

# Development of Turbopump for LE-9 Engine

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LE-9 is a new cryogenic booster engine with high performance, high reliability, and low cost, which is designed for H3 Rocket. It will be the first booster engine in the world with an expander bleed cycle. In the designing process, the performance requirements of the turbopump and other components can be concurrently evaluated by the mathematical model of the total engine system including evaluation with the simulated performance characteristic model of turbopump. This paper reports the design requirements of the LE-9 turbopump and their latest development status.

## 1. Introduction

The H3 rocket, intended to reduce cost and improve reliability with respect to the H-II A/B rockets currently in operation, is under development toward the launch of the first H3 test rocket in FY 2020.

In rocket development, engine is an important factor determining reliability, cost, and performance, and as a new engine for the H3 rocket first stage, an LE-9 engine<sup>(1)</sup> is under development.

A rocket engine uses a turbopump to raise the pressure of low-pressure propellant supplied from a tank, injects the pressurized propellant through an injector into a combustion chamber to combust it under high-temperature and high-pressure conditions. The turbopump accelerates the combustion gas flow to supersonic velocity through a nozzle to thereby generate thrust.

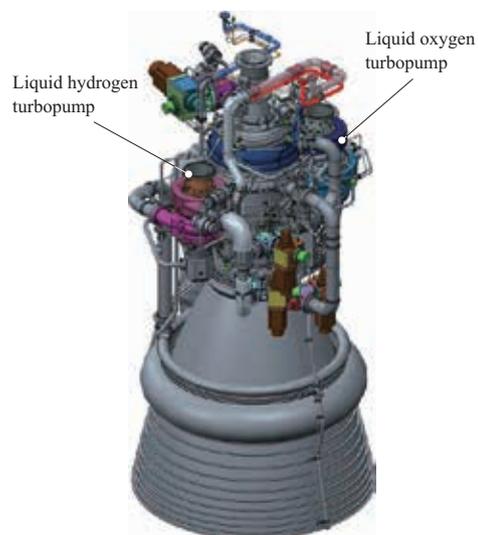
**Figure 1** illustrates an image of the LE-9 engine<sup>(1)</sup>, and **Fig. 2** illustrates an LE-9 engine cycle<sup>(2)</sup>. The LE-9 engine is the world's first high thrust engine using liquid oxygen and liquid hydrogen as propellant and employing an expander bleed cycle that is a simple and robust engine cycle.

This paper describes the required specifications of the LE-9 engine and the technical features of turbopumps under development by us, as well as describes the progress of the development.

## 2. Outline of LE-9 engine

### 2.1 Engine concept

The concept of the LE-9 engine is to reduce cost and improve reliability<sup>(2)</sup>. Accordingly, the LE-9 engine was configured as an engine such that as described above, by employing the expander bleed cycle, the need for a combustor for driving a turbine needed by a gas generator cycle or a two-stage combustion cycle was eliminated to



**Fig. 1** Image of LE-9 engine<sup>(1)</sup>

simplify an engine system, and by reducing the temperature of a turbine portion including an exhaust gas duct, both high reliability and low cost were achieved.

On the other hand, in order to obtain predetermined output, the expander bleed cycle requires high turbine efficiency because turbine driving gas is low in temperature as compared with combustion gas. Note that as another method for ensuring turbine output, the flow rate of the turbine driving gas may be increased; however, in the case of the expander bleed cycle, the increase in the flow rate causes a reduction in engine specific impulse, and therefore performance requirements are not easily satisfied.

In order to solve such a problem, the specifications of the LE-9 engine were set in accordance with a design approach<sup>(3), (4)</sup> that comprehensively selects an optimal design point from a number of component design parameter groups,

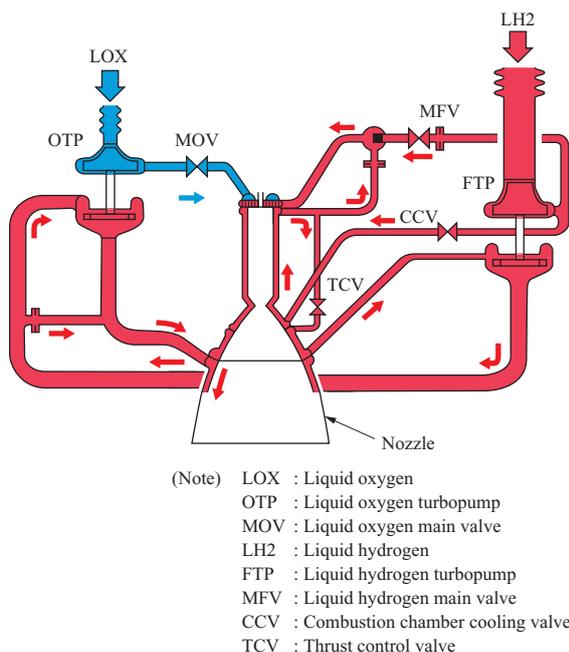


Fig. 2 LE-9 engine cycle<sup>(2)</sup>

and thereby turbopump design specifications, such as turbine efficiency, for enabling the achievement of high engine specific impulse were obtained.

To optimally design the engine, by constructing an interface model necessary for comprehensive analysis between a combustion system and a supply system (turbopumps), the problem of interface adjustment, which had required great effort in the past, and the problem of local optimal due to ensuring mutual margins were eliminated, thus making it possible to optimally design the entire engine system in a short time<sup>(4)</sup>.

On the other hand, cost reduction was also facilitated from the conceptual design stage by taking account of a plan to reduce the number of parts/components and a plan to reduce the number of special processes, and in terms of manufacturing, by applying innovative technologies such as those on HIP (Hot Isostatic Pressing) sintered material and AM (Additive Manufacturing) material.

## 2.2 Interface model

As described above, to examine the specifications of the LE-9 engine system, the interface model between the combustion system and the supply system was constructed to allow the entire engine to be optimally examined. **Figure 3** illustrates an image of the interface model<sup>(4)</sup>. Specifically, a turbopump interface model (a response surface with design parameters common to the engine system as arguments) capable of collectively representing the characteristics of the supply system described below was constructed.

### (1) Design diagram

A diagram representing the characteristics of the turbopumps with the design parameters as arguments

### (2) Evaluation indices

Constraint conditions representing the feasibility of the turbopumps

### (3) Performance curves

Functions representing the characteristics of the turbopumps at a selected design point and at an off-nominal point (at a value outside design reference value)

## 2.3 Engine characteristics

The main characteristics of the LE-9 engine are listed in **Table 1**<sup>(2)</sup>. Engine thrust is 1 471 kN and specific impulse is 425 s.

The engine is characterized by high thrust as described

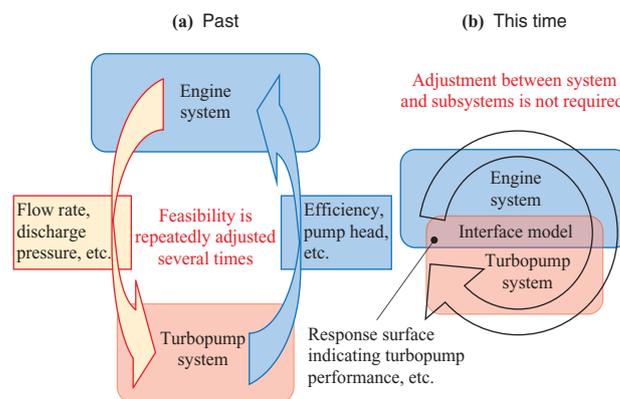


Fig. 3 Interface model<sup>(4)</sup>

Table 1 LE-9 engine characteristics<sup>(2)</sup>

Item	Unit	LE-9 engine	LE-7A engine
Engine cycle	—	Expander bleed cycle	Two-stage combustion cycle
Thrust (in vacuum)	kN	1 471 (63%-throttling enabled)	1 100
Specific impulse ( $I_{sp}$ ) <sup>*1</sup>	s	425	440
Mass	t	2.4	1.8
Total length	m	3.75	3.70
Mixture ratio	—	5.9	5.9
Combustion pressure	MPa	10.0	12.3
FTP discharge pressure	MPa	19.1	28.1
OTP discharge pressure	MPa	17.9	17.8 (Main) 26.6 (Split)
Valve drive system	—	Electric valve	Pneumatic valve

(Note) \*1: Magnitude of thrust with respect to propellant mass flow rate

above on one hand, and on the other hand, by employing the expander bleed cycle as an engine cycle. In addition, employing electric valves in a valve drive system enables engine thrust throttling.

LE-9 engine FTP characteristics are listed in **Table 2**<sup>(2)</sup>. The liquid hydrogen turbopump (Fuel TurboPump: hereinafter referred to as FTP) is such that although the nominal rotation speed is 41 600 rpm, which is comparable to that of the LE-7A engine (hereinafter referred to as LE-7A), the turbine expansion ratio is as very high as 8.5, and the turbine efficiency also has a high value of 0.65. On the other hand, the pump discharge pressure is 19.1 MPa, which is a value slightly less than approximately 70% of that of the LE-7A.

LE-9 engine OTP characteristics are listed in **Table 3**<sup>(2)</sup>. The liquid oxygen turbopump (Oxidizer TurboPump: hereinafter referred to as OTP) for the LE-9 engine is characterized in that the nominal rotation speed is 17 000 rpm, which is lower than that for LE-7A, and the turbine inlet pressure is as extremely low as 0.94 MPa, whereas the turbine efficiency exhibits a high value of 0.71.

### 3. Features of LE-9 engine turbopumps

#### 3.1 Liquid hydrogen turbopump

**Figure 4** illustrates an LE-9 engine FTP rotor assembly. In the case of LE-7A, FTP required a configuration including a single stage inducer and a two-stage impeller, whereas in the case of the LE-9 engine, since the discharge pressure requirement was relaxed, FTP was configured to include a two-stage inducer and a single-stage impeller. Along with a reduction in shaft length due to the impeller change from the two-stage to the single-stage, despite of a high rotation speed of 40 000 rpm or more, rated operation at secondary critical speed or less was allowed to thereby improve vibration



**Fig. 4** LE-9 engine fuel turbopump rotor assembly

stability, as well as to eliminate a damper mechanism needed for LE-7A.

In addition, pressure distribution was controlled by employing a swirl breaker mechanism for the back surface of the impeller, and also self-excited vibration was suppressed by ensuring a rotor system damping ratio. Further, in order to reduce cost, relax the manufacturing constraint conditions, and ensure a structural strength margin, the impeller was configured as an open shroud impeller with no shroud. Still further, in order to improve pump efficiency by reducing a bearing cooling flow rate, a hybrid ceramic bearing was employed as a bearing, and also in order to obtain high output from the turbine driving gas with low enthalpy, a two-stage supersonic impulse turbine having an increased turbine expansion ratio was employed as a turbine.

**Table 2** LE-9 engine fuel turbopump characteristics<sup>(2)</sup>

Item	Unit	LE-9 engine		LE-7A engine
			63 (Throttling)	
Engine thrust level	%	100	63 (Throttling)	—
Rotation speed	rpm	41 600	34 800	42 300
Pump discharge pressure	MPa	19.1	13.8	28.1
Pump mass flow rate	kg/s	51.6	32.4	37.2
Turbine inlet pressure	MPa	8.3	4.5	20.9
Turbine expansion ratio	—	8.5	8.3	1.6
Turbine inlet temperature	K	443	443	701
Turbine mass flow rate	kg/s	9.1	4.9	35.4

**Table 3** LE-9 engine oxidizer turbopump characteristics<sup>(2)</sup>

Item	Unit	LE-9 engine		LE-7A engine
			63 (Throttling)	
Engine thrust level	%	100	63 (Throttling)	—
Rotation speed	rpm	17 000	13 300	18 300
Pump discharge pressure	MPa	17.9	13.1	17.8 (Main) 26.6 (Split)
Pump mass flow rate	kg/s	303	190	219
Turbine inlet pressure	MPa	0.94	0.51	19.6
Turbine expansion ratio	—	2.5	2.4	1.4
Turbine inlet temperature	K	318	330	707
Turbine mass flow rate	kg/s	8.3	4.5	16.4

### 3.2 Liquid oxygen turbopump

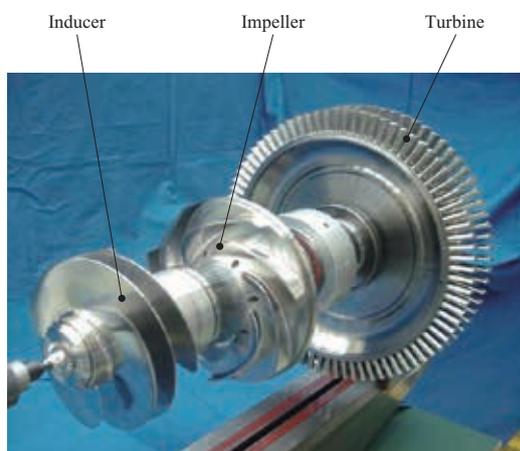
**Figure 5** illustrates an LE-9 engine OTP rotor assembly. In order for the OTP turbine with low inlet pressure to generate high output, the speed ratio and nozzle area must be designed large, so the diameter of the turbine disk was designed very large. In addition, a second-stage transonic reaction turbine was employed as a turbine.

A vibration mode at the primary critical speed of OTP has a mode shape characterized by a turbine whirl, so a rigid rotor configuration having an increased shaft diameter and allowing steady operation at the primary critical speed or less was employed for OTP. However, along with the increase in shaft diameter, increases in bearing diameter and shaft seal diameter were required, and some technical problems associated with the increases occurred in glass woven fabric used for a bearing cage, but the problems were overcome through a predetermined element test and other such tests to find a prospect for the increases. In addition, as with FTP, the swirl breaker mechanism was employed for the back surface of the impeller, and by controlling pressure distribution, a margin was ensured for the allowance for rotor position adjustment.

### 3.3 Cost reduction

From the conceptual design stage, cost reduction ideas in all fields, such as ① a reduction in the number of parts/components, ② changes in processing methods, ③ changes and eliminations of special processes, ④ changes in materials, and ⑤ changes and eliminations of assembly steps were extracted, and for each of them, feasibility was pursued.

As a result of eliminating a sub-combustor required for a conventional engine, the discharge pressures of the turbopumps could be suppressed low, and the impeller change from the two-stage to the single-stage allowed the number of parts/components to be reduced. In addition, the high temperature of the turbine gas was lowered, and thereby cost could be reduced by switching to a new turbine material, which had not been employed because of the high temperature, blisk formation, elimination of gold plating, and so on. As an impeller, the open impeller with no shroud was employed for each of FTP and OTP to reduce the number of



**Fig. 5** LE-9 engine oxidiser turbopump rotor assembly

processing steps, thus achieving cost reduction. As the material of the turbine nozzle, a net shape material was employed to reduce processing man-hour for airfoil formation, thus succeeding in significant cost reduction. **Figure 6** illustrates the second nozzle using the HIP sintered material.

Also, the annual production of the H3 rockets is planned to be increased in number as compared with the H-II A/B rockets. Accordingly, by making some facilities dedicated to a machining process, production efficiency is improved to achieve cost reduction as well as schedule shortening.

## 4. Unit tests of LE-9 engine turbopumps

### 4.1 Test objectives

**Figure 7** illustrates the development schedule of the LE-9 engine. Since 2014, element level tests had been performed, and after confirmation of device functions and performance, the engineering models of the turbopumps had been manufactured since FY 2016. At the end of FY 2016, the unit tests of the first turbopumps were performed.

The purpose of the turbopump unit tests is to acquire turbopump unit characteristics described below to reduce risk prior to an engine hot firing test, as well as to confirm that required engine performance is satisfied.

- (1) Turbopump performance characteristics (Pump, Turbine)
- (2) Shaft vibration characteristics (Axial, Radial)
- (3) Mechanical system characteristics (Bearing, Bearing seal)
- (4) Internal circulation characteristics

In addition, the tests were performed at the Kakuda Space Center (Miyagi Pref.) of the National Research and Development Agency, Japan Aerospace Exploration Agency (JAXA).

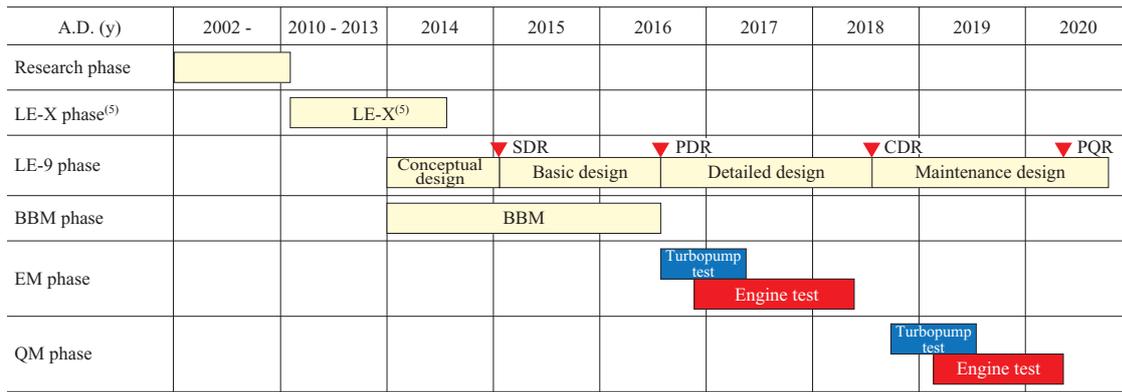
**Figures 8** and **9** illustrate the LE-9 engine FTP unit test and the LE-9 engine OTP unit test, respectively.

### 4.2 Test results

The results of the LE-9 engine turbopump unit tests are listed in **Table 4**.



**Fig. 6** Material of hot isostatic pressing (Second Nozzle)



(Note) LE-X : Prototype  
 BBM : Bread board model  
 EM : Engineering model  
 QM : Qualification model  
 SDR : System design review  
 PDR : Basic design review  
 CDR : Detailed design review  
 PQR : Post-qualification test review

Fig. 7 Development schedule of LE-9 engine<sup>(2)</sup>

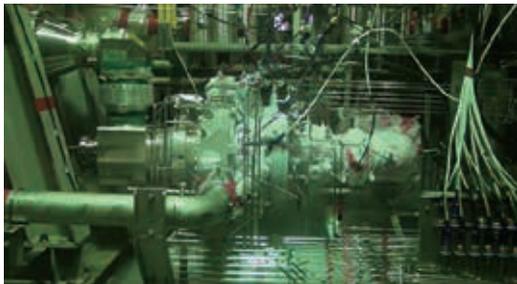


Fig. 8 LE-9 engine fuel turbopump cold flow test at JAXA

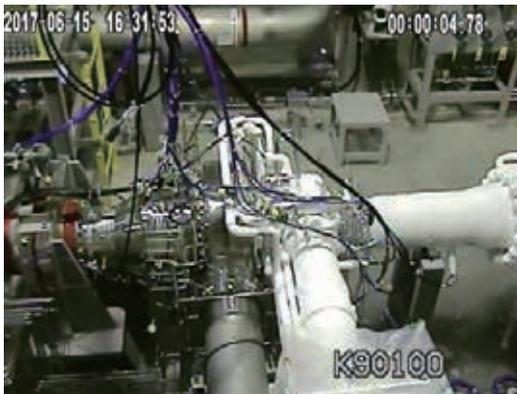


Fig. 9 LE-9 engine oxidizer turbopump cold flow test at JAXA

Table 4 Data of LE-9 engine turbopump cold flow test

Item	Unit	FTP	OTP
Total number of tests	times	4	6
Total test time	s	69.5	70.9

Also, Fig. 10 illustrates an example of LE-9 engine turbo pump unit test data. The rated operation of each turbopump was checked while from a gas accumulator in which GH<sub>2</sub> (Hydrogen Gas) was accumulated and pressurized, supplying the gas to a corresponding turbine, and from a run tank,

supplying LH<sub>2</sub> (Liquid Hydrogen) or LOX (Liquid OXygen). As indicated by the histories of the rotation speeds, the rotation speeds were smoothly increased, kept, and decreased, and start/stop transient characteristics had no problem, so the characteristics of both the FTP and OTP turbopumps during the steady operation nearly satisfied design predictive values.

### 4.3 Suppression of self-excited vibration

Before the test of the FTP engineering model, a turbopump test using a bread board model was performed. In the bread board model test, a phenomenon where the rotor system greatly vibrated in its axial direction occurred. The cause for the vibration was estimated to be self-excited vibration due to insufficient damping ratio of the rotor position adjustment mechanism. Therefore, before manufacturing the engineering model, the internal circulation design of the turbopump was performed with the damping ratio as design rating, and as a result, it was confirmed that the self-excited vibration occurring in the bread board model was suppressed and the steady performance was stably exhibited.

## 5. LE-9 engine hot firing test

### 5.1 Outline of test

The engineering models after the end of the turbopump unit tests were assembled in the engine system, and in order to acquire the following characteristics, since April 2017, a combustion test had been performed at the Tanegashima Space Center (Kagoshima Pref.) of JAXA as the first engine.

Figure 11 illustrates the LE-9 engine hot firing test.

- (1) Confirmation of steady performance
- (2) Establishment of start/stop/throttling sequence
- (3) Confirmation of transient characteristics
- (4) Acquisition of turbopump dynamic characteristics
- (5) Acquisition of operating point control characteristics based on electric valves
- (6) Acquisition of precooling characteristics

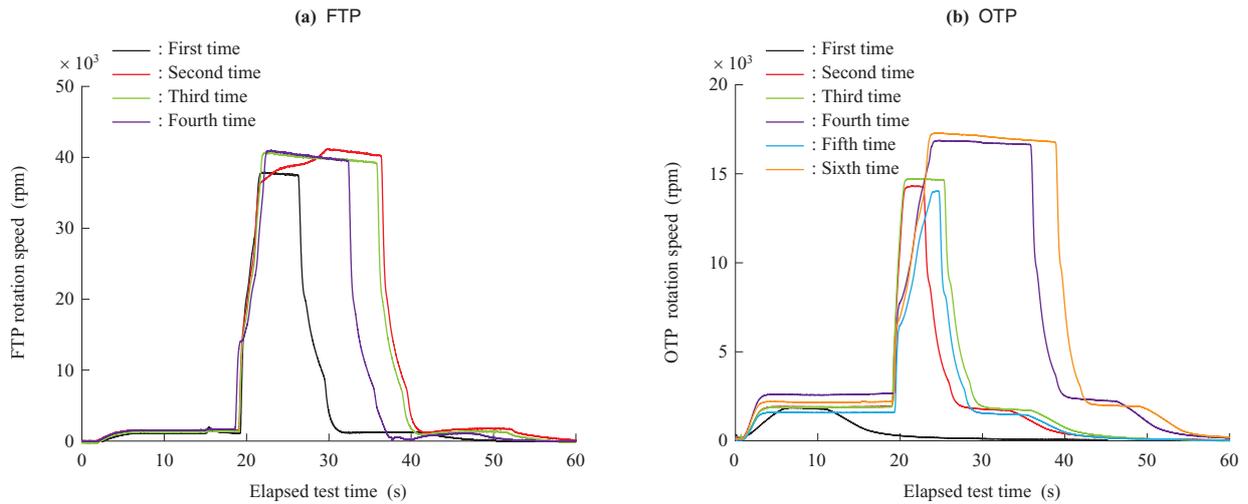


Fig. 10 Data of LE-9 engine turbopump cold flow test

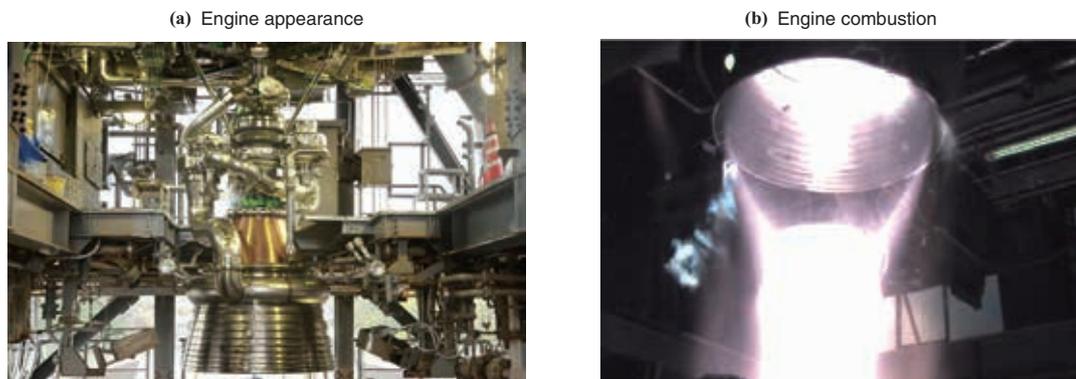


Fig. 11 LE-9 engine hot firing test

## 5.2 Test results

The hot firing test was performed 11 times in total. **Figure 12** illustrates an example of the operation history of the LE-9 engine hot firing test. This test is one performed in such a manner that immediately after the start of the engine, the engine thrust was increased to high thrust, and then decreased by throttling control, a Thrust Control Valve (TCV) was frequency-controlled by itself, and then a main LOX valve (MOV) was frequency-controlled by itself.

As indicated by the histories of rotation speeds, the rotation

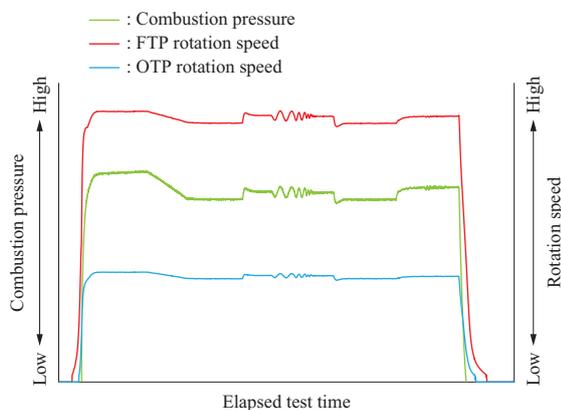


Fig. 12 Data of LE-9 engine hot firing test

speeds of the turbopumps smoothly increased and decreased, and the start/stop transient characteristics had no problem. In addition, the characteristics of both the FTP and OTP turbopumps during the rated operation nearly reproduced the turbopump unit test results, and the followability of the turbopump characteristics to the frequency control also had no problem, so good dynamic characteristics data could be acquired. For the engine system, data on the dynamic characteristics of thrust and mixture ratio with respect to the valve control was acquired. Through the series of the hot firing tests of the first engine, functions and performance at an engine thrust level of 60 to 90% could be confirmed.

In the future, we will plan to confirm feasibility and lifetime with respect to an operating range through the engine hot firing test of the second and subsequent engines.

## 6. Conclusion

The outline of the LE-9 engine-related development, the engine design specifications, and the technical features of the turbopumps have been introduced.

The LE-9 engine is an engine obtained by applying the expander bleed cycle to the high thrust engine unprecedented in the world. Also, as a design approach, the optimal design approach was used, and the interface model-based comprehensive design was employed between the engine and

turbopumps. Further, the innovative production technologies and thorough cost reduction allowed the engine satisfying both high reliability and low cost to be obtained.

Up until now, the design and manufacturing of the engineering model have been completed, and after it has been confirmed through the turbopump unit tests that the predetermined functions and performance are satisfied, the technical feasibility of the LE-9 engine system has been confirmed through the engine hot firing tests.

In the future, we will continue to test the engineering model, as well as plan to move to a qualification model test toward launching a test rocket.

This development is being carried out under development contract with the National Research and Development Agency, Japan Aerospace Exploration Agency.

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