DOI: 10.13009/EUCASS2017-189

The Modified Fuel Turbopump of 2nd stage engine for H3 launch vehicle

Naoki Nagao, Hideaki Nanri*, Koichi Okita*, Yohei Ishizu**, Shinnosuke Yabuki** and Shinichiro Kohno***
**Japan Aerospace Exploration Agency*
2-1-1 Sengen, Tsukuba-shi, Ibaraki 305-8505
***IHI Corporation*
229 Tonogaya Mizuho-machi, Nishitama-gun, Tokyo 190-1297

Abstract
The turbine of fuel turbopump of 2nd stage engine for H3 launch vehicle was changed from a partial admission type to a full admission type to meet the requirement of longer firing duration in a flight. The full admission type had an advantage of increasing the efficiency because of the uniform flow in circumference direction, on the other hand, had a disadvantage of decreasing the efficiency caused with the smaller height of turbine blade. The design of turbine was carefully modified and it was verified with experiments that the turbine had 10% higher performance than the previous design.

1. Introduction

The next generation Japanese mainstay launch vehicle; H3 launch vehicle, has been developed since April 2014 to increase the launch capability of domestic launchers and to enhance the international competitiveness based on the “Basic Plan on Space Policy” [1]. As the result of system study on H3 launch vehicle, the second stage engine of H-IIA/B rocket, named LE-5B-2 is modified and adopted to H3 launch vehicle, because the performance of LE-5B-2 almost meets the requirement of the system and the high reliability of LE-5B series has been proved in the long-term operation. Since the size of H3 launch vehicle becomes larger than that of H-IIA/B in order to increase the launch capability as shown in Fig. 1, the propellant mass of the second stage is increased and thus the firing duration of the second stage engine in a flight becomes longer; 534 seconds in H-IIA/B rocket and 740 seconds in H3 launch vehicle. The modified second stage engine named LE-5B-3 needs to meet the requirement of longer durability and then the development of LE-5B-3 has been started.

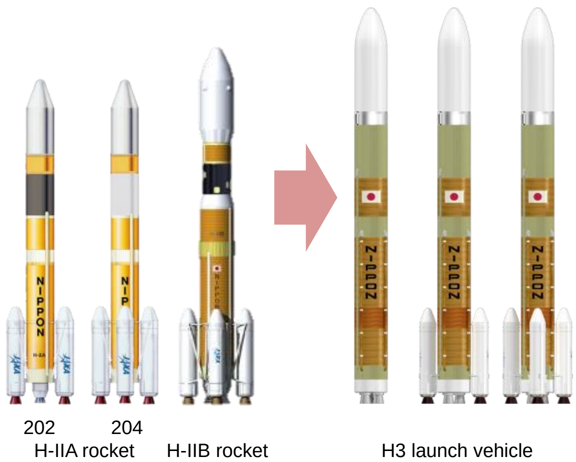


Figure 1: Comparison of the vehicle size between H-IIA/B and H3 launch vehicle

DOI: 10.13009/EUCASS2017-189

2.LE-5B-3

Figure 2 shows the outside drawing of LE-5B-3 and Table 1 shows the comparison of specifications between LE-5B-2 and LE-5B-3. The major differences of specification between the engines are the firing duration and the Isp.
The firing duration of LE-5B-3 is 740 seconds and it is about 1.4 times length of LE-5B-2. In the past development of LE-5B-2, the turbine of the fuel turbopump caused cracks on the blade and the disk shaft due to high cycle fatigue which was generated by the partial admission flow. Although the measures of the cracks had been taken to LE-5B-2, the risk of causing the crack in LE-5B-3 was increased because of the requirement of longer duration. For the purpose of meeting the revised requirement of durability and supressing the high cycle fatigue in the turbine blade, the turbine of the fuel turbopump of LE-5B-3 was changed from a partial admission type of LE-5B-2 to a full admission type. The Isp of LE-5B-3 is 448 seconds and it is 1.2 seconds higher than that of LE-5B-2. The value of 1.2 seconds is small but the launch capability to GTO is increased about 40 kg. The mixer is the key component of increasing the Isp for LE-5B-3. Liquid hydrogen from the fuel turbopump and gaseous hydrogen from regenerative cooling channel are mixed in the mixer as shown in Fig. 3. When the mixer has lower performance, the gas with nonuniform temperature flows into the injector and it causes temperature distribution of combustion gas and then it causes temperature distribution in the wall of combustion chamber. The performance of heat exchange of such chamber becomes worse and the gas temperature downstream of regenerative cooling channel becomes lower, then larger flow rate of turbine driven gas is needed to maintain the turbine output. Since the turbine driven gas is exhausted outside the chamber, the larger flow rate of turbine driven gas decreases the Isp. The design of mixer for LE-5B-3 was optimized to decrease the temperature distribution in the wall of combustion chamber. There are some other components of LE-5B-3 which are modified in order to increase the reliability and decrease the cost [2].

Figure 2: Outside drawing of the second stage engine of H3 launch vehicle; LE-5B-3

Table 1: Comparison of specifications between LE-5B-2 and LE-5B-3

		LE-5B-2	**LE-5B-3**
Propellant		LOX/LH2	LOX/LH2
Vacuum Thrust	[kN]	137.2	137.2
Vacuum Isp	[sec]	***446.8***	***448.0***
Chamber Pressure	[MPa]	3.58	3.61
Nozzle Expansion Ratio		110	110
Engine Length	[m]	2.79	2.79
Engine Mass	[kg]	298	303
Engine Cycle		CEB [a]	CEB
Mixture Ratio		5.0	5.0
Throttling Capability		60%	None
Restart Capability		Yes	Yes
Nominal Firing Duration	[sec]	***534***	***740***
First Flight Year		2008	2020(Plan)

[a]CEB: Chamber Expander Bleed

DOI: 10.13009/EUCASS2017-189

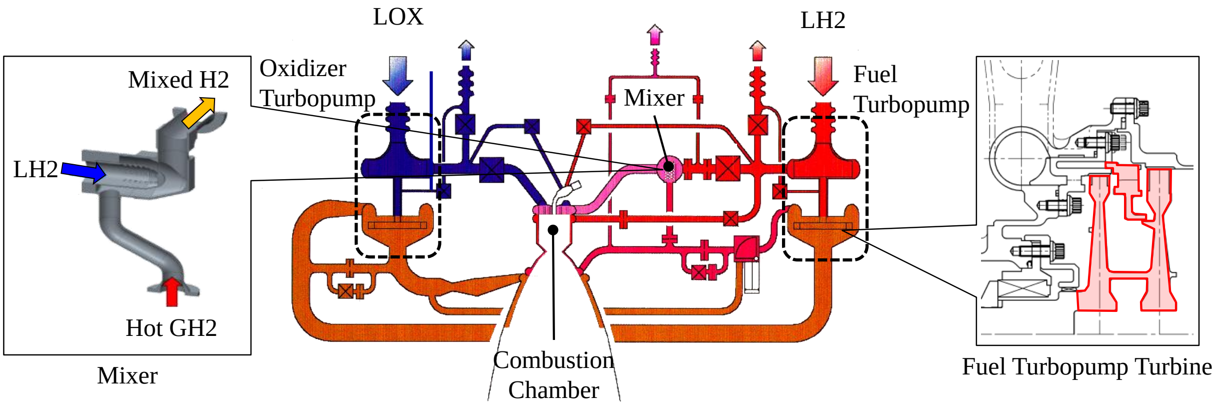


Figure 3: Major improved components from LE-5B-2 to LE-5B-3

3. Fuel turbopump(FTP) turbine design

There are two types of turbine nozzle admission. A partial admission type has blockages partially in the fluid inlet of a turbine nozzle and a full admission type has no blockage all around the fluid inlet of a turbine nozzle. The fuel turbopump (FTP) of LE-5B-2 adopts a partial admission turbine for the purpose of increasing the height of turbine blade and decreasing leakage loss from tip clearance. On the other hand, the partial admission type excites pressure and thermal fluctuation to the turbine blade and disk shaft because there is partial blockages at the inlet of turbine nozzle, and the partial admission type has a possibility to cause a damage of high cycle fatigue to the turbine system. In fact, cracks were observed on the turbine which adopted the partial admission type in past development of LE-5B-2. Ensuring the reliability of an engine in a flight, the Japanese rocket engine is required to meet the four times lifecycle to a flight. Therefore, the durability of firing duration for LE-5B-3 is required to 3,160 seconds, whereas the LE-5B-2 to about 2,300 seconds. Because the firing duration of LE-5B-3 is longer than that of LE-5B-2, the risk of damage to the turbine caused by high cycle fatigue is higher than that of LE-5B-2. Then a full admission turbine was selected for LE-5B-3 FTP to suppress the high cycle fatigue and to meet the durability requirement. Generally, the performance of a full admission type is better than that of a partial admission type because there is no blockage at the inlet of the nozzle and the gas flow is uniform in the circumferential direction. On the other hand, the height of the turbine blade of a full admission type becomes smaller than that of a partial admission type and then the loss of the turbine performance is foreseen to be increased because the relative tip clearance becomes larger than that of a partial admission type. For that reason, the design of the new turbine was carefully modified.

Figure 4 shows the comparison between the LE-5B-2 turbine and the LE-5B-3 turbine. LE-5B-3 turbine is a 2 stage impulse turbine which is a same type with LE-5B-2 turbine. Since the turbine flow rate of LE-5B-3 is almost same as that of LE-5B-2, the blade height of LE-5B-3 turbine becomes lower than that of LE-5B-2 turbine by adopting a full admission type. The height of turbine blade of LE-5B-3 becomes about 4 mm which is the smallest value in the past development in Japanese rocket engines, and the estimation method of performance loss in turbine needed to be improved. A new loss model, based on Craig and Cox model [3], was built to estimate the loss precisely of the small height of turbine blade. Using the new loss model, the mean line design of LE-5B-3 turbine was carried out and the performance of the design was verified with 3D-CFD analysis. Furthermore the design of LE-5B-3 turbine was verified with the turbopump assembly test and the engine firing test as described in the following.

DOI: 10.13009/EUCASS2017-189

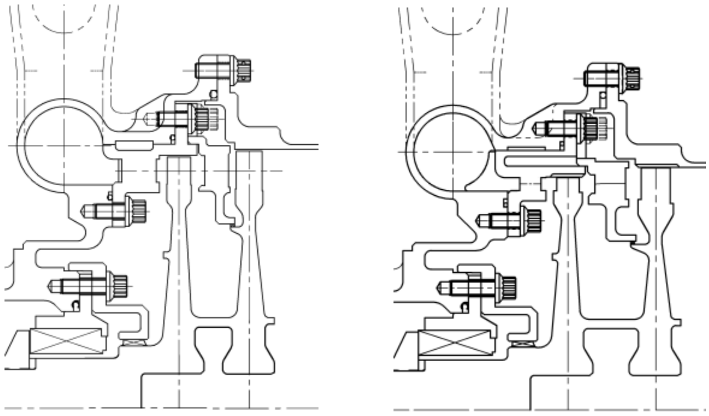


Figure 4: Comparison between the LE-5B-2 turbine and the LE-5B-3 turbine

4. Verification result with experiments

The results of the turbopump assembly test and the engine firing test showed that the turbine efficiency of LE-5B-3 was higher than that of LE-5B-2. The content of each test is described below.

4.1 Turbopump assembly test configuration

The turbopump assembly test was carried out in the liquid hydrogen turbopump test facility in IHI Co. Aioi test site from December 2016 to January 2017. Figure 5 shows the turbopump assembly test configuration and Fig. 6 shows the system diagram of the liquid hydrogen turbopump test facility. There are bottles for high pressure gaseous hydrogen (GH2) storage and the GH2 is regulated and flown into the liquid hydrogen (LH2) run tank. The pressurized run tank feeds LH2 to the turbopump through a pipe line. The operating turbopump discharges pressurized LH2 to a LH2 catch tank, and the discharged flow rate of LH2 is controlled with an orifice and a valve between the turbopump and the LH2 catch tank. High pressure GH2 gas in the bottles is regulated and the regulated gas drives the turbine of turbopump. The value of regulated pressure controls the flow rate of GH2 because of the choke flow in the inlet nozzle of turbine, and an orifice in the outlet of turbine determines the ratio of inlet and outlet turbine pressure. The exhausted GH2 from turbine is vented to atmosphere. Whereas the temperature of turbine driven gas is about 400 K in the engine, the temperature of gas in the turbopump assembly test is room temperature, so the thermal condition at the turbine is not simulated in the turbopump test.

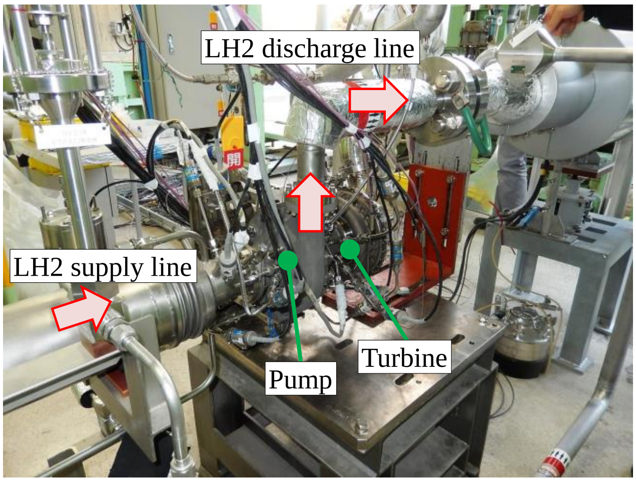


Figure 5: LE-5B-3 turbopump assembly installed on the test stand

DOI: 10.13009/EUCASS2017-189

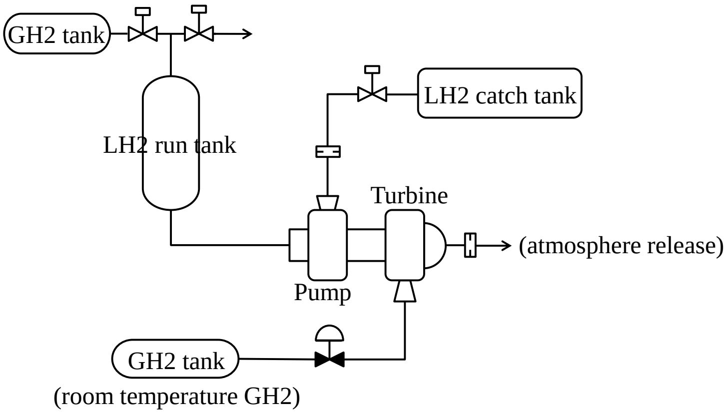
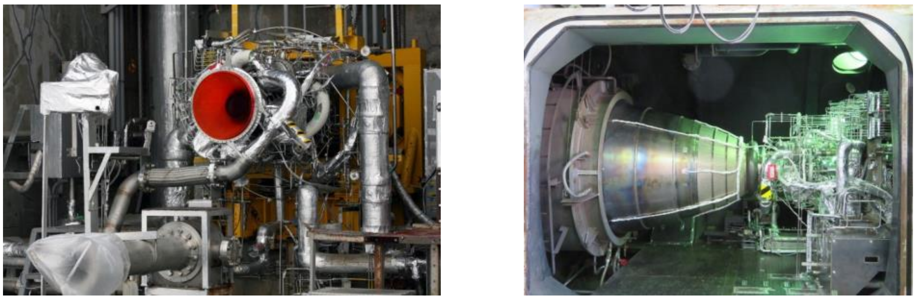


Figure 6: System diagram of the liquid hydrogen turbopump test facility

4.2 Engine firing test configuration

The FTP was installed on the engine system after the turbopump assembly test and the FTP was tested as a component of the engine in firing tests. The firing tests were carried out in two conditions; sea level condition and vacuum condition. The firing test in sea level condition was carried out in Mitsubishi Heavy Industry Co. Tashiro test site from March to April 2017. The firing test in vacuum condition was carried out in High Altitude Test Stand (HATS) in JAXA Kakuda Space Center. Figure 7 shows the pictures of LE-5B-3 installed on each test facility. The nozzle expansion was detached from LE-5B-3 in the sea level test because the nozzle would be broken by the pressure difference between inside and outside nozzle in the firing. Since the exhaust gas from the turbine of oxidizer turbopump of LE-5B-3 is vented to vacuum condition in a flight and it needs to simulate the vacuum condition in the sea level test, there is a small ejector to create a low pressure condition around the exit of exhaust gas line.



LE-5B-3 installed on Tashiro test facility   LE-5B-3 installed on HATS

Figure 7: LE-5B-3 installed on each test facility

4.3 Experimental result

Figure 8 shows the obtained turbine efficiencies in the turbopump assembly test and the engine firing test. The vertical axis shows turbine efficiency η_T and the horizontal axis shows U/C0 which is the value of a peripheral velocity at a turbine tip divided by an axial velocity in turbine blade. The value of turbine efficiency and U/C0 are normalized with each value of design point. The closed plots show the result of the turbopump assembly test and the open plots show the result of the engine firing test. The solid line shows the design performance curve and the broken line shows the required performance curve, which is equal to the performance of the turbine of LE-5B-2.
The obtained turbine efficiencies were almost same with the design performance, which means that the new loss model for the turbine was reasonable and the design tool was established. And the turbine efficiency in the engine firing test were about 10% of design point higher than the required efficiency which is equal to that of the turbine of LE-5B-2. The difference of efficiency between the turbopump assembly test and the engine firing test seems to be caused by the difference of tip clearance. As mentioned in the chapter 4.1, the temperature of turbine driven gas in the firing test is higher than in turbopump assembly test. According to the FEM analysis, the thermal deformation of the turbine makes the tip clearance small and then the loss at the tip clearance becomes smaller in the firing test.

DOI: 10.13009/EUCASS2017-189

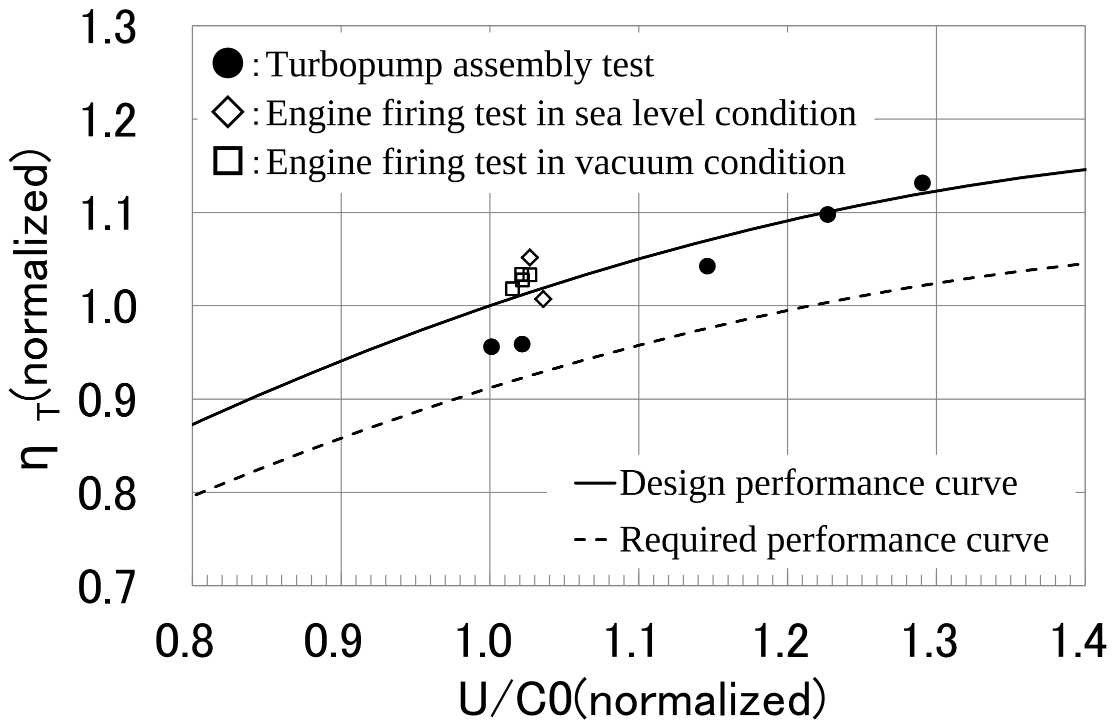


Figure 8: Turbine efficiency experimental results

5. Development schedule

Figure 9 shows the development schedule of LE-5B-3. The design of LE-5B-3 is planned to be qualified with only two engines because LE-5B-3 is not a fully new engine but a modification type of LE-5B series. The second turbopump will be manufactured and will be tested as turbopump assembly in the middle of 2018. Then the second turbopump will be applied to the second engine and the firing test will be carried out until the beginning of 2019. Performance of another modified turbine will be obtained through these tests and the design will be verified with two samples. Finally the development of LE-5B-3 will be completed by the first quarter of 2019.

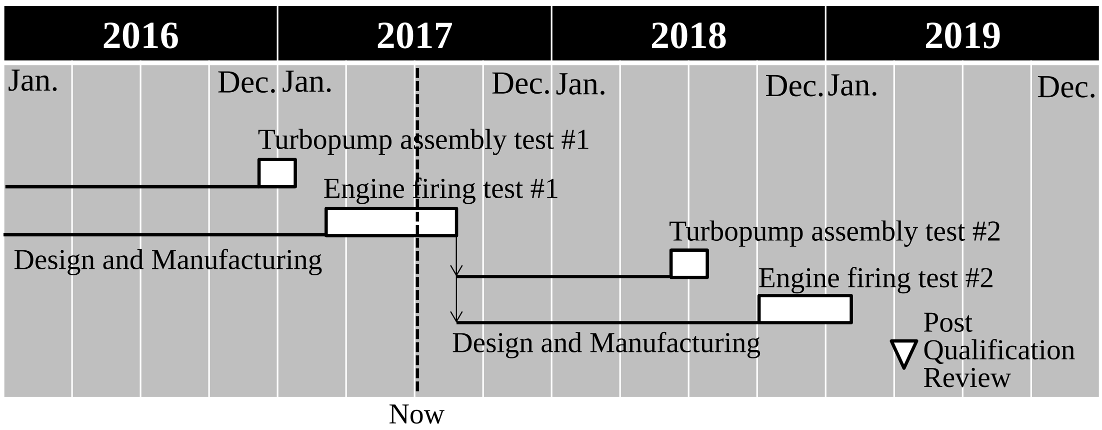


Figure 9: LE-5B-3 development schedule

DOI: 10.13009/EUCASS2017-189

6. Summary

The turbine of the fuel turbopump of the second stage engine (LE-5B-3) for H3 launch vehicle was modified in order to meet the requirement of longer durability, and the design of the turbine was changed from a partial admission type to a full admission type for the purpose of suppressing the high cycle fatigue on the blade and the disk shaft. Since the size of the turbopump of LE-5B-3 is small, the height of a turbine blade becomes small (about 4 mm) by adopting the full admission type, which decreases the performance of the turbine because the larger relative tip clearance increases the gas flow loss in the turbine. On the other hand, performance of a full admission turbine is generally better than that of a partial admission turbine, because the gas flow is uniform in circummundane direction. Considering the advantage and disadvantage, the turbine was redesigned and verified with CFD analysis and experiments, then the followings were clarified.
(1)The proper loss model for the turbine with smaller height of turbine blade was set and the design of the turbine shape was optimized with the mean line design. Then the turbine efficiency was estimated about 9% of design point higher than LE-5B-2.
(2)The result of the turbopump assembly test and the engine firing test showed that the value of the turbine efficiency was well matched to the mean line design. In addition, the turbine efficiencies of the engine firing test were about 10% of design point higher than that of previous turbine design.
(3)These results mean that the new loss model for the turbine was reasonable and the design tool was established.

References

[1] Basic Plan on Space Policy, established by Strategic Headquarters for Space Policy, Government of Japan, January 25. 2013

[2] Kazuhiro, H., Naoki, N., Hideaki, N., Koichi, O., Akira, O., Junya, T., Hideo, S., Katsuhiko, N., Tsutomu, M., Shinichiro, K., and Yusuke, A. 2016. Development of the 2nd stage engine for next flagship launch vehicle “H3 launch vehicle”. Space Propulsion 2016. 3124846.

[3] Craig, H. R. M., Cox, H. J. A., Performance estimation of axial flow turbines. Proc. I. Mech. E., Vol. 185 32/71, 1970-71, pp.407-424.