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Component tests of a LOX/methane full-expander cycle rocket engine: Single-shaft LOX/methane turbopump

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Abstract
The single-shaft turbopump for a liquid oxygen and liquid methane engine was validated to have good performance through operating tests. Research on a methane engine has been carried out in Japan for the purpose of increasing the specific impulse and a small full-expander cycle engine was selected to demonstrate the research actibity. The turbopump is designed and manufactured to satisfy the required performance from the engine and to demonstrate fast and low cost production technology. As the result, the turbopoump met the required performance and was produced in less than one third period and cost compared to exsisting technology.

1. Introduction

Research and development of liquid oxygen (LOX)/methane rocket engines have been expanding, since there are many advantages of applying methane as rocket propellant compared to hydrogen. For examle, the boiling point of methane is higher than that of hydrogen, so that a methane tank needs less thermal insulators and becomes lighter than a hydrogen tank. In other point, the evaporation rate of methane is smaller than that of hydrogen, and a spacecraft of long term mission can use the propellant with smaller loss. Also, liquid methane is denser than liquid hydrogen (LH2) and can decrease a size of a propellant tank. These mean that the structural efficiency of the vehicle can be improved. Moreover, methane is inexpensive. Therefore, methane could be a dominant candidate for a next generation rocket engine propellant suitable for wide applications such as a reusable booster engine and a deep space transport. On the other hand, specific impulse (Isp) of LOX/methane engine is lower than that of the LOX/LH2 engine.

In Japan, research and development have been carried out on a regenerative cooling LOX/methane rocket engine to achieve higher performance than the past demonstration [1]. In 2016, based on a system study, many types of LOX/methane shear co-axial injectors for the main combustor were designed and then the firing tests of single injector element were performed under high pressure condition [2][3][4]. The test results showed that several promising candidates of injector element design have such high performance.

JAXA and IHI has carried out the research and development of the LOX/methane rocket engine and designed an engine for technical demonstration. [1]. The major components, electrically actuated valves, a single-shaft LOX/methane turbopump, a multi-element injector and a regeneratively cooled combustion chamber are manufactured in order to validate the performance of the conceptual engine. A series of test campaigns of the componets were carried out in IHI AIOI test facility. The turbopump test were carried out to demonstrate the operation of the turbopump applied with additive manufacturing to many prats, and to acquire the turbopump performance characteristics. The multi-element injector tests and regeneratively cooled combustion tests were carried out to acquire the performance characteristics of the combustion chamber [5]. The electrically actuated valves were used for engine flow control and were demonstrated in the turbopump tests, the multi-element injector tests and regeneratively cooled combustion tests [6]. This paper reports the result of the tests on LOX/methane turbopump in January and February 2019. In 2020, we plan to demonstrate the firing tests of the full expander cycle engine with combined components.

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2. Reference engine

A target value of Isp has been selected as 370s based on current LOX/methane engines among competitors, and a conceptual analysis on rocket engine system was conducted. As a result, a full expander cycle with a thrust target of 30kN is proposed. Table 1 and Figure 1 show the specifications and schematic of the technical demonstrator engine. The engine adopts as a full expander cycle, which is an engine cycle with high Isp, for improving the performance of the LOX / methane rocket engine.

Table 1: The specifications of the full expander cycle engine

Propellant	LOX/methane
Thrust(vacuum) [kN]	30
Isp(vacuum) [s]	370
Mixture ratio [-]	3.3
Combustion Pressure MPa(abs.)	4.7
Throttling	50 to 100 %

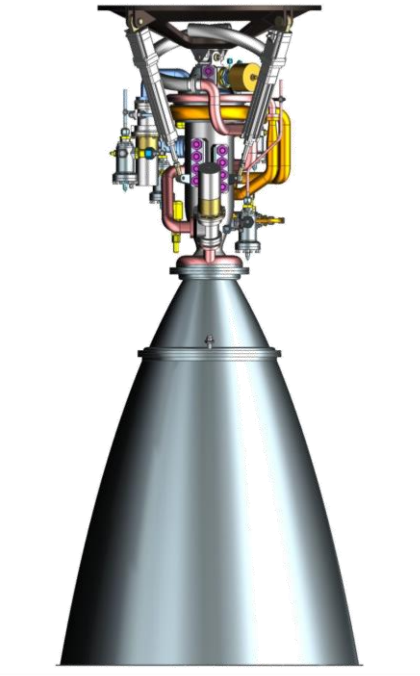

Figure 1: Schematic of full expander cycle engine

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3. Design of the turbopump

A turbopump was designed to realize the full expander cycle engine specifications shown in Table 1. Table 2 and Figure 2 show specifications and cross-sectional view of the turbopump designed for the full expander cycle engine. Functional features of the turbopump are as follows.

- Single-shaft turbopump: The LOX pump and the methane pump are driven by the one turbine through single-shaft.
- Balance piston mechanism: Balance piston is adopted for axial thrust adjustment.
- Labyrinth seal: the labylinth seals are used to reduce the shaft length and manufacturing cost.
- Throttling capability: Designed to meet the approximately 50% throttling requrement.
- Rigid rotor design: The turbopump aims a rated rotational speed of 65,000 rpm and also 42,000 rpm as a throttling operation whereas a primary critical speed of about 70,000 rpm.
- Small and lightweight: The small and lightweight turbopump with a mass of about 14.6 kg and a total length of about 300 mm. (Figure 3: Photgraph of the turbopump)

Table 2: The specifications of the turbopump for the full expander cycle engine

	Design point	50% throttling
Rotational speed [rpm]	65,000	41,550
LOX pump inlet pressure [MPa(abs.)]	0.40	0.40
LOX pump discharge pressure [MPa(abs.)]	6.17	3.04
LOX pump flow rate [kg/s]	6.47	3.30
methane pump inlet pressure [MPa(abs.)]	0.40	0.40
methane pump discharge pressure [MPa(abs.)]	11.64	5.41
methane pump flow rate [kg/s]	1.96	1.00
Turbine inlet pressure [MPa(abs.)]	10.74	4.40
Turbine outlet pressure [MPa(abs.)]	5.45	2.83
Turbine flow rate [kg/s]	1.93	0.77
Total mass [kg]	14.6	

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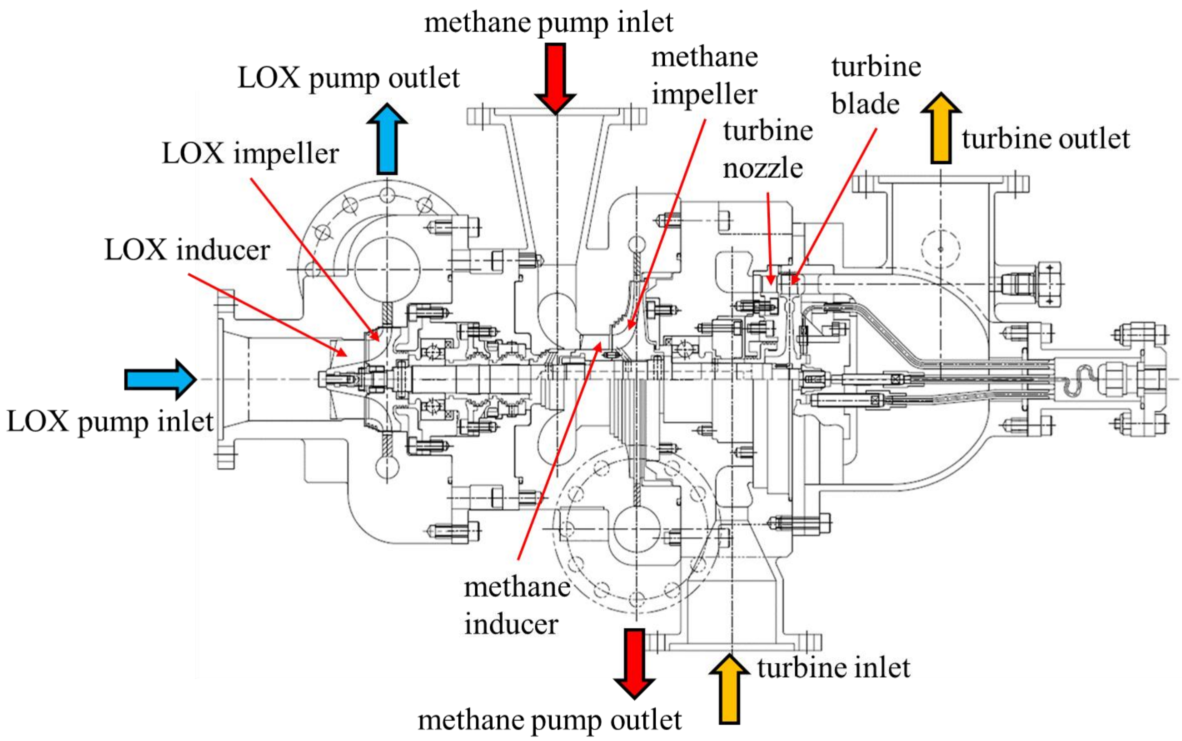

Figure 2: The half- sectional view of the turbopump

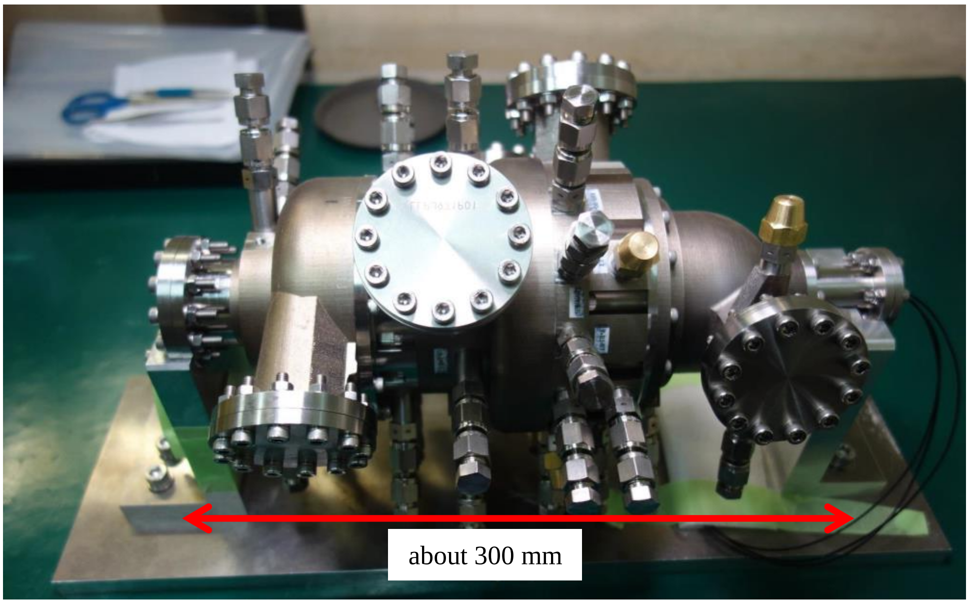

Figure 3: The photograph of the turbopump

4. Manufacturing of the turbopump

The turbopump was designed and manufactured not only to be used for the engine but to demonstrate the fast and low cost production technology. As shown in Figure 4, many parts of the turbopump were applied for additive manufacturing. The main features of the turbopump are as follows.

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・Low manufacturing cost: Manufacturing cost of the first prototype were reduced to about one third of the conventional one as shown in Figure 5.
・Reduction of the manufacturing period: Manufacturing period of the first prototype were reduced to about one third of the conventional one as shown in Figure 5.

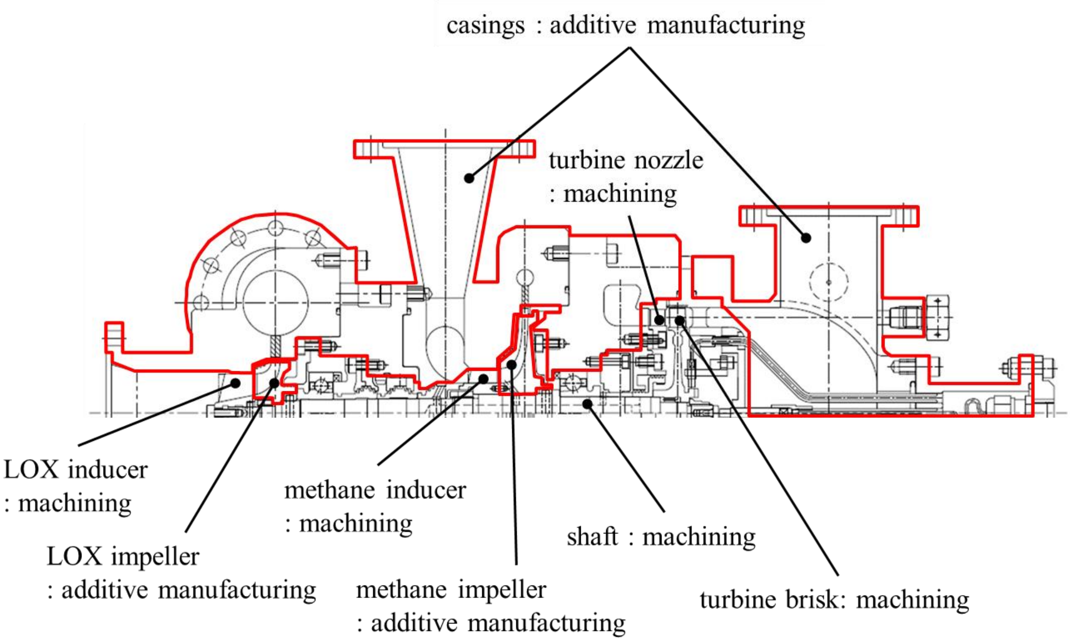

Figure 4: The manufacturing method of each part of the turbopump

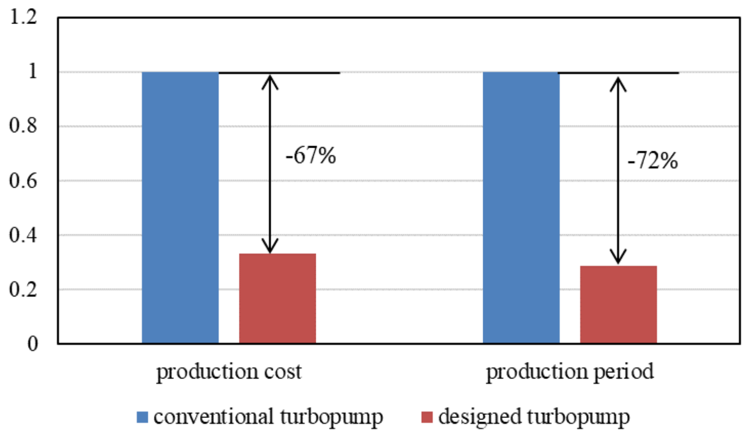

Figure 5: Comparison of production period and cost of the first prototype; the designed turbopump and the conventional turbopump

One of the major technical challenges of additive manufacturing is the reduction of the surface roughness. The surface roughness of the components affects the turbopump performance significantly. The effect of surface roughness of the designed turbopump is more significant than conventional turbopumps since the component sizes of the designed turbopump are rather small, and the effect of the surface roughness is relatively large.

For example, it was verified through a component test that a polished impeller with additive manufacturing has higher head coefficient than non-polished one. The results are shown in Figure 6. As shown in Figure 6, the head coefficient of the impeller by additively manufactured without polished is lower by about 15% at maximum compared to the impeller by additively manufactured with polished, and the influence of the surface roughness is large. For this reason,

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in the prototype turbo pump, the fluid passage of the parts by additively manufactured are specially polished to prevent the performance from decreasing.

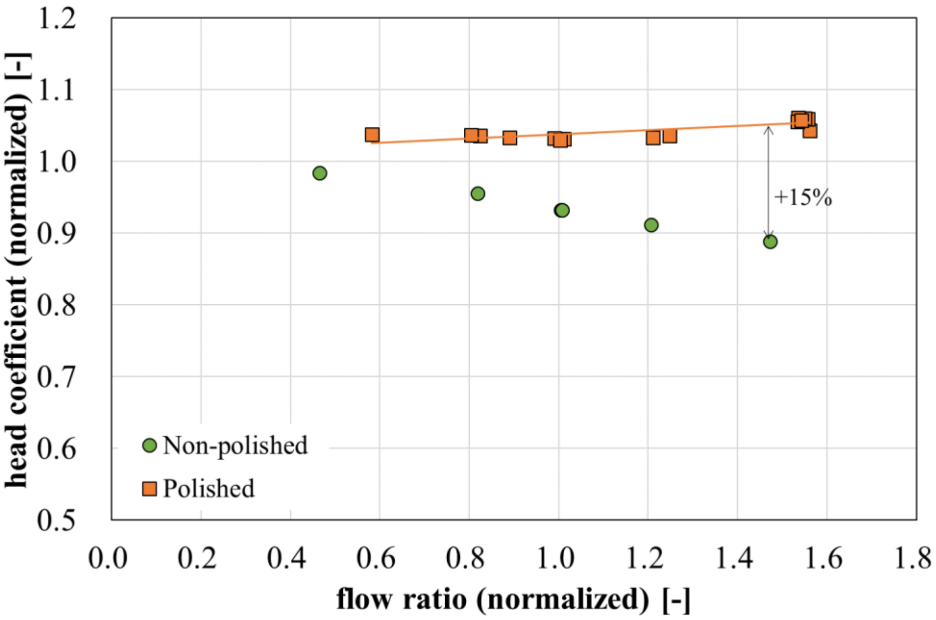

Figure 6: Comparison of head coefficient of impellers; additive manufacturing without polish and additive manufacturing with polish

5. Component test of the turbopump

5.1 Test configuration

A test campaign of the designed turbopump was conducted to acquire turbopump performance characteristics. The test was conducted on a test stand in IHI AIOI test facility. The specifications of the test stand are shown in Table 3, the turbopump test diagram is shown in Figure 7. LOX is fed from a 25 m^3 run tank through a flow meter to the turbopump, pressurized with the turbopump, decompressed with the orifices and discharged to a vent stack. Liquefied methane is also fed from a 25 m^3 run tank through a flow meter to the turbopump, pressurized with the turbopump, decompressed by the orifices and discharged to a vent stack. Gaseous methane for driving the turbine of the turbopump is fed from a 19.6 MPa pressure, 18.5 m^3 (11 m^3 + 7.5 m^3) storage tanks through a flow meter. The high-pressurised gaseous methane is fed through a flow control valve to the turbine of the turbopump, and after driving the turbine, the gas is depressurized by the orifice and released to the vent stack.

The turbopump test is a cold run using gaseous methane at ambient temperature as a turbine driving gas. In the full expander cycle engine configuration, high temperature methane heated in the regenerative cooling channel is used as a turbine driving gas. So, it was desirable to test with hot turbine driving gas according to the engine, but it was conducted by cold turbine driving gas (ambient temperature) due to the restriction of equipment. The test was conducted with a high pressure ratio to match the turbine power to the engine.

The turbopump performance characteristics were acquired under various test conditions. The pump head coefficients against various flow ratio are acquired by changing the pump flow rates and pump speed. The pump flow rates are controlled with the discharge orifices. To acquire the turbine efficiency against isentropic velocity ratio (U/C0), turbine pressure ratio is changed by using the exhaust pressure control orifice.

In the test operation, the LOX pump and the methane pump are precooled using the fluid in the tanks at the same time and after the pumps are sufficiently cooled, the turbine driving gas is fed to the turbine to rotate the turbopump. After acquisition the operating data, the rotation of the turbopump is safely stopped by shutting down the supply of the turbine driving gas. The operating duration in a test is limited about 70 seconds, mainly due to the lower limit of the turbine driven gas temperature. The temperature of the supplied gas inside the pressurized tanks becomes lower in a test due to its adiabatic expansion.

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Table 3: The specifications of the test stand in IHI AIOI test facility

LOX run tank volume [m^3]	25
LOX run tank regular pressure [MPa(abs.)]	1.0
Liquefied methane run tank volume [m^3]	25
Liquefied methane run tank regular pressure [MPa(abs.)]	1.0
Gaseous methane storage tank volume [m^3]	11 + 7.5
Gaseous methane storage tank pressure [MPa(abs.)]	19.7

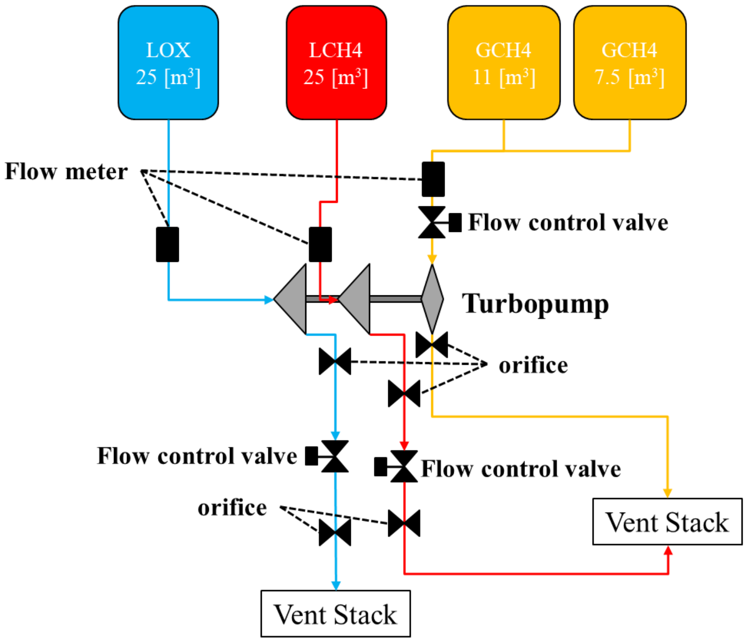

Figure 7: The turbopump test diagram

5.2 Test result

The performance data of the turbopump acquired through tests are shown in Figure 8 to Figure 12. In the figures, the design point is indicated by triangle plot (▲). The data acquired in the tests are normalized by the values at the design point on both the vertical and horizontal axes, and are indicated by square plots(■).

The design point and test results for the head coefficient of the LOX pump are shown in Figure 8. The horizontal axis in Figure 8 represents the flow ratio of the LOX pump, and the vertical axis represents the head coefficient of the LOX pump. The design point of the LOX pump head coefficient roughly matches the curve connecting the test results. The head coefficient at the design flow ratio calculated from the curve is about 4% higher than the design point.

The design point and test results for the efficiency of the LOX pump are shown in Figure 9. The horizontal axis in Figure 9 represents the flow ratio of the LOX pump, and the vertical axis represents the efficiency of the LOX pump. The curve connecting test results is higher than the design point. The efficiency at the design flow ratio calculated from the curve is about 7% higher than the design point.

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The dimensionless flow ratio range of the LOX pump operated by the engine is shown in Figure 8 and Figure 9. Tests were conducted covering the operating range of the LOX pump. There was no trend of performance degradation in the operating range, and it was confirmed that the LOX pump had the performance as designed.

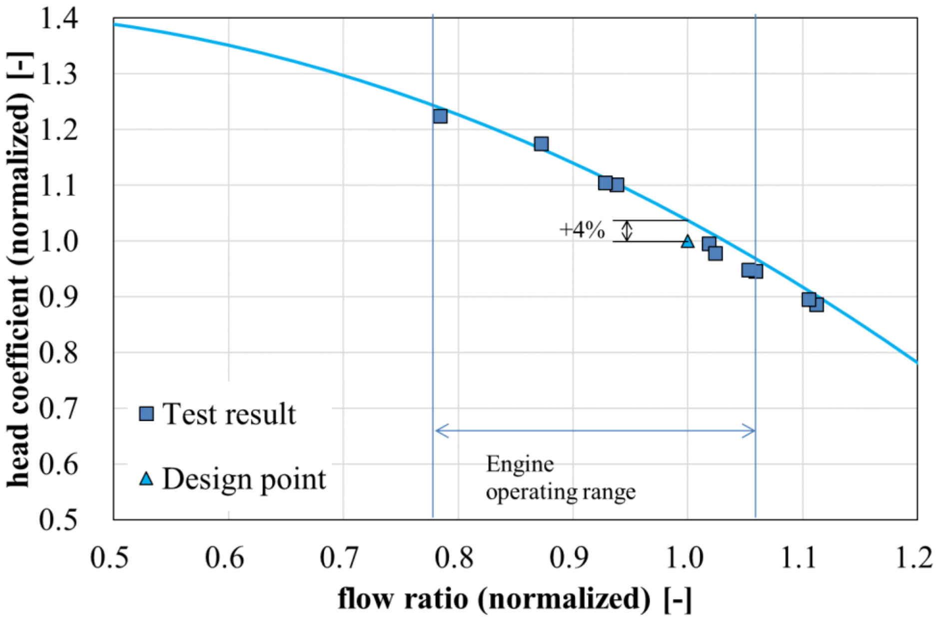

Figure 8: Head coefficient of the LOX pump (Vertical and horizontal axes normalized by design point)

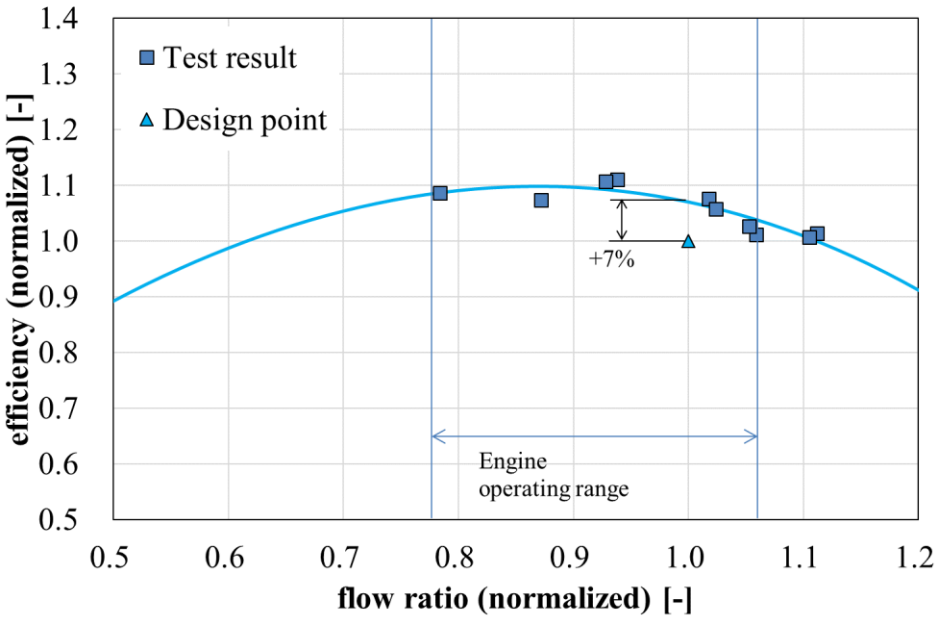

Figure 9: Efficiency of the LOX pump (Vertical and horizontal axes normalized by design point)

The design point and test results for the head coefficient of the methane pump are shown in Figure 10. The horizontal axis in Figure 10 represents the flow ratio of the methane pump, and the vertical axis represents the head coefficient of the methane pump. The design point of the methane pump head coefficient roughly matches the curve connecting the test results. The head coefficient at the design flow ratio calculated from the curve is about 3% higher than the design point.

The design point and test results for the methane pump efficiency are shown in Figure 11. The horizontal axis in Figure 11 represents the flow ratio of the methane pump, and the vertical axis represents the methane pump efficiency.

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The curve connecting test results is lower than the design point. The efficiency at the design flow ratio calculated from the curve is about 13% lower than the design point. The methane pump internal flow rate at the test flowed 15% more than that flow rate at the design in order to adjust axial thrust for the balance piston contact avoidance and to conduct the test safely. This corresponds to a 15% decrease in the efficiency of the methane pump. It is considered that the methane pump had efficiency as designed when the designed internal flow rate of the turbo pump flows.

The dimensionless flow ratio range of the methane pump operated by the engine is shown in Figure 10 and Figure 11. The tests were conducted covering the operating range of the methane pump. There was no tendency of the performance degradation in the operating range considering the internal flow of efficiency, and it was confirmed that the methane pump had the performance as designed.

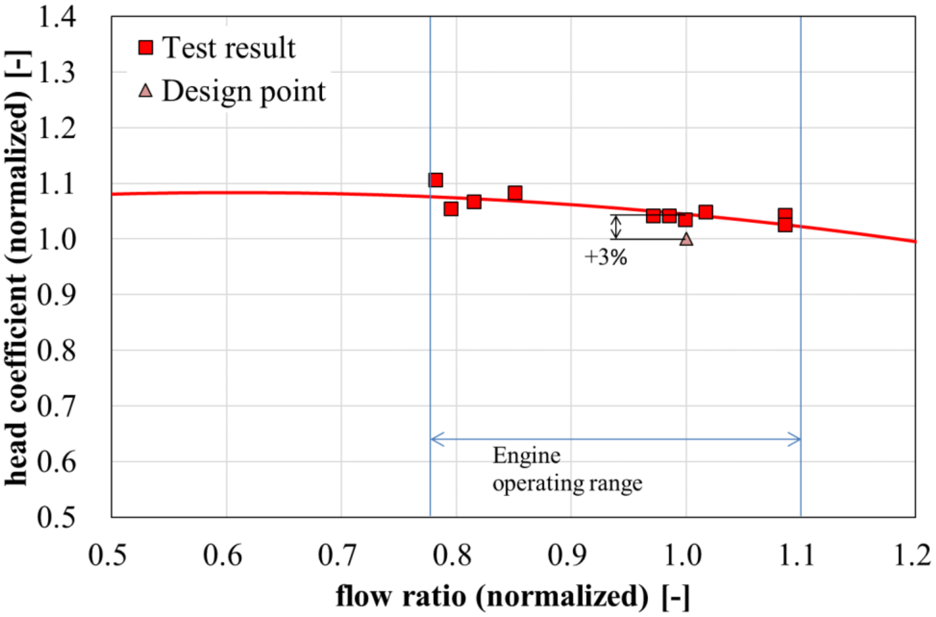

Figure 10: Head coefficient of the methane pump (Vertical and horizontal axes normalized by design point)

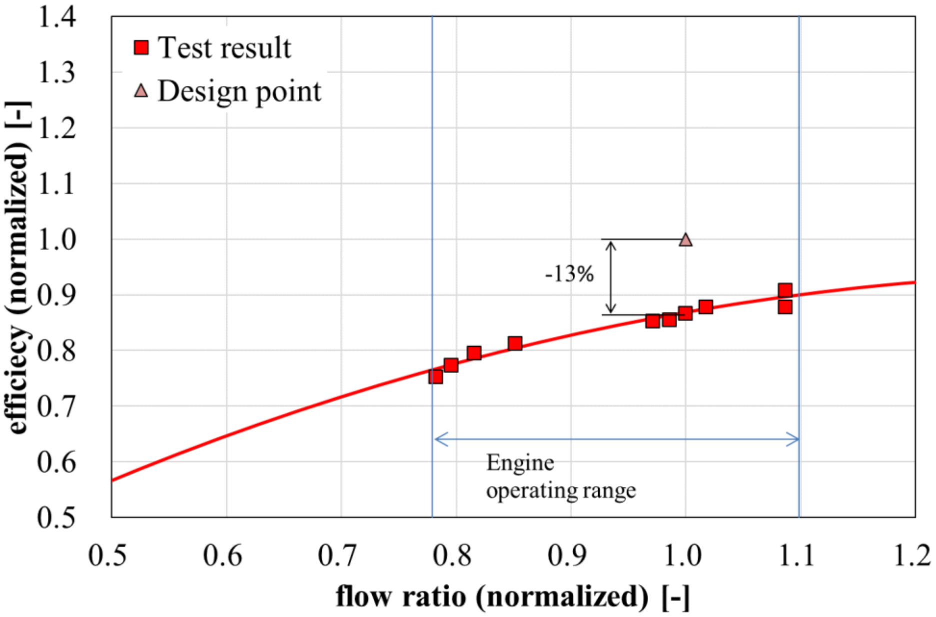

Figure 11: Efficiency of the methane pump (Vertical and horizontal axes normalized by design point)

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The design point and test results for the efficiency of the turbine are shown in Figure 12. The horizontal axis in Figure 12 represents U/C0, and the vertical axis represents the turbine efficiency. The dimensionless U/C0 range of the turbine operated by the engine is shown in Figure 12. Tests were conducted covering the operating range of the turbine. The design point is almost on the line of the curve connecting the test results, which means that the turbine performed as designed.

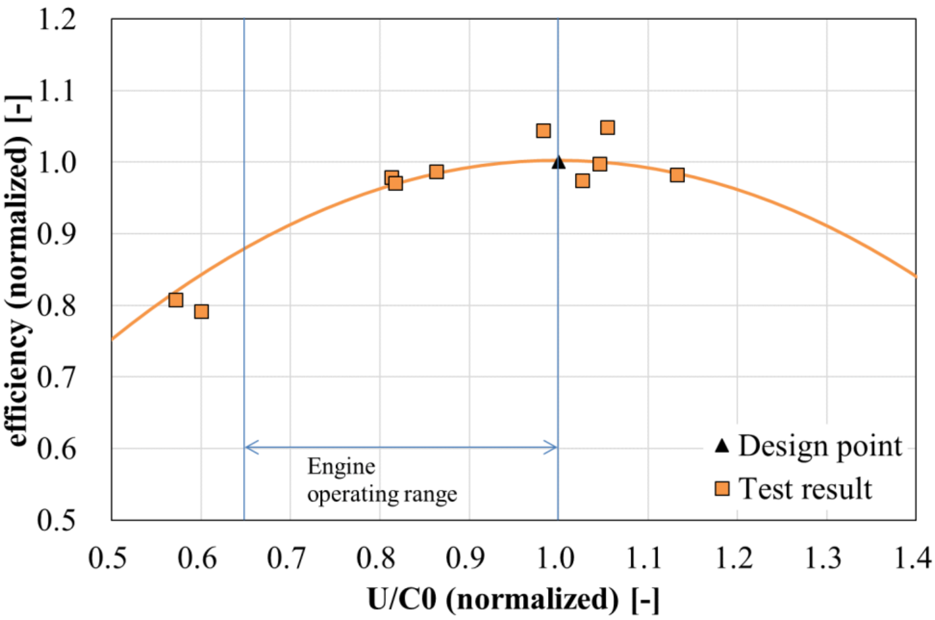

Figure 12: Efficiency of the turbine (Vertical and horizontal axes normalized by design point)

The turbopump worked well in the total six runs and 315 sec of the operating time. In the turbopump tests, the operating point was changed to cover the operating area as shown in Figure 8 to Figure 12 and it was validated that the turbopump has the designed performance in the wide range. After the turbopump tests, the turbopump was used as a workforce for the combustion tests and worked well in the total 9 runs of 192 sec.

6. Conclusion

Research on a methane engine has been carried out in Japan for increasing the specific impulse and a small full expander cycle engine was selected to demonstrate the research activity. The turbopump, one of the main components of the engine was manufactured and tested.
As a result, we demonstrated the following.

- The single-shaft turbopump worked well in the wide range through the tests and it performed as designed.
- Additively manufacturing almost all parts of the turbopump, the cost and period of the production were reduced to about one third of the conventional one.
- Special polish on the flow passage was effective to avoid the performance loss caused with the surface roughness of the additively manufacturing.

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