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2nd qualification test series results of the upper stage engine LE-5B-3 for H3 rocket

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Abstract
The major requirements for the H3 rocket's upper stage engine LE-5B-3 are to increase the specific impulse (ISP) and to extend the engine life-cycle from those of LE-5B-2 for H-IIA/B rockets. To increase ISP, we improved the design of mixer, which is installed at the upstream of injector and mixes the gaseous hydrogen from regenerative cooling channels and the liquid hydrogen from fuel turbopump. The fuel turbopump turbine design was also improved to extend the engine life-cycle. The qualification test results showed that LE-5B-3 satisfied the product requirement specifications.

1. Introduction

The H3 rocket is the new Japanese flagship launch vehicle targeted at the higher flexibility, reliability, and cost performance. It will offer various vehicle configurations by selecting the type of fairing and the number of the first stage liquid rocket engines and the solid rocket motors to deal with various payloads and orbits [1]. The H3 rocket is now under development to be the successor to the present flagship launch vehicles the H-IIA/B rockets, and its first flight is scheduled for Japanese fiscal year 2020.

The upper stage engine of the H3 rocket, LE-5B-3, is the latest version of LE-5 engine series [2,3], which has been used as the upper stage engine of Japanese successive space launch vehicles for over four decades (figure 1). The first Japanese LOX/LH2 engine, the LE-5 engine [2,4], was practically used for the H-I rocket in 1984. The engine adopted the gas generator cycle and had the thrust level of 10,500 kg and the specific impulse (ISP) in vacuum of 450 sec. Then, LE-5 had been improved from 1986 to 1991 to become LE-5A [2] for the H-II rocket. It adopted a coolant bleed cycle, the expander bleed cycle which only Japan has been adopted for practical use until now. The cycle uses the gaseous hydrogen from the regenerative cooling channels to drive turbines of both LOX/LH2 turbopumps. The LE-5A increased the thrust level to 12,400 kg and the ISP to 452 sec. To make the more reliable and cost-effective engine, LE-5A had been improved from 1994 to 2002 to be LE-5B [2,3,5-7] for the H-IIA rocket. In order to pursue more cost-effectiveness, the system of the expander bleed cycle was changed from nozzle bleed cycle in which the bleed line goes through chamber and nozzle extension region for LE-5A to the chamber bleed cycle where the bleed line only exists in chamber region for LE-5B. LE-5B has the thrust level of 14,000 kg and the ISP of 447 sec. In 2003, the development of LE-5B-2 [8] as an upgraded version of LE-5B was started to be robust against the combustion instability. This upgrade improved the injector and the mixer, which is installed at the upstream of the injector and mixes the liquid hydrogen from the turbopump and the gaseous hydrogen from the regenerative cooling channels.

Since 2014, the LE-5B-3 engine has been under development mainly for increasing the ISP and the engine firing duration. The mixer design has been improved to increase the ISP. The fuel turbopump turbine design also has been changed to extend the engine firing duration. Thus far, the feasibility test was conducted and the results showed that increasing ISP by the design improvement of the mixer has a feasibility [8]. In the turbopump assembly testing, the fuel turbopump with the design improved turbine satisfied the necessary performance [9]. Also, the first qualification test series (QT#1) and second qualification test series (QT#2) of the LE-5B-3 engine were successfully completed in 2017 [10] and 2019, respectively.

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This paper summarises the results of the qualification test series focusing on increasing ISP and extending the engine firing duration, and discusses the validity of the related design improvement of the mixer and the fuel turbopump turbine.

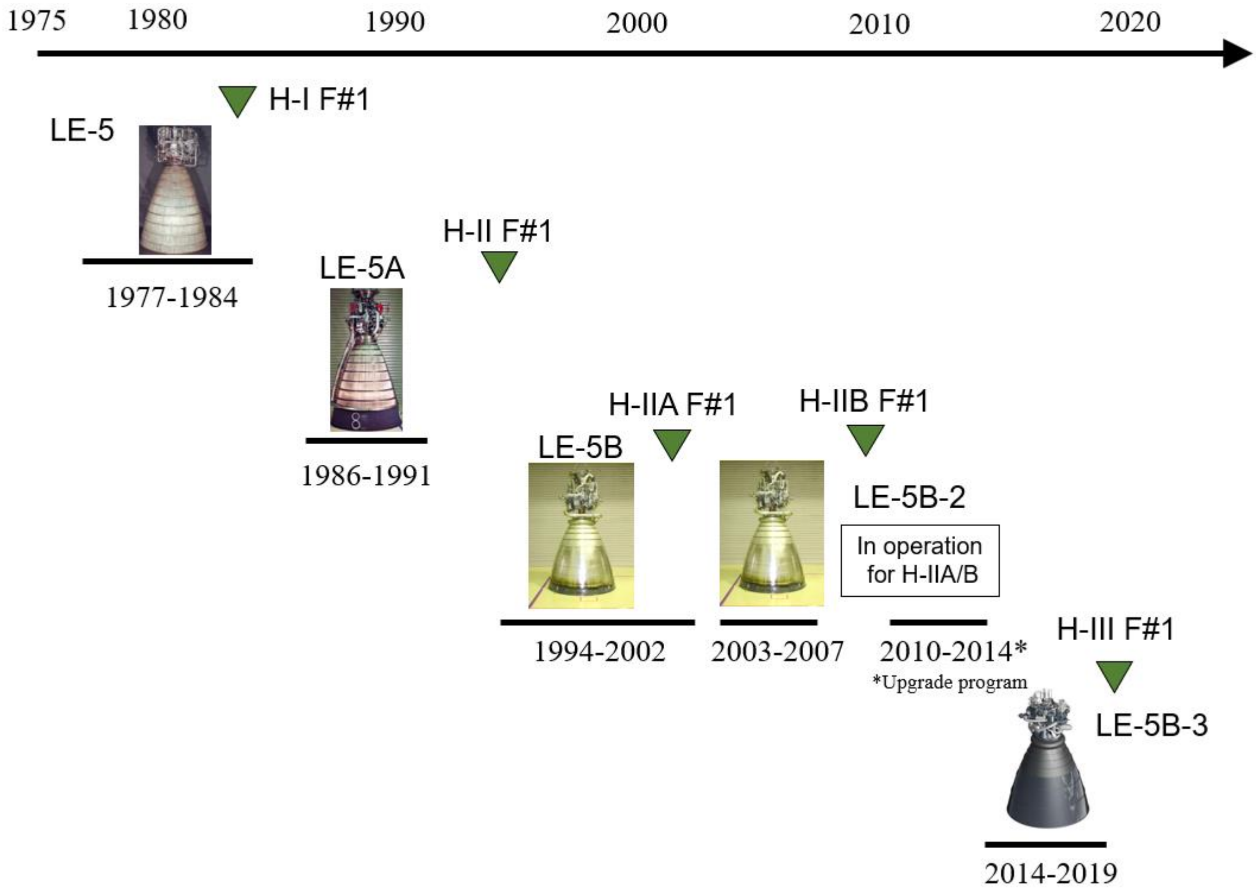

Figure 1: History of LE-5 engine series. The duration described under the engines shows the development period of each engine.

2. Specification and design of LE-5B-3

Table 1 shows the major specifications of the LE-5B-3 engine. There are two main updated items from LE-5B-2: one is the increased ISP and the other is the extended firing duration.
The ISP has increased from 446.8 sec. for LE-5B-2 to 448.0 sec. for LE-5B-3 by 1.2 sec. It is worth noting that the 1.2 sec. corresponds to around 40 kg increase in the launch capability for a geostationary transfer orbit mission [9]. This increased ISP was achieved by improving the design of the mixer, a component installed at the upstream of the injector for mixing the liquid hydrogen from the fuel turbopump and the gaseous hydrogen from the regenerative coolant channels (see figure 2). If the mixing of gaseous and liquid hydrogen is insufficient, the flow of hydrogen having large temperature distribution in the circumferential direction goes into the manifold, and then into the chamber. This leads to non-uniform temperature distribution of the chamber wall in the circumferential direction as well, because chamber wall is heated by the combustion in chamber, which is affected by the injected flow. In the expander bleed cycle of LE-5B, the turbine driven gas is generated and heated through the regenerative cooling channels of the chamber, so that the efficiency of heat exchange decreases when the chamber wall temperature has some distributions in the circumferential direction, and thus, the turbine driven gas temperature becomes low as well. Low turbine gas temperature requires more flow rate to have enough turbine power, leading to decreasing the ISP. Figure 3 shows the comparison of the mixer designs of LE-5B-2 and LE-5B-3. Gaseous hydrogen is injected into liquid hydrogen through small holes in LE-5B-2, and vice versa in LE-5B-3 [8]. In Figure 3, CFD analysis shows that this design change reduces the difference between the maximum and minimum injection temperatures by a factor of 10.

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Table 1: Engine specifications of LE-5B-3 [2].

		LE-5B-2 	LE-5B-3 
Item	Unit		
Vacuum thrust	kN	137.2	137.2
Vacuum Isp	sec.	446.8	448.0
Mixture ratio	-	5.0	5.0
Firing duration	sec.	534	740
Chamber pressure	MPa	3.58	3.61
Nozzle expansion ratio	-	110	110
Length	m	2.79	2.79
Mass	kg	298	303
Engine cycle	-	Expander bleed	Expander bleed

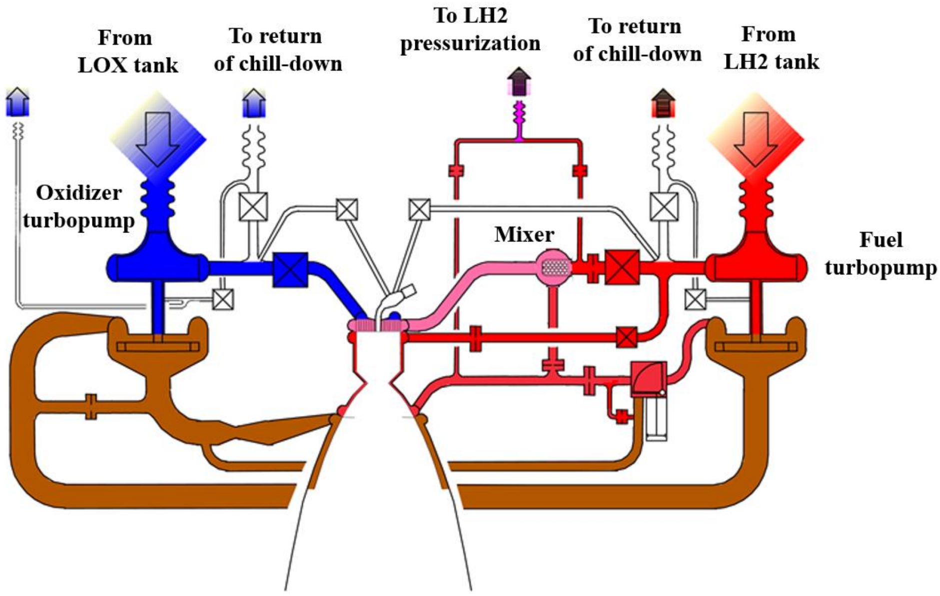

Figure 2: Engine schematic of LE-5B-3. The mixer is installed at the upstream of injector for mixing the liquid hydrogen from fuel turbopump and gaseous hydrogen from the regenerative cooling channels.

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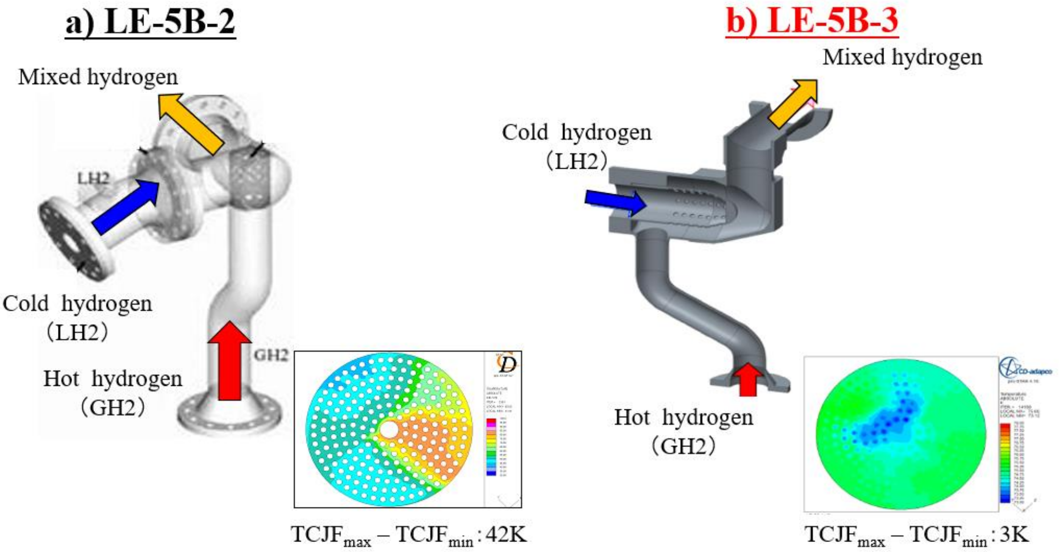

Figure 3: Mixer designs and CFD analysis results of a) LE-5B-2 and b) LE-5B-3. $TCJF_{max}$ and $TCJF_{min}$ denote the maximum and minimum fuel injection temperature, respectively [8].

The other main target of LE-5B-3 is to extend the firing duration to satisfy the system requirement from the vehicle. The mission duty cycle is changed from 534 sec. for LE-5B-2 to 740 sec. for LE-5B-3 (see table 1). Thus, the requirement for the life-time cycle set with considering 4 mission duty cycles has been increased from 2336 sec. for LE-5B-2 to 3160 sec. for LE-5B-3. The key component for the extension of the firing duration was identified in the LE-5B-2 development activities, because cracks were found on the turbine blades and disk-shaft of the fuel turbopump due to high cycle fatigue when the engine operation exceeded 2336 sec. in the firing tests. To solve this issue, the turbine design has been improved in LE-5B-3. LE-5B-2 adopts the partial admission turbine in which the nozzle inlet has blockages in the circumferential direction to have turbine blade height enough for improving manufacturability and decreasing leakage loss which is affected mainly by the relative scale of tip clearance to turbine blade height (see figure 4). However, the blockages destabilize the flow and increase the pressure fluctuation, enhancing the risk of the high cycle fatigue. Then, LE-5B-3 adopts the full admission turbine having no blockage at the nozzle inlet to reduce the risk of high cycle fatigue [9]. The 1st stage turbine blade height has almost halved to have similar flow rate to LE-5B-2. To predict the small size turbine performance accurately, a new loss model based on Craig and Cox model [11] has been developed and used for its design.

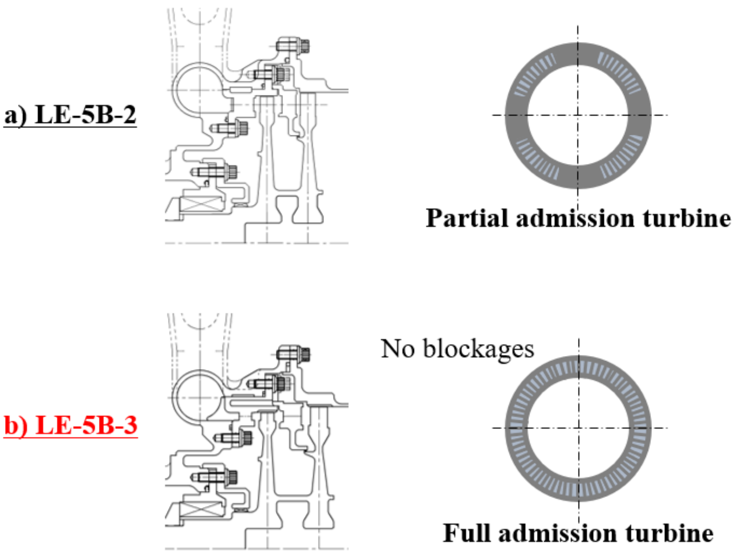

Figure 4: Design difference of turbine: a) Partial admission turbine for LE-5B-2 and b) full admission turbine for LE-5B-3 [9].

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3. Qualification Test

3.1 Test configuration

The engine testing was mainly conducted at the high altitude test stand (HATS) in JAXA's Kakuda space centre as shown in Figure 5 a). The engine with the nozzle extension was installed in the vacuum chamber to simulate a flight environment. In addition to HATS testing, the testing without the nozzle extension in an atmosphere environment was conducted at the Tashiro test cite of Mitsubishi Heavy Industries LTD. (MHI) (see figure 5 b). The acceptance test is planned to be carried out in Tashiro test site in order to decrease the testing cost in the same way as that of LE-5B-2. The objective of Tashiro test campaign is to obtain a correlation of the performance between with- and without-nozzle extension engines to predict the precise performance in the flight environment using the acceptance test data obtained in Tashiro test cite [10].

a) Kakuda HATS b) Tashiro

Figure 5: Engine test stands at: a) High altitude test stand (HATS) in JAXA's Kakuda space center and b) MHI's Tashiro test site [10].

3.2 Test results

The engine operated for total 23 times ignition and 3160 sec. burning duration in each qualification test series, and both engines for QT#1 and QT#2 satisfy the life-cycle requirements of 16 ignitions and 3160 sec. burning duration. Figure 6 shows the qualification test results of the vacuum thrust F_v v.s. the engine mixture ratio MRE. The values are obtained by 5 seconds averages at the engine combustion steady state. The engine worked well at every test point and the engine performance data was acquired in a broad range including outside the qualification test range drawn with black solid line as shown in Figure 6. This qualification test range was set with the engine performance variance being 3σ, where σ is the standard deviation.

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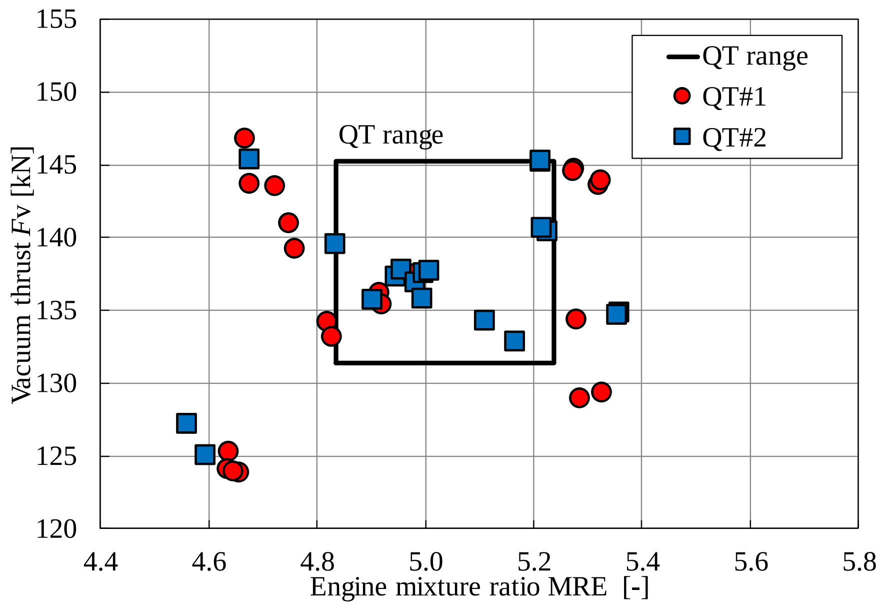

Figure 6: The qualification test results of the vacuum thrust *F*v v.s. the engine mixture ratio MRE.

In addition, our evaluation of QT#1 and QT#2 results shows that the nominal ISP of LE-5B-3 satisfies the requirement of 448.0 sec. Here, we check if the design change of the mixer for increasing ISP improves the fuel injection temperature distributions. Figure 7 shows the qualification test results of the injection temperature distribution based on the difference between the maximum and minimum fuel injection temperatures. The values are obtained by the following two steps: i) 5 seconds averaged values at the engine combustion steady state are obtained by each test result, and ii) the values obtained in 1) are averaged again with the following four categories: a) QT#1 Kakuda HATS, b) QT#1 Tashiro, c) QT#2 Kakuda HATS and d) QT#2 Tashiro. The results showed that the difference between the maximum and minimum injection temperatures was 1.5 to 2.5 K, which was in good agreement with the CFD prediction of 3K shown in figure 3. Therefore, the design change of the mixer increased ISP, as planned.

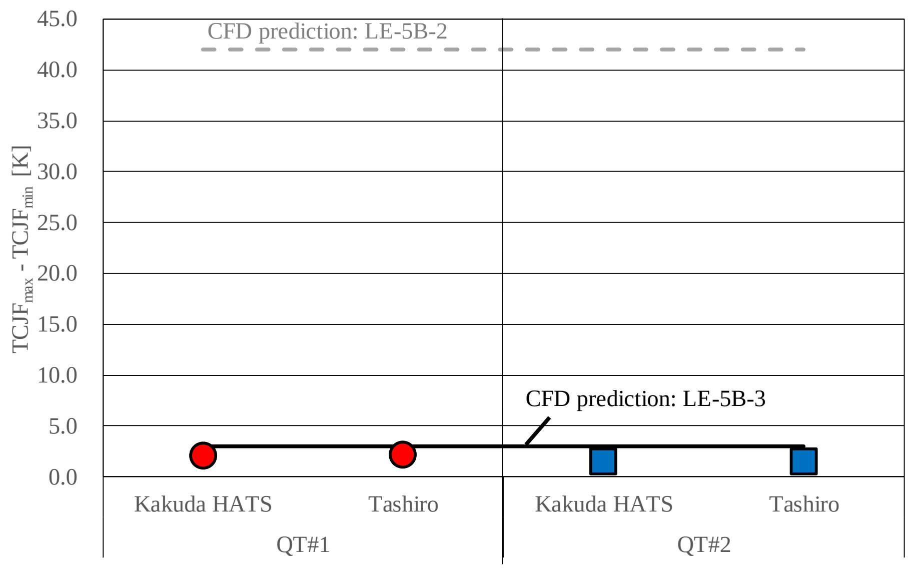

Figure 7: The qualification test results of fuel injection temperature distribution based on the difference between the maximum and minimum fuel injection temperatures. $TCJF_{max}$ and $TCJF_{min}$ denote the maximum and minimum fuel injection temperature, respectively.

Finally, the design improvement of the fuel turbopump turbine to extend the engine life-cycle is discussed. The fuel turbopumps were disassembled after each qualification test and every component including the turbine was inspected. The results showed that all the components were found to be intact with no cracks at the turbine blade and the disk shaft. As for the performance of the turbine, the results of turbine efficiency of fuel turbopump based on iso-entropy efficiency are shown in Figure 8. The values were also obtained by 5 seconds averages at the engine combustion steady state. The obtained values were above the design curve drawn with black solid line, proving that the fuel turbopump turbine design improvement extended the engine life-cycle while maintaining good performance.

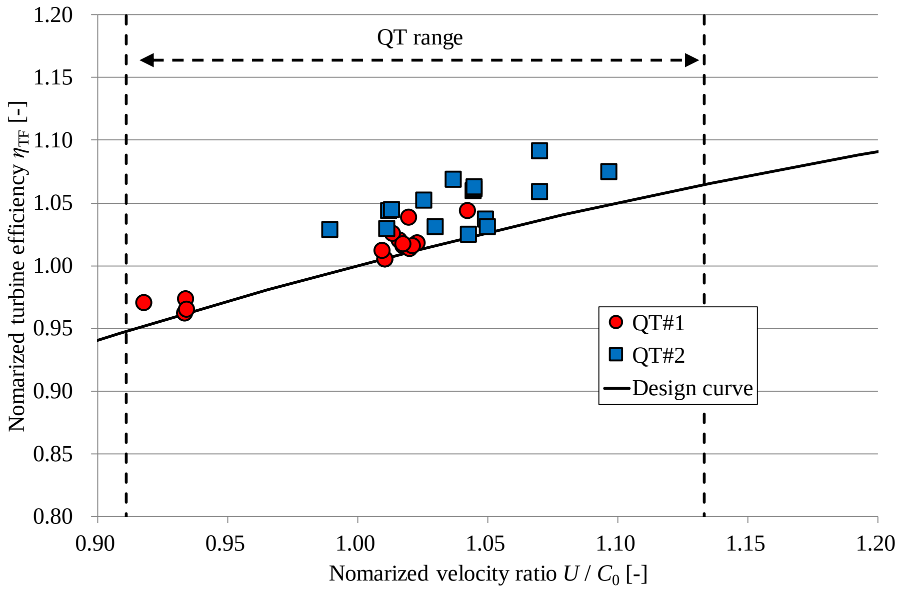

Figure 8: The qualification test results of fuel turbopump turbine efficiency η_{TF} based on iso-entropy efficiency, where U / C_0 is the speed ratio between blade rotational speed U and the ideally expanded turbine gas speed c_0.

4. Conclusions

This paper summarises the results of the qualification test series of the upper stage of the H3 rocket, the LE-5B-3 engine.

The major requirements for LE-5B-3 are to increase the specific impulse from 446.8 sec. for LE-5B-2 to 448.0 sec. and to extend the engine life-cycle from 2336 sec. for LE-5B-2 to 3160 sec. The increased ISP has been achieved by the improvement of the mixer and the extended engine life-cycle has been realized by the fuel turbopump turbine design improvement.

Two qualification test series showed that LE-5B-3 satisfies ISP requirement. Also, the results of inspection after the qualification test series showed that all components were intact, indicating the extended life-cycle. Based on the results, the LE-5B-3 engine successfully completed its development activities in May 2019.

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