Development of Turbopump for LE-X Engine

MIZUNO Tsutomu : P. E. Jp, Manager, Space Technology Group, Research & Engineering Division, Aero-Engine & Space Operations
KOBAYASHI Satoshi : P. E. Jp, General Manager, Space Technology Group, Research & Engineering Division, Aero-Engine & Space Operations
OGUCHI Hideo : General Manager, Space Development Department, Aero-Engine & Space Operations

The LE-X is a new cryogenic booster engine with high performance, high reliability, and low cost, which is designed for the next generation Japanese launch vehicle. It will be the first booster engine in the world with an expander cycle. In the designing process, the characteristics of a turbopump and other components can simultaneously be evaluated in engine system calculation with response surface models that have the characteristics of information of turbopump of various shapes. This paper reports the characteristics of LE-X engine, and baseline specifications of turbopump.

1. Introduction

The second stage of an H-I launch vehicle that was launched in August 1986 was equipped with Japan's first liquid oxygen and liquid hydrogen engine, the LE-5. The turbopumps adopted for this engine were made by IHI. The subsequent 24 years saw the H-I launch vehicle replaced with the H-II, the H-IIA, and then the H-IIB, and the engine replaced with the LE-5A, the LE-5B, the LE-7, and then the LE-7A. IHI has been engaged in the design and manufacture of all turbopumps under a contract with the Japan Aerospace Exploration Agency (JAXA).

JAXA and manufacturers are now engaged in joint research into the development of the LE-X engine[1] based on a recognition of the need to develop booster engines that offer functions and performance that can be extended to reusable and manned launch vehicles in the future, as well as to provide a higher degree of reliability to ensure international competitiveness. **Figure 1** shows an illustration of the exterior of the LE-X engine. Using liquid oxygen and liquid hydrogen as propellants, the LE-X engine significantly increases the impulse provided by a simple, robust engine cycle called an expander bleed cycle.[2] **Figure 2** illustrates the LE-X engine cycle. As combustion gas is not used to drive the engine's turbines in the expander bleed cycle, the engine output changes only gradually, which means that there is an extremely low chance of a catastrophe occurring. Given this, the expander bleed cycle is considered to be inherently suitable for use in future manned transportation systems.

This paper describes the basic specifications for the LE-X engine and the technical features of turbopumps designed by IHI.

Fig. 1 Illustration of LE-X engine exterior

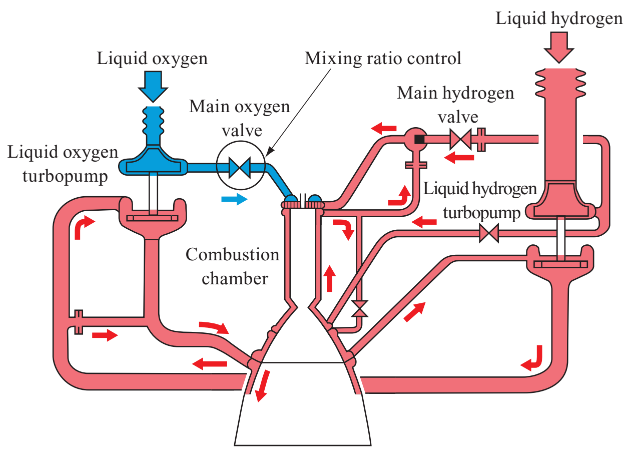

Fig. 2 LE-X engine cycle

2. Outline of research and development into the LE-X engine

2.1 Concept behind the engine

One of the principal concepts behind the development of the LE-X engine is improved reliability. The LE-X employs a simplified, more reliable engine system that operates using the expander bleed cycle, eliminating the need for the auxiliary combustor that would be required for a gas generator cycle or 2-stage combustion cycle.

The expander bleed cycle does not preheat the turbine drive gas, so high turbine efficiency is required to provide the required output. Another way of generating a high output is to increase the flow rate of the turbine drive gas, but this reduces the engine's specific impulse. For this reason, expander bleed cycles were considered inappropriate for high-impulse engines. To overcome this problem, the authors are conducting research to achieve high turbopump efficiency and a high specific impulse for the LE-X engine by taking a design approach that adopts quality engineering techniques and selecting an optimum solution that meets multiple objectives from all of the various possible solutions available.

To achieve this optimum engine solution, the authors constructed an innovative interface model between the engine system and turbopumps.[3] This allowed them to achieve the optimum solution for the whole engine system, including the turbopumps, by eliminating a lot of the labor involved in making the temporal specifications for the interface between the engine and the turbopumps and repeatedly calculating the local optimum solution for the turbopumps.

2.2 Characteristics and specifications of the engine

Table 1 shows the (provisional) main characteristics of the LE-X engine.

The LE-X engine has been technically proven to have an impulse of 1 448 kN and a combustion chamber pressure of 12.5 MPa.

Table 2 shows the specifications of the turbopumps.

The liquid hydrogen turbopump (hereinafter called FTP) has a nominal rotational frequency of 40 144 rpm, which is at the same level as that of the LE-7A engine (hereinafter called LE-7A), but has a high turbine expansion ratio of 9.3. The pump does not require high pressure for an auxiliary combustor, and the turbopump has a discharge pressure of 18.3 MPa, which is about 60% lower than that of the LE-7A.

The liquid oxygen turbopump (hereinafter called OTP) has a nominal rotational frequency of 16 573 rpm, which is also at the same level as that of the LE-7A, but has a very low turbine inlet pressure of 1.22 MPa.

The OTP has a turbine expansion ratio of 2.35, which is relatively higher than that of the LE-7A, but its nominal turbine outlet temperature is as low as 359 K. These are the characteristics of the LE-X engine and its turbopumps.

The authors plan to conduct preliminary tests at the component level to demonstrate items that are extremely important in terms of the reliability of the LE-X engine and some new technologies. After this, they plan to perform pump rig tests and turbine rig tests for the turbopumps, and then unit tests for the turbopumps and the combustors. Finally, the authors will conduct technical demonstration tests for a prototype engine to ascertain the technical feasibility of the LE-X engine system.

Table 1 LE-X engine characteristics

Item	Unit	LE-X
Impulse (in vacuum)	kN	1 448
Combustion pressure	MPa	12.5
Mixing ratio	—	2.9
Expansion ratio	—	37

Table 2 LE-X turbopump specifications

Item	Unit	FTP	OTP
Rotational frequency	rpm	40 144	16 573
Pump flow rate	kg/s	49.7	293.3
Turbine flow rate	kg/s	7.9	6.8
Pump discharge pressure	MPa	17.6	19.2
Turbine expansion ratio	—	9.3	2.4
Pump efficiency	—	0.75	0.75
Turbine efficiency	—	0.50	0.70
Power	kW	16 148	6 277

3. Characteristics of the LE-X engine

3.1 Selecting the engine working points

Engine system working points were conventionally selected by conducting comparative studies of limited items and determining the working points that meet several limiting conditions for an engine system. In recent years, there have been calls for more optimum solutions that meet multiple objectives in order to improve quality, cost, and delivery (QCD) in design and development.

In this study, the authors constructed and tested the innovative interface model they constructed between the engine system and the turbopumps with a view to eliminating the need for conventional interface specification settings and repeated turbopump designing and smoothly identifying an optimum solution for the whole engine system.[3]

In concrete terms, the authors constructed a turbopump interface model (a response surface model with design parameters shared by the engine system as arguments) that comprehensively represented the turbopump characteristics in all of the following.

- Design charts for turbopump characteristics
- Performance curves for turbopump characteristics
- Performance indexes for the feasibility of turbopumps

Integrated with the engine system, this interface model eliminated the need for a frequent exchange of information on interface adjustment. The optimum solution for the whole engine system was smoothly developed by horizontally allocating design margins for the engine and turbopumps, for each of which a local optimum solution had been individually developed. **Figure 3** shows a conceptual diagram of the interface model.

3.2 Liquid hydrogen turbopump

Figure 4 shows a cross-section of the FTP. The adoption of the expander bleed cycle reduces the required discharge pressure, and the pump head is secured in place by a 2-stage inducer and a single-stage high-head impeller. At the same time, the shaft length was reduced by adopting a single-stage impeller to enable operations at a rotational frequency of 40 000 rpm, which is high but does not exceed the second critical speed. The authors adopted an open-shroud impeller in order to reduce the cost, ease manufacturing restrictions, and secure margins of structural strength.

Figure 5 shows a 2-stage inducer undergoing a test.

The results of a test conducted in March 2009 revealed that the inducer satisfied the functions and performance level required for LE-X engines. **Figure 6** shows an impeller during a running water test conducted in February 2009. The impeller was also found to satisfy the functions and performance level required for LE-X engines.

The authors selected hybrid ceramic bearings to reduce the bearing cooling water flow rate, and thereby improve the pump efficiency. The authors adopted an ultrasonic turbine designed to have a high turbine expansion ratio in order to provide high output from low-enthalpy turbine drive gas.

The authors applied a high-quality engineering design approach to the design of all devices and the turbopump system.[4]

3.3 Liquid oxygen turbopump

Figure 7 shows a cross-section of an OTP. The adoption of the expander bleed cycle resulted in a reduction in inlet pressure for the OTP turbine. To enable it to generate a high output, the turbopump needs to be designed to have a high speed ratio and a large nozzle area. This results in the turbine disc having an extremely long diameter. When the OPT is operating at the first critical speed, vibration is maximized at the edges of the turbine. There is a concern, however, that if the OPT is operating steadily at a speed in

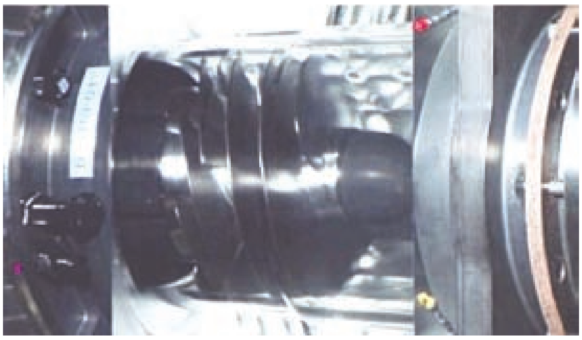

Fig. 5 FTP 2 stage inducer

Fig. 6 FTP open impeller

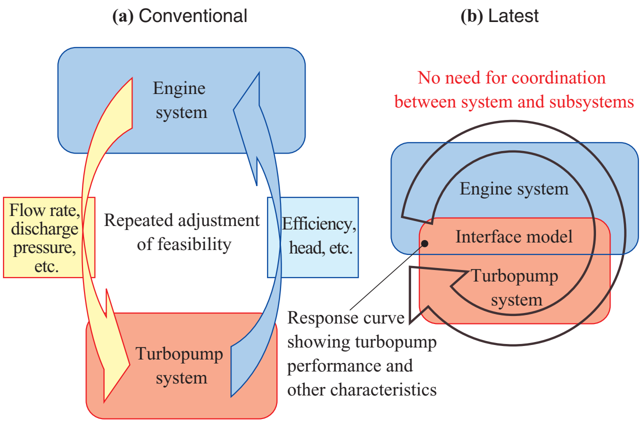

Fig. 3 Interface model

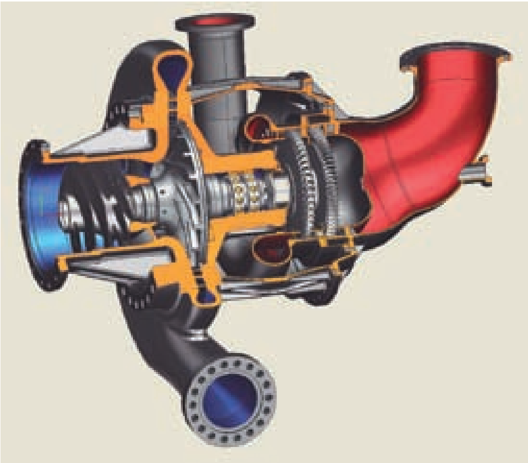

Fig. 4 Illustration of FTP

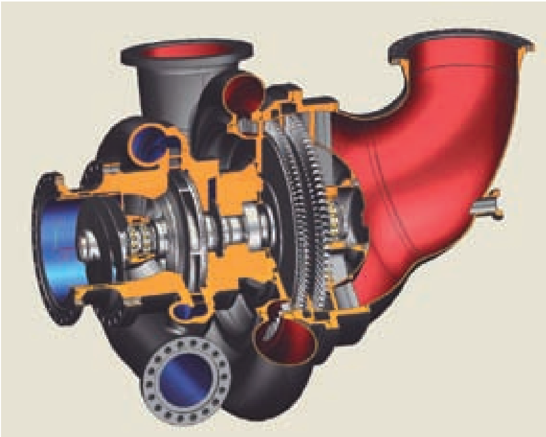

Fig. 7 Illustration of OTP

excess of the first critical speed, unstable vibration may be generated due to insufficient damping caused by internal damping. For this reason, the authors adopted a rigid rotor operating at a speed that did not exceed the first critical speed for the OTP.

Specifically, the authors positioned bearings at the rear of the turbine, and positioned the inducer, the impeller, the seal, the turbine, and other major components between these two bearings. The authors plan to adopt a lubricating system with impregnated volatile oil for bearings, instead of the conventional self-lubricating system. Doing so will exploit the fact that adopting the expander bleed cycle results in a reduction in the turbine outlet temperature to about 360 K. For the inducer and the impeller, the authors applied a design for high-suction specific speed that had been successfully developed for the LE-7A. For the shaft seals and pump bearings, the authors made full use of devices that had already been successfully applied to the LE-7A.

The authors applied a high-quality engineering design approach to the design of all devices and the turbopump system, just as they had for the FTP.

4. Conclusion

This paper provides an overview of the research conducted by the authors into the development of the LE-X engine, the basic specifications for the engine, and the technical characteristics of the turbopumps.

The LE-X engine is the world's first high-impulse engine to use the expander bleed cycle. The authors adopted high-quality engineering design techniques and advanced analysis techniques as their design approach, as well as a comprehensive design based on their innovative interface model, which is located between the engine and the turbopumps.

The authors plan to test various types of elements, conduct unit tests for the turbopumps to confirm that they offer the required functions and performance level, and conduct technical demonstration tests for a prototype engine to ascertain the technical feasibility of the LE-X engine system.

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