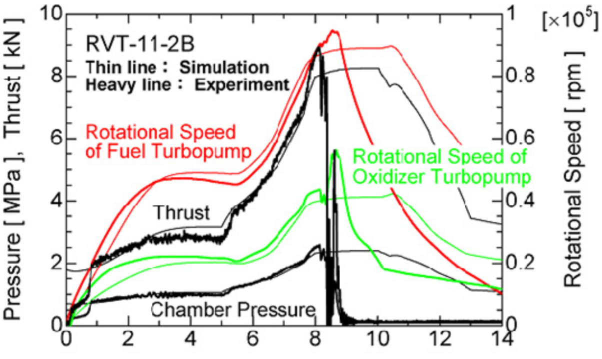


Fig. 12. Comparison of test data with simulation result.

After the test series, we had decided to thoroughly redesign the FTP except for the impeller: and then build new one. A series of component tests of the assessment of FTP had been successfully conducted at KSPC/JAXA in September 2007. Successive captive firing tests of the above-mentioned newly-proposed engine system with the new FTP have been performed from November to December last year. We tried to start up the new engine system four times with varying condition setting, but we failed all of them due to excess whirling of the rotor of the FTP. From the results of our failure investigation so far, a rotor dynamic imbalance, which was caused by a rotor contact with casing early in the first firing test, have been identified as the cause of the whirling. Hence, we have decided to thoroughly redesign the rotor including the shaft and the impeller for both enhancing its stiffness and improving pump efficiency. The next series of captive firing tests with the FTP renewed is planned in the second half of FY2008.

4. Experimental Study of GOX/GH$_2$ Thrusters

Experimental study of GOX/GH$_2$ RCS thrusters have been also conducted as a part of a conceptual study of integrated propulsion and power system (IPPS) that is a technical issue associated with simplification and reliability improvement of future reusable vehicle. The IPPS is the concept of activating all the onboard system by only the propellants loaded for main propulsion system. Similar system, which employed for car, airplane, and ship have been already practical and mature technology. However, because hydrogen fueled power system, which gives the most contributive solution to the environmental problem, is operated practically only in the area of space transportation, there is some possibility of leading the field of hydrogen-fueled technologies. Ideal IPPS proposed is described schematically in Fig. 13.

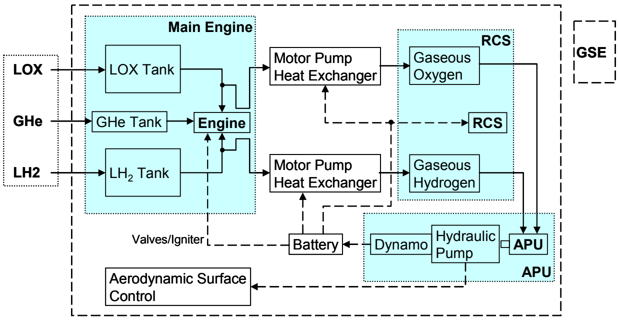
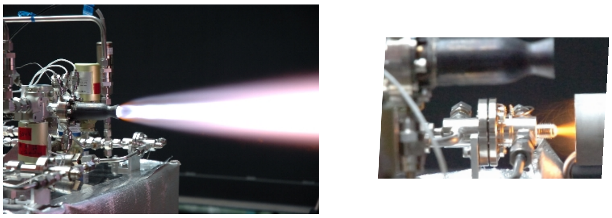


Fig. 13. Ideal integrated propulsion / power system.

We aim to fully or partially replace the previous nitrogen cold-gas-jet thrusters for attitude control system with the present hot-gas thrusters in the RVT campaign. So far, both a 140 N thruster with CMC chamber for yaw and pitch control and a 10 N class catalytic one for roll control have been demonstrated experimentally. Fig. 14. shows appearances of firing tests of both thrusters.



140 N yaw / pitch thruster

10 N roll thruster

Fig. 14. Prototype GOX/GH$_2$ thrusters firing.

Propulsion system integration with propellant-sharing system of main engine and RCS would be a technical issue in full-scale vehicle development. The present activity would partially become preceding study for the vehicle development.

5. Concluding Remarks

Through the activity of RVT campaign, we have succeeded in three flight tests of vertical take-off and landing. Furthermore, the concept that ‘to achieve efficient reuse, the vehicle components must be inspected and adjusted without detecting them’ could be proved by those flight tests.

The next target of this research activity is to perform flight tests with entire sequence of full-scale operation using a turbopump-fed engine. Component tests have been succeeded but system firing demonstrations have not completed yet, because of the difficulty of turbopump-fed system in both design and operation. But we have solved major problems to build a successive propulsion system so far. We are now under preparation for the next flight test campaign with the upgraded turbopump-fed propulsion system.

Acknowledgements

The authors would like to thank all the people who participated in the design and development of the propulsion system for their help. The authors are also grateful to all the participants who contributed to the flight tests, the captive firing tests, and the component tests.

References

1) Inatani, Y., Naruo, Y., Ishii, N., Ogawa, H., Nonaka, S., Tokudome, S., and Yamakawa, H.: Flight Testing of A Reusable Rocket Vehicle, *Space Technology*, **25** (2005), pp.219-228.
2) Naruo, Y., Tokudome, S., Ishii, M., and Higashino, K.: Design and Operational Aspect of LOX/LH_2 Propulsion System of Reusable Vehicle Testing (RVT), AIAA/NAL-NASDA-ISAS 10th International Space Planes and Hypersonic Systems and Technologies Conference, AIAA-2001-1841, (2001).
3) Naruo, Y., Inatani, Y., Morita, Y., Nakai, S., and Mori, H.: Throttling Dynamic Response of LH_2 Rocket Engine for Vertical Landing Rocket Vehicle, The seventh International Space Conference of Pacific Basin Societies, AAS-97-421, (1997).
4) Higuchi, K., Takeuchi S., Sato, E., Naruo Y., Inatani, Y., Namiki, F., Tanaka, K., and Watabe, Y., : Development and Flight Test of Metal-Lined CFRP Cryogenic Tank for Reusable Rocket, The 55th International Astronautical Congress, IAC-04-IAF-V5.04, (2004).
5) Tokudome, S., Yagishita, T., Suzuki, N., Tokunaga, Y., Shida, M., Arakawa, S., and Yasuda, S.: Small Test Equipment for Development Studies of Liquid Rocket Engines: Proceedings of Asian Joint Conference on Propulsion and Power 2005, AJCPP2005-22004, (2005).