DOI: 10.13009/EUCASS2023-380
Aerospace Europe Conference 2023 – 10TH EUCASS – 9TH CEAS

Verification of Turbopump in the Small Thrust LOX/Methane Engine Firing Tests

Keisuke Bando†, Toru Kuga*, Toru Tsukano*, Satoshi Takada**, and Hiromitsu Kakudo***
** IHI Corporation*
229, Tonogaya, Mizuho-machi, Nishitama-gun, Tokyo 190-1297, Japan,
**** Japan Aerospace Exploration Agency*
1 Koganezawa, Kimigaya-aza, Kakuda-shi, Miyagi 981-1525, Japan
bando8989@ihi-g.com – kuga9054@ihi-g.com
† Corresponding Author

Abstract

This study reports on the development status and test results of a compact single-shaft turbopump in LOX/Methane engine firing test. The turbopump has been developed and manufactured for 30 kN-class LOX/Methane full-expander cycle rocket engine by JAXA/IHI. The turbopump test as component test was conducted in FY2018. Based on the test result, the seal between fuel pump and turbine was changed to reduce propellant leakage. The full-expander cycle engine firing tests were conducted using this modified turbopump in FY2021 and FY2022. The test result shows that the turbopump can be applied for flight engines.

1. Introduction

Methane is attracting attention as a fuel for rocket engines due to the following advantages: superior propulsion per unit density, less soot generation, or evaporation and less risk of leakage, and common use of parts with oxidizer due to the similar temperature and quantity required in engine operation. In recent years, the development of rocket engines using LOX/methane as propellant, such as Prometheus, M-10, Raptor and BE-4, has been progressing worldwide. In Japan, research and development to improve the performance of regeneratively-cooled LOX/methane rocket engines for application to future space transportation systems was started in 2013, and after component tests and open-cycle engine tests in 2018 and 2019, closed-cycle engine demonstration tests were conducted starting in 2020 [1].

This engine uses a single-shaft LOX/methane turbopump. All component tests conducted in FY2018 (turbopump test, multi-element injector firing test, regeneratively cooled combustion chamber firing test) using this turbopump were successful [2][3]. The test results showed that the propellant leakage through the shaft seal between fuel pump and turbine during chill-down phase must be decreased. In order to improve the sealing performance of the shaft seal between the fuel pump side and turbine side, the sealing element was changed from a floating ring seal to a mechanical seal. Using this modified turbopump, the full-expander cycle engine firing tests were conducted in FY2021 and FY2022.

DOI: 10.13009/EUCASS2023-380

2. Reference engine

The LOX/methane engine under development adopts a full-expander cycle, which is expected to have a high specific impulse (Isp). The target vacuum thrust is 30 kN and the target vacuum Isp is 370 sec. The design specifications are shown in Table 1, and the engine is shown in Figure 1.

Table 1: 30 kN-class LOX/Methane Full Expander Engine Specifications

Item	Value
Propellant	LOX/Methane
Thrust (vacuum)	30 kN
Isp (vacuum)	370 sec
Mixture ratio	3.3
Combustion pressure	4.7 MPa (abs.)
Throttling	50 - 100 %

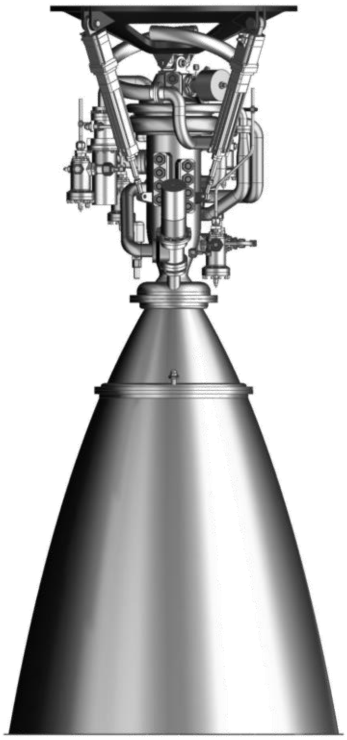

Figure 1: 30 kN-class LOX/Methane Engine [2]

DOI: 10.13009/EUCASS2023-380

3. Design and manufacturing of the turbopump

The turbopump was designed for the engine shown in section 2. The specifications of the turbopump are shown in Table 2, and the turbopump is shown in Figure 2. The basic features of the turbopump are as follows:

・Single shaft:
The oxidizer pump, fuel pump, and turbine are connected to the single shaft.

・Compact size / Lightweight:
The turbopump was designed to be compact with a full length of about 350 mm and weight of about 16 kg.

・Balance piston mechanism:
Axial thrust of the turbopump shaft is self-adjusted by a balance piston mechanism.

・Compact mechanical seal:
The liquified methane in the fuel pump and gaseous methane in the turbine are separated by a compact mechanical seal. The width of this mechanical seal is 25 mm or less, and the outer diameter is 60 mm or less.

・Labyrinth seals and purge gases:
The LOX and liquified methane are separated by labyrinth seals and the purge gases.

・Throttling operation:
The turbopump is capable of throttling between 42,000 - 65,000 rpm.

・Additive manufacturing:
All casings, the LOX impeller and the Methane impeller were made by additive manufacturing.

Table 2: Basic specifications of the turbopump

Item	Value	
	Design point	50% throttling
Rotational speed	65,000 rpm	42,000 rpm
Oxidizer pump inlet pressure	0.40 MPa (abs.)	0.40 MPa (abs.)
Oxidizer pump outlet pressure	6.17 MPa (abs.)	3.04 MPa (abs.)
Oxidizer pump flow rate	6.47 kg/s	3.30 kg/s
Fuel pump inlet pressure	0.40 MPa (abs.)	0.40 MPa (abs.)
Fuel pump outlet pressure	11.64 MPa (abs.)	5.41 (abs.)
Fuel pump flow rate	1.96 kg/s	1.00 kg/s
Turbine inlet pressure	10.74 MPa (abs.)	4.40 MPa (abs.)
Turbine outlet pressure	5.45 MPa (abs.)	2.83 MPa (abs.)
Turbine flow rate	1.93 kg/s	0.77 kg/s

DOI: 10.13009/EUCASS2023-380

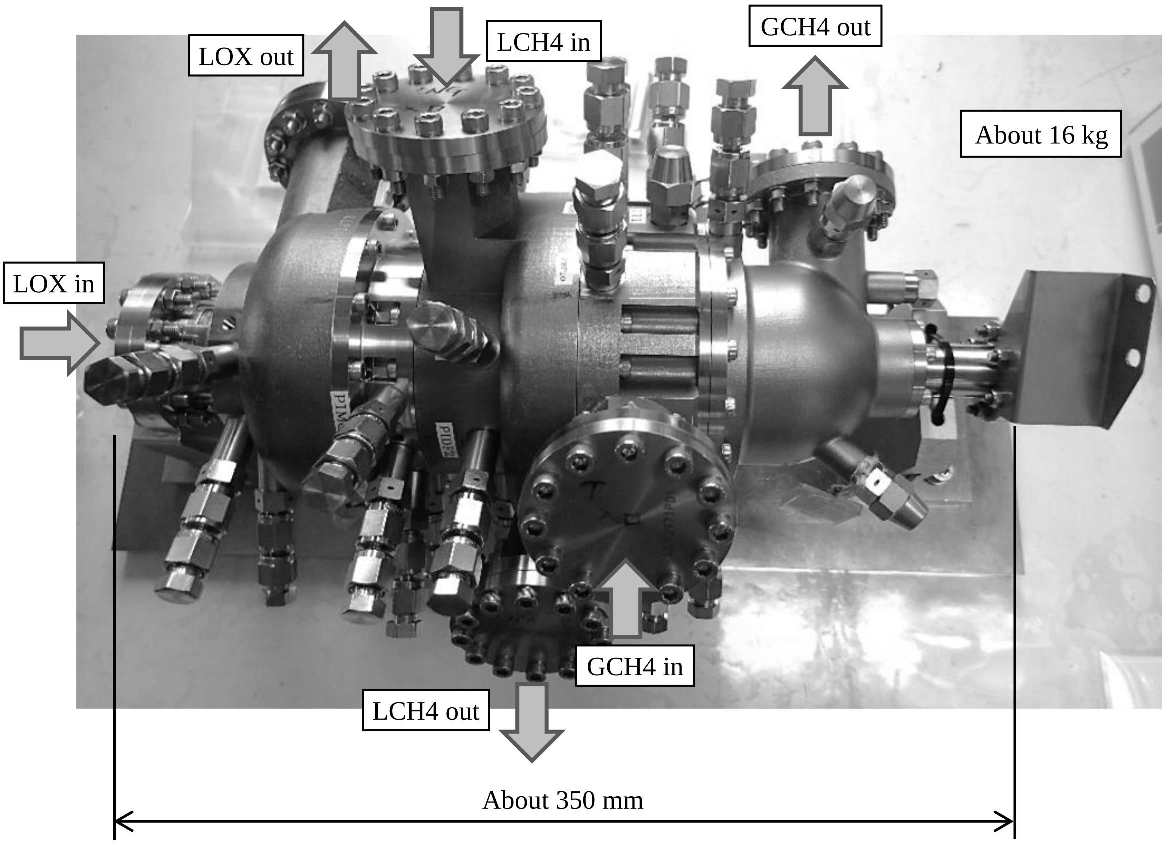

Figure 2: The turbopump

DOI: 10.13009/EUCASS2023-380

3.1 Design modification of turbopump from FY2018

Liquified methane leakage from the fuel pump side to the turbine side of the shaft seal during low rotational speed of turbopump occurred in the FY2018 test. The engine configuration in FY2018 was open-cycle, that is, gaseous methane as turbine gas was fed from a pressurized tank through separate line from fuel supply line to the main combustor. Therefore, there were no major problems in the ignition of combustor in engine firing test.

On the other hand, the tests planned for FY2021 and FY2022 were to be conducted in the full-expander closed-cycle configuration. If liquified methane were to leak to the turbine side during chill-down phase, gaseous methane will flow into the injector and the combustion chamber downstream before ignition of combustor. This increases the risk of ignition failure. Therefore, in order to improve sealing performance of the shaft seal between the fuel pump and the turbine, the sealing element was changed from a floating ring seal to a mechanical seal. It makes possible to reduce propellant leakage from the fuel pump to the turbine with no shaft rotation by changing from a non-contact seal to a contact seal. In order to install a mechanical seal in such a compact turbopump, a compact mechanical seal was developed and the internal propellant flow of the turbopump was redesigned.

The turbopump has a full length of about 350 mm, so that the area where the mechanical seal must be installed is extremely small. The mechanical seal had to be made be smaller in both axial and radial directions than conventional ones, which was a technical challenge. However, a compact mechanical seal with a width of 25 mm or less and an outer diameter of 60 mm or less that satisfies this requirement was developed by JAXA. And it was verified that it has sufficient sealing performance and lifetime through component tests of the mechanical seal and was adopted for the turbopump.

In addition, the internal propellant flow of the turbopump was redesigned to control the differential pressure between the upstream and the downstream of the mechanical seal and the axial thrust of the turbopump shaft, since the mechanical seal will be damaged if the differential pressure is out the operational range. The operational range of differential pressures is between 0 to 1.3 MPa.

Furthermore, adjusting the differential pressure across the seal means changing the internal pressure distribution of the turbopump from the FY2018 test, and the pressure applied to the front and back of each rotor part will change. The axial thrust of the turbopump shaft changes according to changes in the pressure applied to the front and back of each rotor part. Therefore, if only the adjustment of the differential pressure is considered, the shaft position where the axial thrust is balanced by the balance piston mechanism will not be suitable position, and the rotating part will contact to stationary parts. In order to prevent contact of parts by controlling axial thrust, the route of the internal propellant flow paths was devised, and several lines were newly installed. The pressure distribution inside the turbopump can be adjusted by changing the diameter of the orifice attached to these internal propellant flow paths. The schematic diagram of the internal propellant flow paths around the mechanical seal is shown in Figure 3.

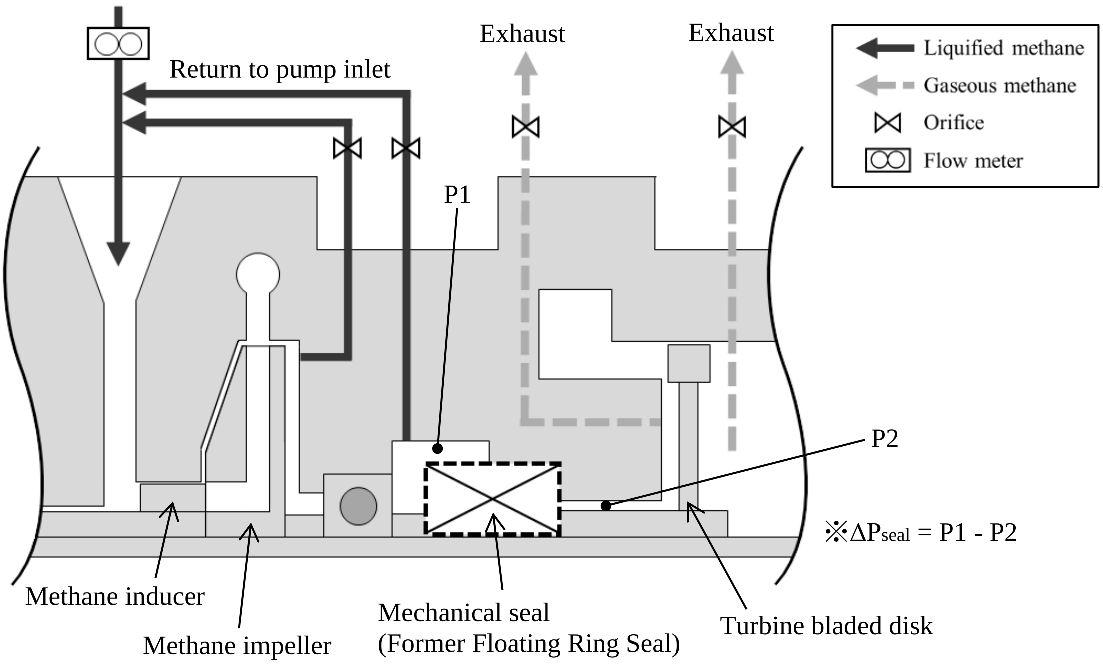

Figure 3: The schematic diagram of the internal propellant flow paths around the mechanical seal

DOI: 10.13009/EUCASS2023-380

4. Full-expander cycle engine firing tests

4.1 Test configuration

The full-expander cycle engine firing tests were conducted at IHI AEROSPACE's Aioi test center in March 2023. A diagram of the full-expander cycle engine firing test is shown in Figure 4. LOX is fed from a pressurized tank through a turbine flow meter and further pressurized by the oxidizer pump. The pressurized LOX is fed to the injector located downstream of the oxidizer pump. Liquified methane is fed in the same way, however, pressurized liquified methane is fed to regenerative cooling channels on the side wall of the combustion chamber where the temperature of methane is increased by combustion heat. The high temperature methane is then fed to the turbine located downstream of the regenerative cooling channels as turbine driving gas, and further fed to the injector located downstream of the turbine. The orifices to regulate propellant flow rate to the injector and regenerative cooling channels are downstream of each pump. There is also an orifice to regulate the turbine gas flow rate upstream of the turbine.

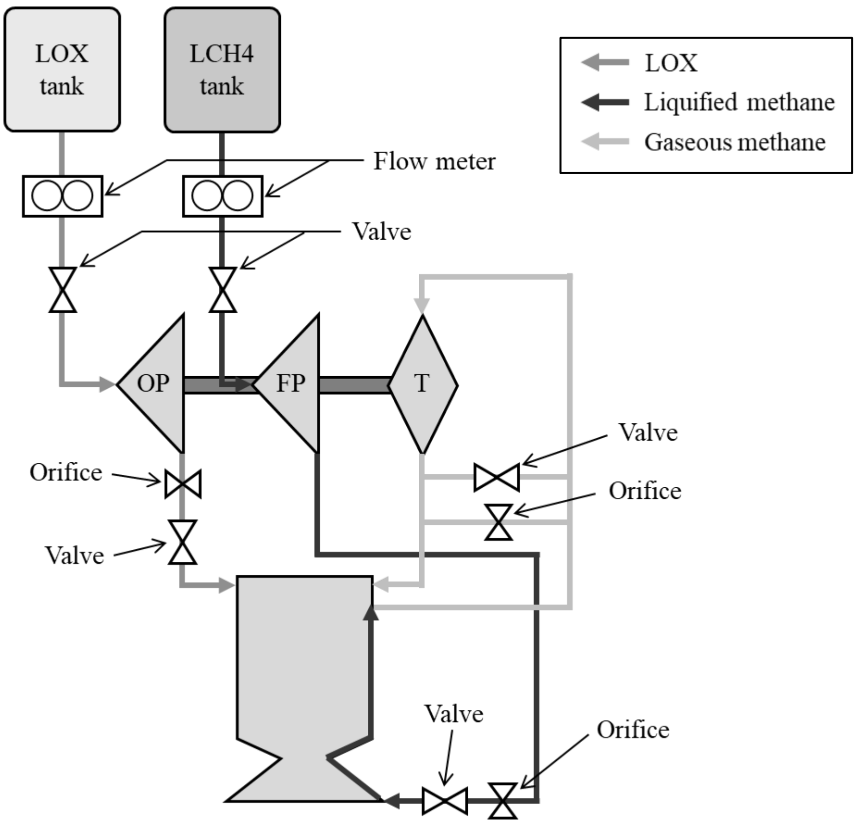

Figure 4: A diagram of the full-expander cycle engine in firing test configuration

DOI: 10.13009/EUCASS2023-380

4.2 Test result

Each performance value and flow ratio shown in Figure 5 - Figure 9 is non-dimensionalized by dividing by the design condition value. Each line and plot are as shown below:

・The solid lines are the performance curve predicted based on the result of the turbopump tests in FY2018.
・White circle plots(○) are the design condition value.
・White triangle plots(△) are the results of the turbopump tests in FY2018.
・White diamond plots(◇) are the results of the open-cycle engine firing tests in FY2018 (open-cycle).
・Gray triangle plots(▲) are the results of the turbopump tests in FY2021.
・Gray square plots(■) are the results of the full-expander cycle engine firing tests in FY2021.
・Black square plots(■) are the results of the full-expander cycle engine firing tests in FY2022.

・Oxidizer pump

The head coefficient of the oxidizer pump is shown in Figure 5 and the oxidizer pump efficiency is shown in Figure 6. The head coefficient of each test was almost the same as the performance curve. On the other hand, the efficiencies were higher in the FY2021 and the FY2022 tests than the performance curve. It seems the increase in calculated efficiencies may have occurred due to the change of the internal propellant flow rate of the oxidizer pump by changing of the internal propellant flow orifices since the LOX inducer and the impeller are the same for the FY2021 and FY2022 tests and the FY2018 test. Even with the oxidizer pump inlet mass flow rate is the same, the mass flow rate passing through the impeller is different by changing the internal propellant flow rate. In other words, the sum of the oxidizer pump inlet flow rate and the internal oxidizer flow rate is the flow rate passing through the impeller. The true value of pump performance is calculated using the flow rate passing through the impeller, while the results in Figure 5 and Figure 6 were calculated using the oxidizer pump inlet flow rate since the oxidizer pump flow rate was measured at the pump inlet. Therefore, the difference in the internal propellant flow rate affected the calculation result of the pump performance.

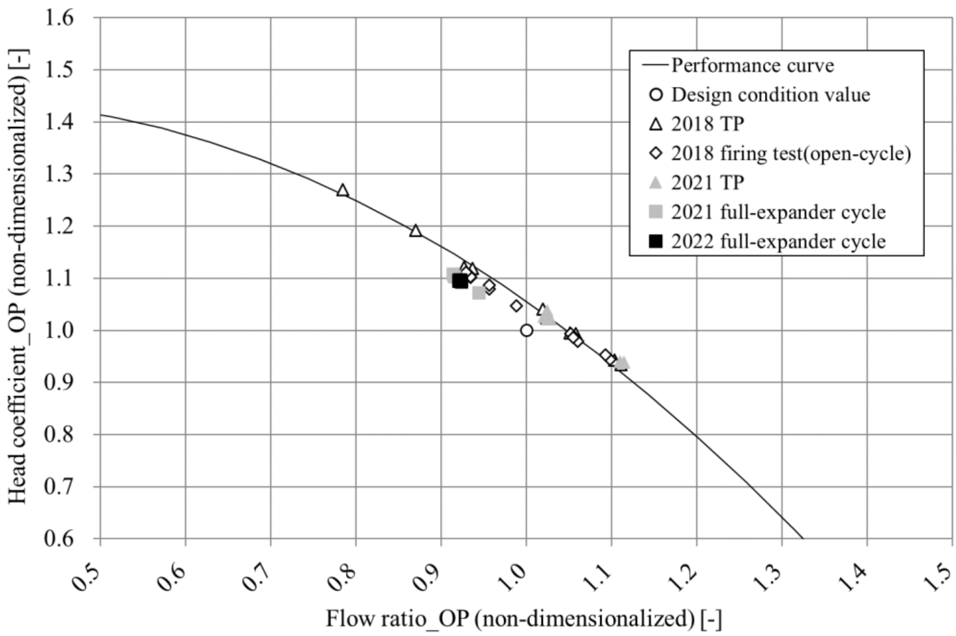

Figure 5: Head coefficient of the oxidizer pump

DOI: 10.13009/EUCASS2023-380

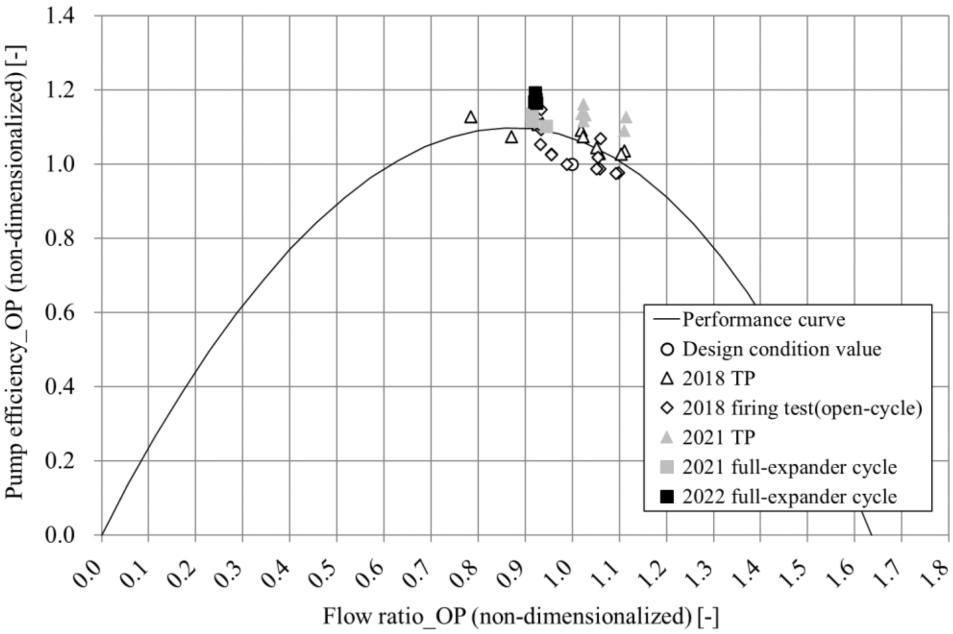

Figure 6: Pump efficiency of the oxidizer pump

・Fuel pump

The head coefficient of the fuel pump is shown in Figure 7 and the fuel pump efficiency is shown in Figure 8. The head coefficient of each test was almost the same as the performance curve. On the other hand, the fuel pump efficiency in the FY2022 test was slightly higher than the performance curve. As with the oxidizer pump, it seems to have occurred due to changing the internal propellant flow rate of the fuel pump by changing of the internal propellant flow orifices since the methane inducer and the impeller are the same for the FY2021 and FY2022 tests and the FY2018 test. The true value of pump performance is calculated using the flow rate passing through the impeller, while the results in Figure 7 and Figure 8 were calculated using the fuel pump inlet flow rate since the fuel pump flow rate was measured at the pump inlet. Therefore, the difference in the internal propellant flow rate affected the calculation result of the pump performance.

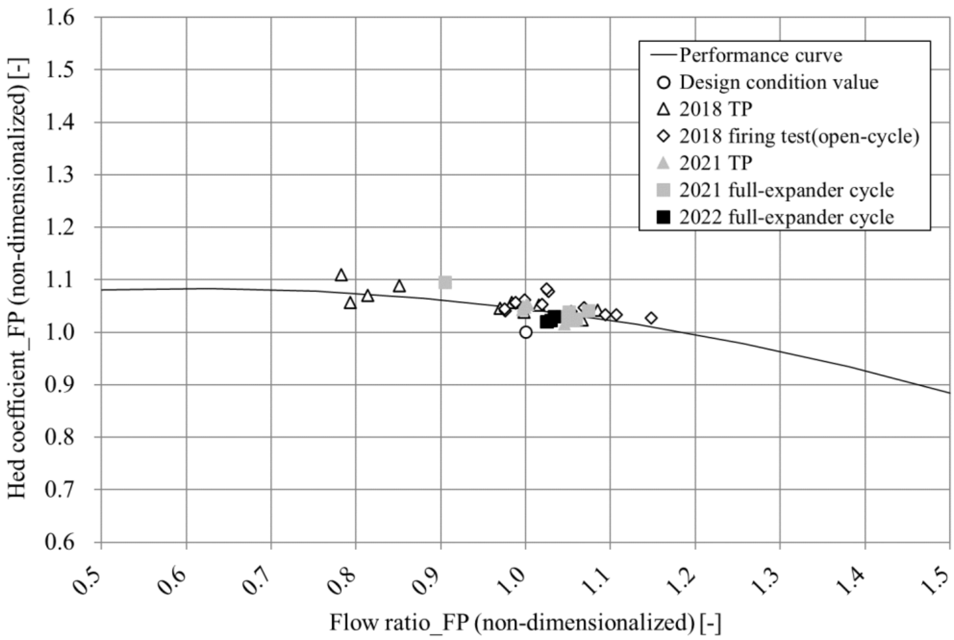

Figure 7: Head coefficient of the fuel pump

DOI: 10.13009/EUCASS2023-380

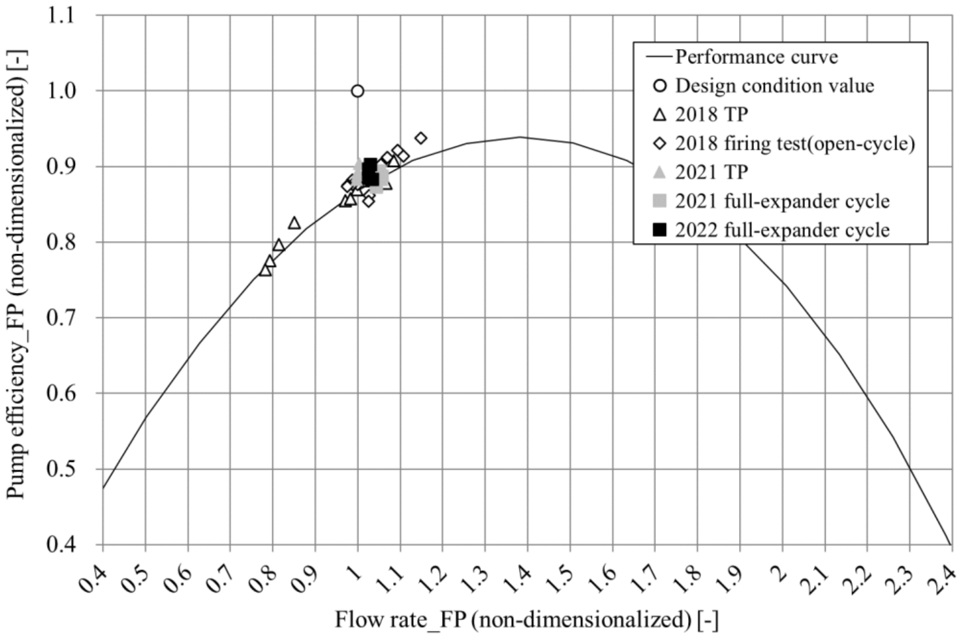

Figure 8: Pump efficiency of the fuel pump

・Turbine

The turbine efficiency is shown in Figure 9. The turbine efficiencies in the FY2021 and the FY 2022 tests were lower than the performance curve. It seems to have occurred due to changing the number of windows for partial admission of turbine nozzle from one in FY2018 to two in FY2021 and FY2022. The partial admission is a method of closing part of the turbine nozzle to adjust the flow area. By doing this, it is possible to adjust the turbine-driven gas flow rate. In general, the turbine efficiency decreases as the number of partial admission windows increases. Although the turbine efficiency has decreased, the required performance from the engine is satisfied.

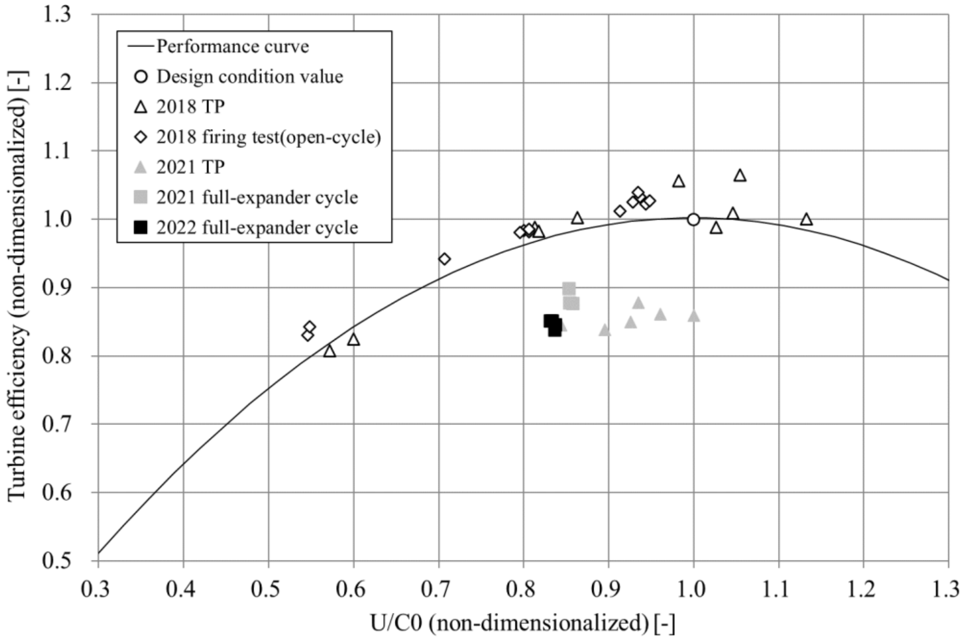

Figure 9: Turbine efficiency

DOI: 10.13009/EUCASS2023-380

・Mechanical seal

If liquified methane leaks from the fuel pump side to the turbine side during chill-down, the temperature at the turbine section will fall to the liquid temperature of methane (about 112 K). The temperature during chill-down in the FY2022 test is shown in Figure 10. TTD2, which indicates the temperature at the turbine section remained above 200 K during chill-down and did not reach the liquid temperature of methane. Therefore, propellant leak prevention between the fuel side pump and turbine during chill-down seems to have been accomplished without any problems.

In order to prevent damage to the mechanical seal, the differential pressure across the seal must be within the tolerance range of 0 to 1.3 MPa. The differential pressure across the seal in the FY2022 test is shown in Figure 11. Although the differential pressure was slightly below 0 MPa during the transient state immediately after engine start, the duration of it was short, and the value of it was very small. Therefore, there is no damage on the mechanical seal. Furthermore, although the differential pressure across the seal increased over time, the maximum value of it was less than 1.3 MPa, which is the maximum operating result in the component test of the mechanical seal. In addition, it seems the axial thrust of the turbopump shaft was controlled as intended since the axial position of the turbopump shaft was suitable position during engine combustion. These results demonstrate that the compact mechanical seal can be applied for the turbopump.

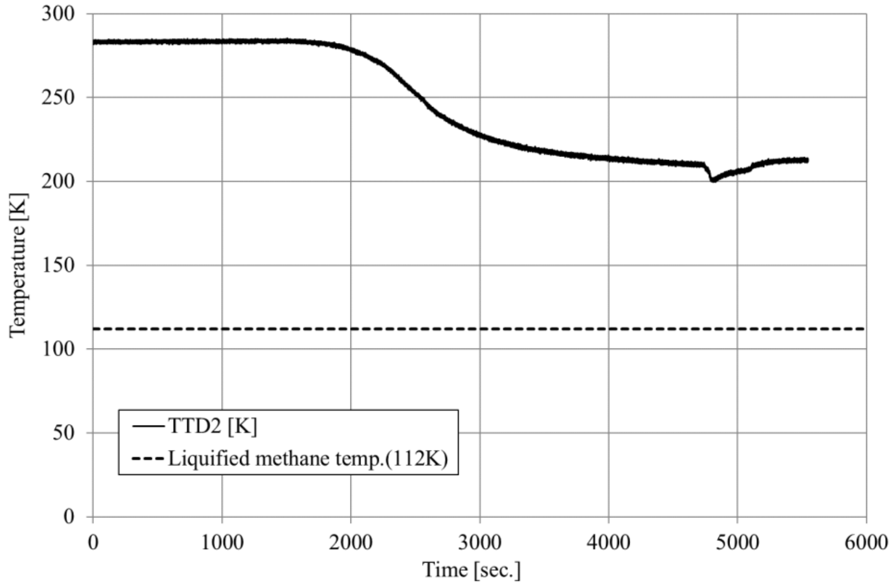

Figure 10: The temperature at the turbine section during chill-down in the FY2022 test

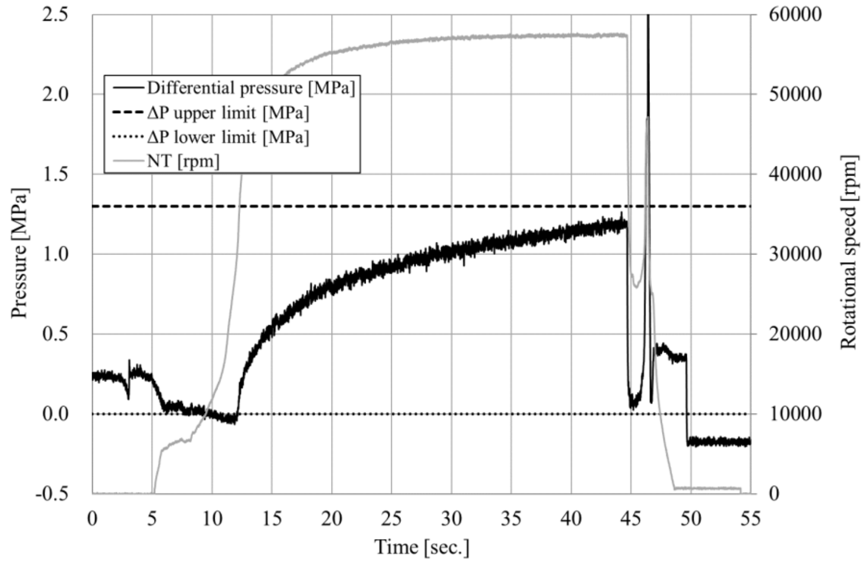

Figure 11: The differential pressure across the mechanical seal in the FY2022 test

DOI: 10.13009/EUCASS2023-380

・Summary of test result

A photograph of the full-expander cycle engine firing test is shown in Figure 12. Throughout the FY2022 test series, the turbopump operated stably, and various performance values satisfied each required value. As a result, the engine was able to achieve stable combustion.

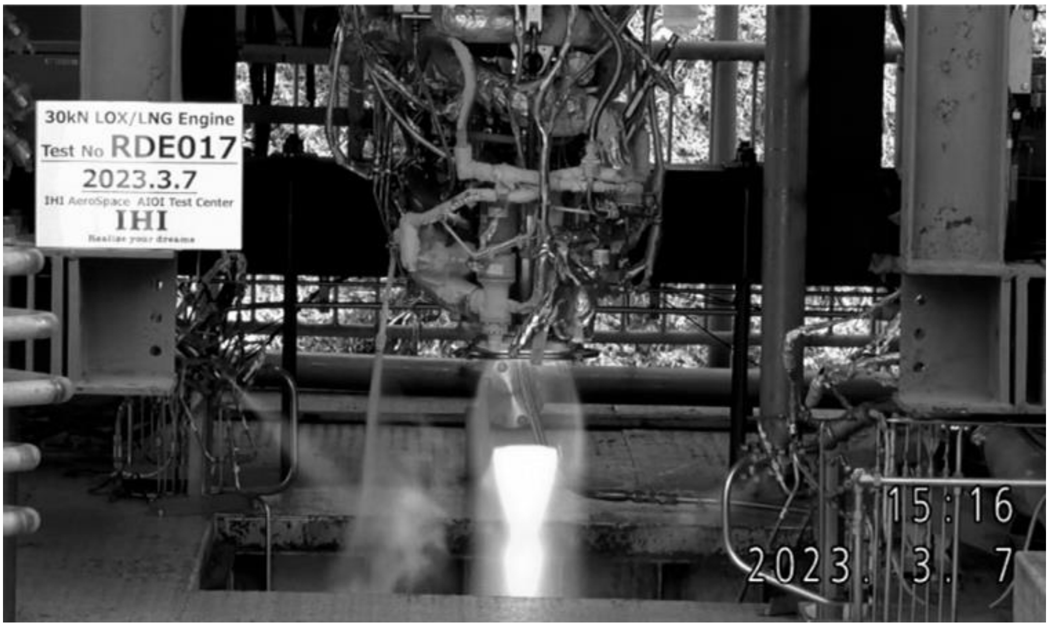

Figure 12: The full-expander cycle engine firing test

3. Conclusion

A compact single-shaft turbopump that satisfies the requirements for a 30 kN-class LOX/methane full-expander cycle engine was developed and manufactured, and the full-expander cycle engine firing tests were conducted in FY2021 and FY2022. The shaft seal of the turbopump was modified from a floating ring seal to a compact mechanical seal. In these tests, the turbopump operated stably and various performance values satisfied requirements. By adopting a compact mechanical seal, propellant leak prevention between the fuel pump and turbine during chill-down was accomplished. And it was also confirmed that the compact mechanical seal could be operated properly by adjusting the internal propellant flow of the turbopump. The test results show that the compact single-shaft turbopump can be applied for flight engines.

References

[1] Ideo Masuda, et al., "JAXA's Current Activities for the Research of a LOX/LCH4 (LNG) Engine", Space Propulsion 2016, Roma, Italy, 2-6 May 2016
[2] Toru Tsukano, et al. "Component tests of a LOX/methane full-expander cycle rocket engine: Single-shaft LOX/methane turbopump", 8th EUCASS, Madrid, Spain, 2019
[3] S. Ukai, et al, "Component tests of a LOX/methane full-expander cycle rocket engine: Injector and regeneratively cooled combustion chamber", 8th EUCASS, Madrid, Spain, 2019