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Subscale Firing Test for Regenerative Cooling LOX/Methane Rocket Engine

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Abstract
JAXA and IHI have been proceeding the research and development activities for high performance LOX/Methane regenerative cooling engine since 2013. It is targeted that the specific impulse of 370 sec will be achieved due to the high combustion efficiency under a super critical pressure and the full expander cycle engine as a high performance closed engine cycle. In 2017, the subscale engine tests are planned to be conducted with the engine-like configuration using the injector elements and the regenerative cooling chamber designed based on the element test results. This paper reports the status of research and development on the LOX/Methane engine and the subscale engine tests plan.

1. Introduction

LOX/Methane as propellant combination of rocket engine is expected to be applied to the future space vehicle such as reusable booster, low cost expendable vehicle, planet launder, and orbital transfer vehicle, due to smaller vehicle based on high density and the long term storage in deep space based on the low boil-off rate. Recently, the LOX/Methane rocket engines attract the great deal of attention and are strategically developed all over the world as shown in Table 1. NASA develops the 20kN class pressure feed film cooling rocket engine HD for lunar lander Morpheus [1]. ASI develops 100kN class full expander cycle engine LM-10 MILA for the upper stage of low cost expendable rocket VEGA [2]. AIRBUS develops the 420kN class gas generator cycle engine ACE-42R for Space Plane reusable engine [3]. Blue Origin develops the 2400kN class staged combustion cycle engine BE-4 for ULA Vulcan rocket reusable booster [4]. SpaceX develops the 3500kN class staged combustion cycle engine Raptor for Interplanetary transport sysstem [5].

In Japan, the 100kN class ablative chamber LOX/Methane engine (LE-8) has been developed from 2002, and the continuous firing of 600 sec mission duty cycle and durable performance of 2200sec accumulated time were tested and Isp 315 sec was achieved. And 30kN class ablative chamber engine was tested at High Altitude Test Stand, and Isp 335 sec of the engine performance in vacuum condition was achieved [6, 7].

Since the performance of ablative chamber engine was getting to reach the upper limit, the 100kN class gas generator cycle regenerative cooling engine has been developed. The sea level firing tests of 27 times and accumulated firing time of 1800sec were performed and expected vacuum Isp 356 sec was achieved [8, 9].

The research and development program for regenerative cooling LOX/Methane engine is proceeded from 2013, to aim to achieve higher engine performance in the world.

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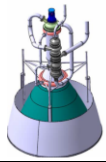
Table 1. LOX/Methane Engine Development

	HD	MIRA	ACE-42R	BE-4	Raptor	LE-8 engine	30kN-class engine	100kN-class engine
								
Country	USA	Italy	France	USA	USA	Japan	Japan	Japan
Company	NASA	Avio	AIRBUS	Blue Origin	SpaceX	IA/JAXA	IA/JAXA	IHI
Vehicle	Morpheus lunar lander	VEGA Upper stage	Space Plane	Vulcan 1st stage	Interplanetary transport system	-	-	-
Thrust [kN]	24	98	420	2400	3500	107	30	98
Isp vac.[sec]	215	364	340	330	382	315	335	356
Engine Cycle	Pressure Feed	Full Expander	Gas Generator	Staged Combustion	Staged Combustion	Gas Generator	Pressure Feed	Gas Generator
Propellant Feeding	Pressure Feed	Turbo Pump	Turbo Pump	Turbo Pump	Turbo Pump	Turbo Pump	Pressure Feed	Turbo Pump
Chamber Cooling	Film Cooling	Regenerative	Regenerative	Regenerative	Regenerative	Ablative	Ablative	Regenerative

2. Objective of research and development

Recently, the LOX/Methane engines are developed in the world to apply the future space transportation vehicle such as reusable booster, low cost expendable vehicle, planet lander and orbital transfer vehicle, and any precursor missions. As mentioned above, though many firing tests are conducted for ablative engine in Japan to obtain the improvement of durability and performance, the sufficient performance has not been accomplished to show the clear advantage for the world. As shown in Figure 1, the higher performance of Isp 350-370 sec is set as the target of this research, which will be able to be achieved only by adopting the closed cycle regenerative cooling engine.

The engine performance of Isp for each engine cycle are shown in Figure 2. To accomplish high performance of Isp 350-370 sec, adopting the full expander cycle or staged combustion cycle is necessary and they are candidate of engine cycle of this research.

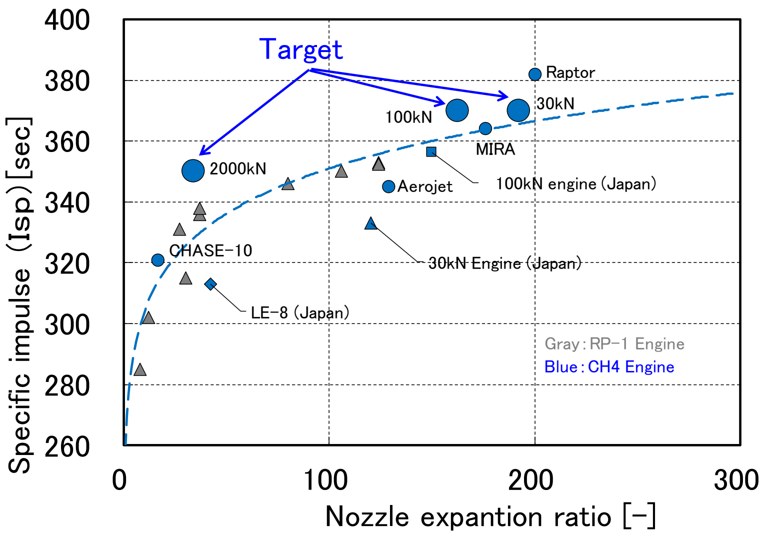


Figure 1. Hydro-carbon Engine Performance

DOI: 10.13009/EUCASS2017-381

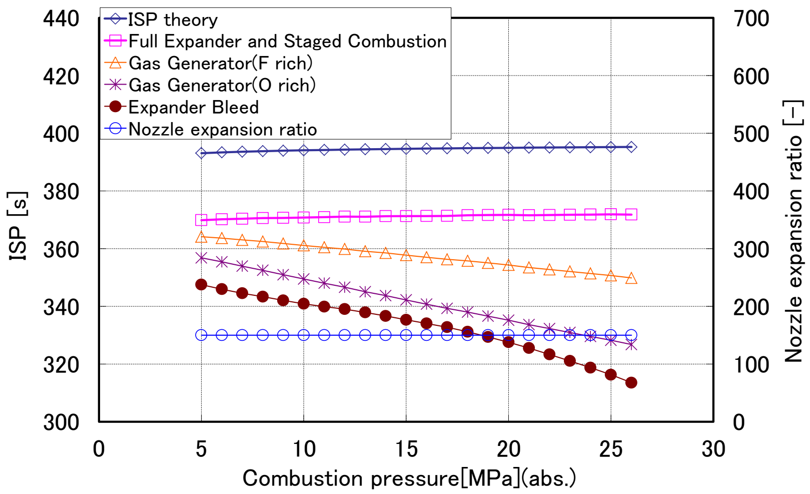


Figure 2. Isp for each engine cycle of LOX/Methane engine

The engine cycle analysis and optimization are performed for each engine cycle and thrust of 30kN, 100kN, 2000kN, and engine components operating pressure and temperature are obtained to achieve the target engine Isp. The combustion pressure comparison between calculated target and experience are shown in Figure 3 and the regenerative cooling path inlet/outlet pressure and temperature comparison between calculated target and experience are shown in Figure 4. The target area of combustion pressure is increased from 5MPa to 8-10MPa. The target area of regenerative cooling pressure is increased from 5-8MPa to 18-21MPa, and target area of regenerative cooling outlet temperature is increased from 300K to 500K. Since the operating condition for each component has not been experienced for the previous LOX/Methane Engine, the investigation by element tests were considered.

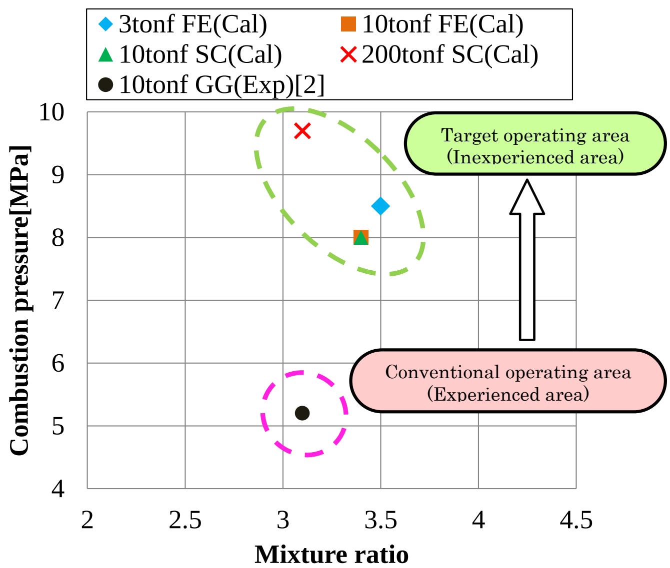


Figure 3. Target Operating Condition of Combustion Chamber

DOI: 10.13009/EUCASS2017-381

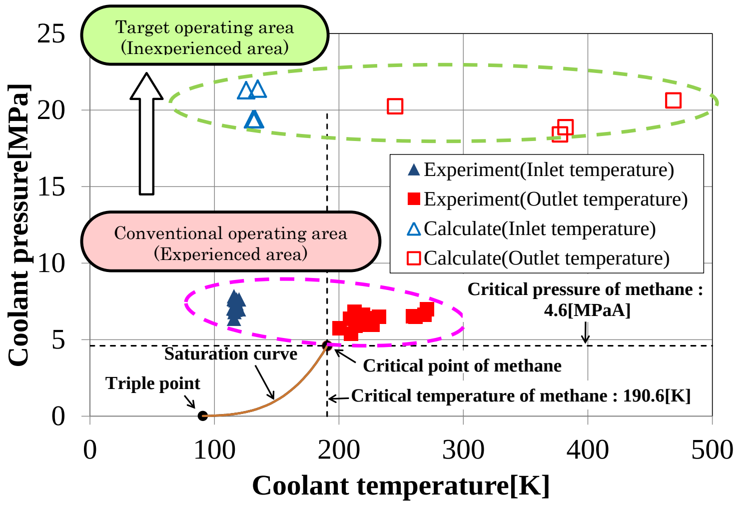


Figure 4. Target Operating Condition of Regenerative Cooling

3. Element Tests

To obtain the perspective on high performance, the element tests have been conducted for the following two objectives till 2015. One is to validate the analysis assumptions such as heat transfer and combustion efficiency, which will be used to engine cycle analysis. The other is physical characteristics such as combustion instability, ignition characteristics, soot generation, which are not shown in the engine cycle analysis. In the above standpoint, the heat transfer test and the single injector element test have been performed. The operating conditions of main engine components were obtained from the engine cycle optimum analysis in the thrust range of 30kN to 2000kN. The element tests were performed for the similar these operating conditions.

DOI: 10.13009/EUCASS2017-381

3.1 Regenerative Cooling Heat Transfer Test

The regenerative cooling heat transfer test was conducted in 2014 at JAXA Kakuda Space Center [10]. The configuration of regenerative cooling heat transfer test is shown in Figure 5. The liquid methane and gas methane were flown into the pipe heated by Joule heat, and heat transfer was obtained from the temperature of fluid and heating pipe wall.

The comparison of Nu number between Dittus-Boelter eq. and test correlated are shown in Figure 6(1). To use the Nu number correlated based on the heat transfer test results, the accuracy of heat transfer prediction was improved. The Nu number evaluated from bended tube test result is shown in Figure 6(2). The Nu number in outer side is larger than that in inner side caused by centrifugal effectiveness. Then the test result was reflected to the engine cycle analysis.

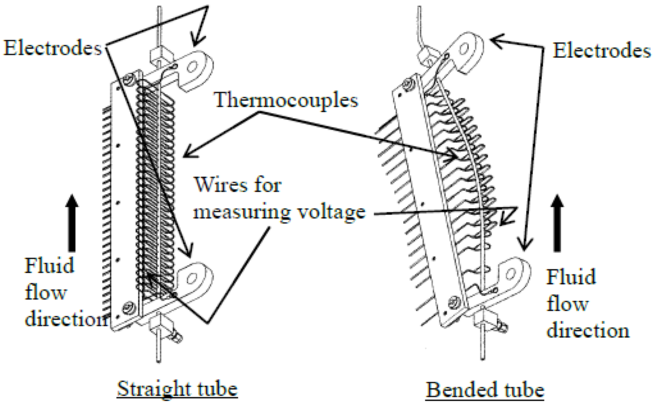
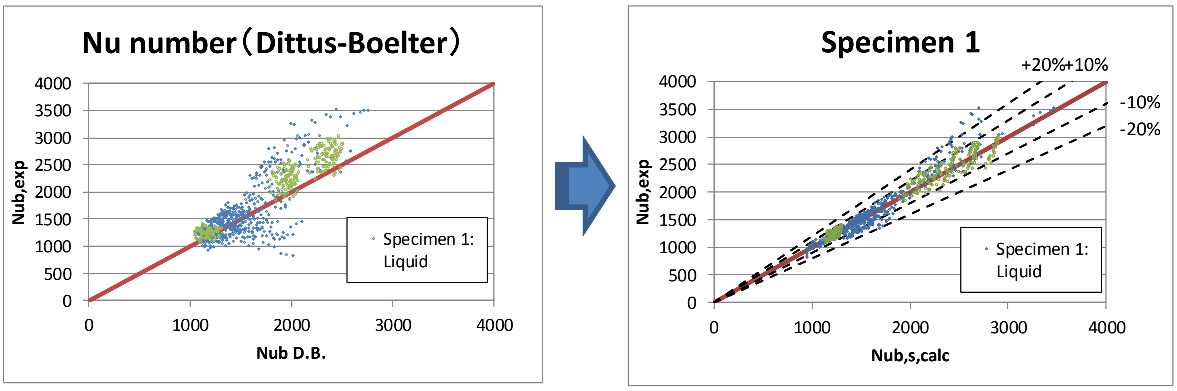
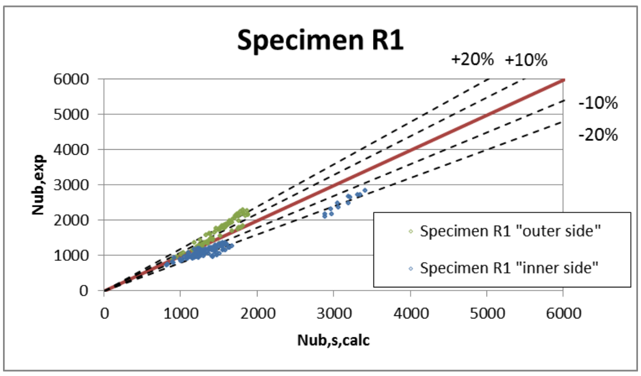


Figure 5. Regenerative Cooling Heat Transfer Test Configuration



(1) Nu number comparison between Dittus-Boelter and test evaluation



(2) Nu number obtained from Bended Tube Test

Figure 6. Regenerative Cooling Heat Transfer Test Result

DOI: 10.13009/EUCASS2017-381

3.2 Single Injector Element Firing Test

The single injector element firing test was performed at IHI aerospace Aioi Rocket Engine Test Center in 2014 [11]. The single injector element configuration is shown in Figure 7. The combustion efficiency was obtained using Cu heat sink combustion chamber, and OH radical and LOX shadow graph were obtained using visualization chamber to correlate the CFD analysis.

The combustion efficiency was obtained for the several types of injector element as shown in Figure 8(1). The c* efficiency for conventional co-axial element with small chamfer angle and central body co-axial element are much better than that of other elements. The elements which was expected to achieve the Isp of 370sec were chosen. The performance of these elements will be confirmed in the multi element test.

The Shadow Image and CH Radical Image for type 2 and type 13 are shown in Figure 8(2). The ended area of LOX sharp boundary in shadow image is matched with start of wide reaction area in CH radical. The The continuous LOX boundary share layer are observed than that of others.

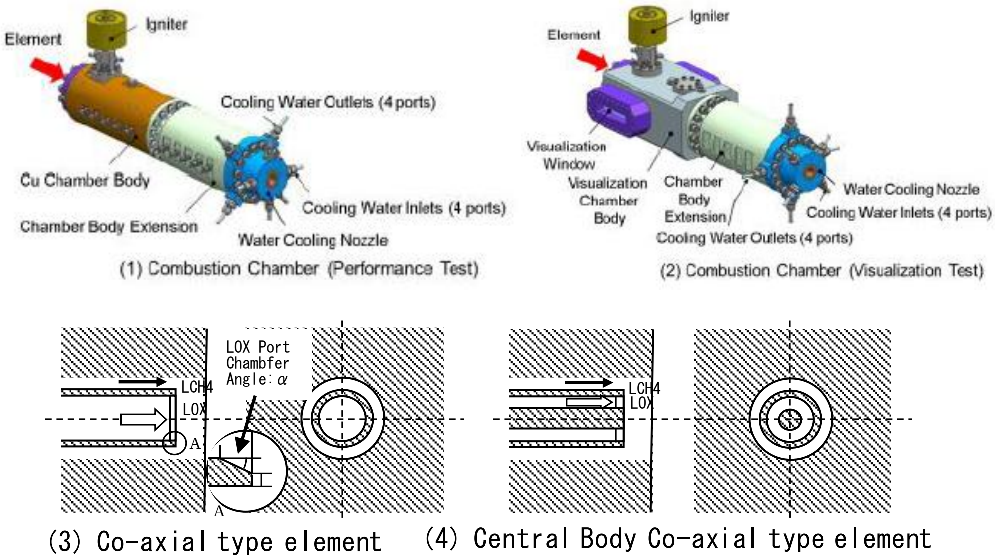


Figure 7. Single Injector Element Firing Test Configuration

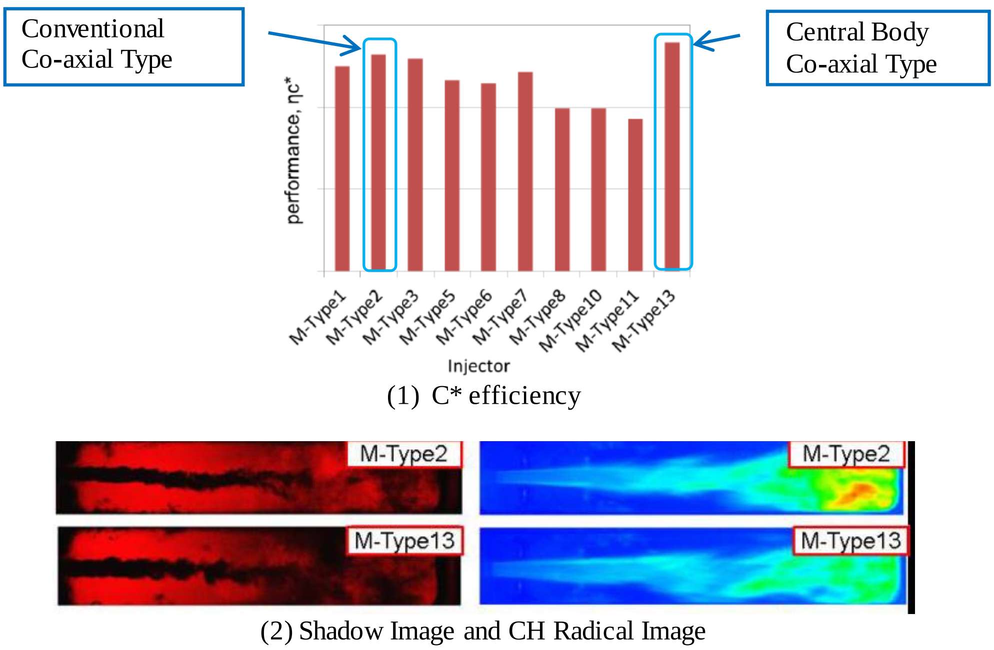


Figure 8. Single Injector Element Firing Test Result

DOI: 10.13009/EUCASS2017-381

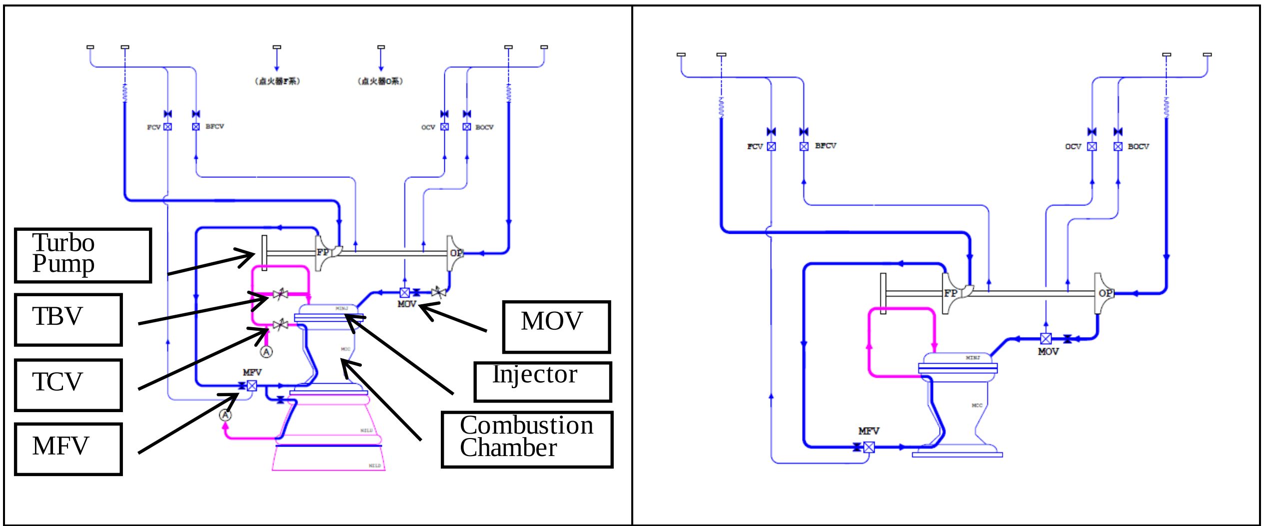
4. Reference Engine

The reference engine was designed to obtain the engine system performance in the sub-scale engine test. The specifications of reference engine are shown in the Table 2. The thrust of 30kN is selected to the reference engine for sub-scale firing test to expect to be applied to any small precursor missions such as reusable vehicle, planet lander, and orbital transfer vehicle. The full expander cycle and Pc 4.7MPa is selected to achieve the higher performance of Isp 370sec. The continuous throttling function is also added to be able to meet the engine thrust throttling requirement from any precursor application.

The engine system diagram with nozzle extension is shown in Figure 9 (1) and the engine system diagram without nozzle extension is shown in Figure 9(2). The propellants are supplied by single shaft turbopump and controlled by four electrical valves. The main fuel valve (MOV) and main oxidizer valve (MOV) used for open/closed the propellants line. MOV is also used for mixture ratio control. The thrust control valve (TCV) is used for regenerative coolant pressure control. The turbine bypass valve (TBV) is used for thrust control during throttling. Thrust Chamber Assembly consist of Co-axial Injector and Regenerative cooling Combustion Chamber. Nozzle consist of Regenerative Cooling Nozzle and Radiative Nozzle.

Table 2. Reference Engine Specification

Item	Specification
Thrust(Vacuum)	30[kN]
Isp	370[sec]
Engine Cycle	Full Expander Cycle
Propellant	LOX/Methane
Pc	4.7[MPa]
MR	3.3[-]
Throttling	50 to 100 % (Continuous)



(1) Engine System Diagram with Nozzle Extension | (2) Engine System Diagram without Nozzle Extension

Figure 9. Reference Engine System Diagram

DOI: 10.13009/EUCASS2017-381

5. Main Engine Components

The full expander cycle reference engine consists of a co-axial element injector, a regenerative cooling combustion chamber, a single-shaft turbo pump, and electrical valves, etc.

The injector and the combustion chamber inner part are shown in Figure 10. Three types of injector head are prepared for the multi injector element firing test. Two of them have different number of same type co-axial element, which was achieved highest performance in the single injector element firing test. The other has different type of center body co-axial element.

Two types of regenerative cooling combustion chamber are prepared for the regenerative cooling test. It is designed by the design tool which is correlated based on the test results of regenerative cooling heat transfer test as mentioned in Section 3. One of the combustion chamber is manufactured by electroforming and the other is manufactured by additive manufacturing.

The electrical valves and Single Shaft Turbo Pump are shown in Figure 11. Two types of electrical valves are designed to meet the continuous throttling characteristics. MFV, MOV, TCV have the function of both shut-off and mass flow control. TBV has the only function of mass flow control. TBV is mainly used mass flow control of engine throttling.

The small single-shaft turbo pump is designed to make stable throttling characteristics. The single-shaft turbo pump will be able to prevent significant change in mixture ratio during engine throttling. The similar volume flow rate and temperature of LOX/Methane propellant combination will be able to achieve the single-shaft turbo pump.

Figure 10. Injector and Combustion Chamber Inner Part

Figure 11. Electrical Valve (MOV/TBV) and Single Shaft Turbo Pump

DOI: 10.13009/EUCASS2017-381

6. Sub-scale firing test

To evaluate the LOX/Methane engine performance by steps, the sub-scale firing tests are planned to be conducted in engine-like configuration from this October at IHI Aerospace Aioi Rocket Engine Test Center. As shown in Table 3, the three steps of the multielement test, regenerative cooling test, and engine system test are planned. Then the technological improvement of the design and analysis will be expected to correlate the analysis tool based on those test result.

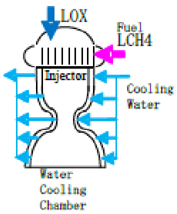
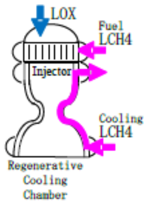
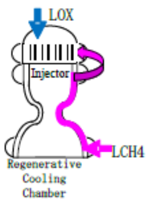
In the first step, the multi element tests will be performed to obtained injector combustion characteristics. The three types of multi element injectors are designed for multi element test.

Two of them have different number of elements and type of element is same, which was showed higher combustion efficiency in the single injector element firing test as mentioned in Section 3. The other injector has a different type of central body co-axial element. The combustion efficiency, combustion instability, and heat flux will be obtained using the water cooled combustion chamber in the multi element test. The combustion efficiency and instability for throttling condition will also be evaluated. After the test, CFD will be performed to correlated the test result and to evaluate the multi element effect.

In the second step, the regenerative cooling test will be conducted to obtain regenerative cooling heat transfer characteristics. It is designed by design tool that is improved by the heat transfer element test results as shown in Section 3. The regenerative cooling chamber is assembled with higher performance multi element injector which is selected in multielement test. The injector fuel is supplied from different root from regenerative cooling fuel. The wide range of regenerative cooling heat transfer and pressure drop characteristics are obtained to change the flowrate and pressure between injector and regenerative cooling independently. The effects for decreasing of mass flow rate and pressure due to throttling will also be evaluated.

In the third step, the engine system test will be conducted to obtain engine performance in the engine configuration of full expander cycle. The multi element injector and regenerative cooling combustion chamber which are used in step1,2, and electrical valve and single-shaft turbo pump mentioned in Section 5 are assembled in engine system test configuration. The engine cycle performance, operating range, and Thrust Vector Control (TVC) operation characteristics are evaluated. The thrust throttling characteristics which is required from precursor mission are also obtained in step3.

Table 3. Sub-scale test steps and configurations

Step	STEP1	STEP2	STEP3
Objective	Multi Element Test	Regenerative Cooling Test	Engine System Test
Test Engine Schematic			
Test Engine Configuration	Water Cooling Chamber 	Regenerative Cooling Chamber 	Engine Assembly 
Test Case	Multi Element Injector a.Co-Axial (large) b.Co-Axial (small) c.Center Body	Regenerative Cooling Chamber a.Electrical Forming b.3D Printing	Multi Element Injector + Regenerative Cooling Chamber
Evaluation	Element Combustion -Efficiency -Instability -Heat flux Profile	Regenerative Cooling -Heat Transfer -Pressure Drop	Engine Cycle -Performance -Operating Range -TVC Operation -Throttling Effect

DOI: 10.13009/EUCASS2017-381

7. Firing test configuration

The STEP1 multi element test configuration is shown in Figure 12. The multi element injector is assembled with water cooled combustion chamber. The propellants of LOX and Methane are supplied by turbopump.
The STEP3 engine system test configuration is shown in Figure 13. The multi element injector and regenerative combustion chamber, which characteristics are obtained in STEP1 and STEP2, are used in STEP3. The electrical valves are used to control the engine and the single shaft turbopump is used to supply the propellants. The TVC actuators are also assembled to confirm the gimbal characteristics.

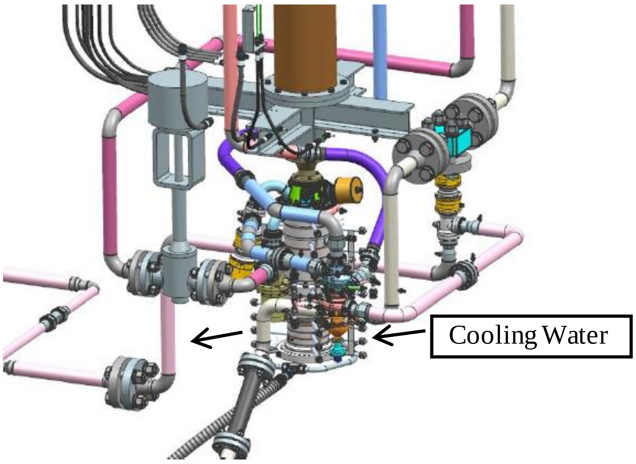


Figure 12. STEP1 Multi Element Test Configuration

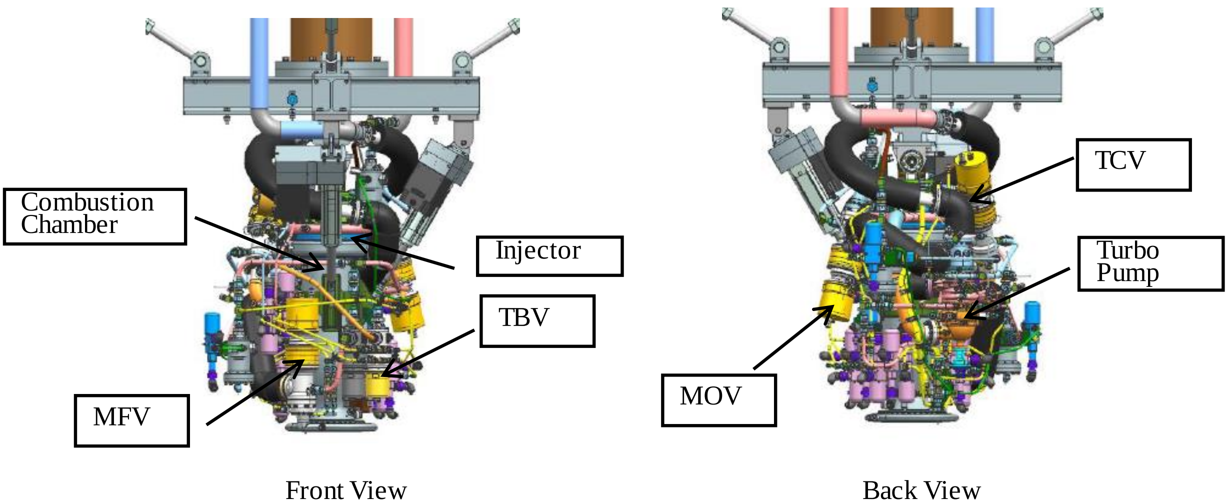


Figure 13. SETP3 Engine System Test Configuration

DOI: 10.13009/EUCASS2017-381

8. Status and Future Vision of LOX/Methane Engine Resarch

The status and future vison of LOX/Methane engine research is shown in Figure 14. The research of LOX/Methane Regenerative Cooling Rocket Engine has been conducted since 2013. The basic study of elementary test such as heat transfer test and single injector element firing test have been performed till 2016. The test article of subscale firing test has been prepared from 2016 and subscale firing test is planned to be performed this year. The engine which is designed based on these test results will be expected to be the flight technology demonstration and the practical use.

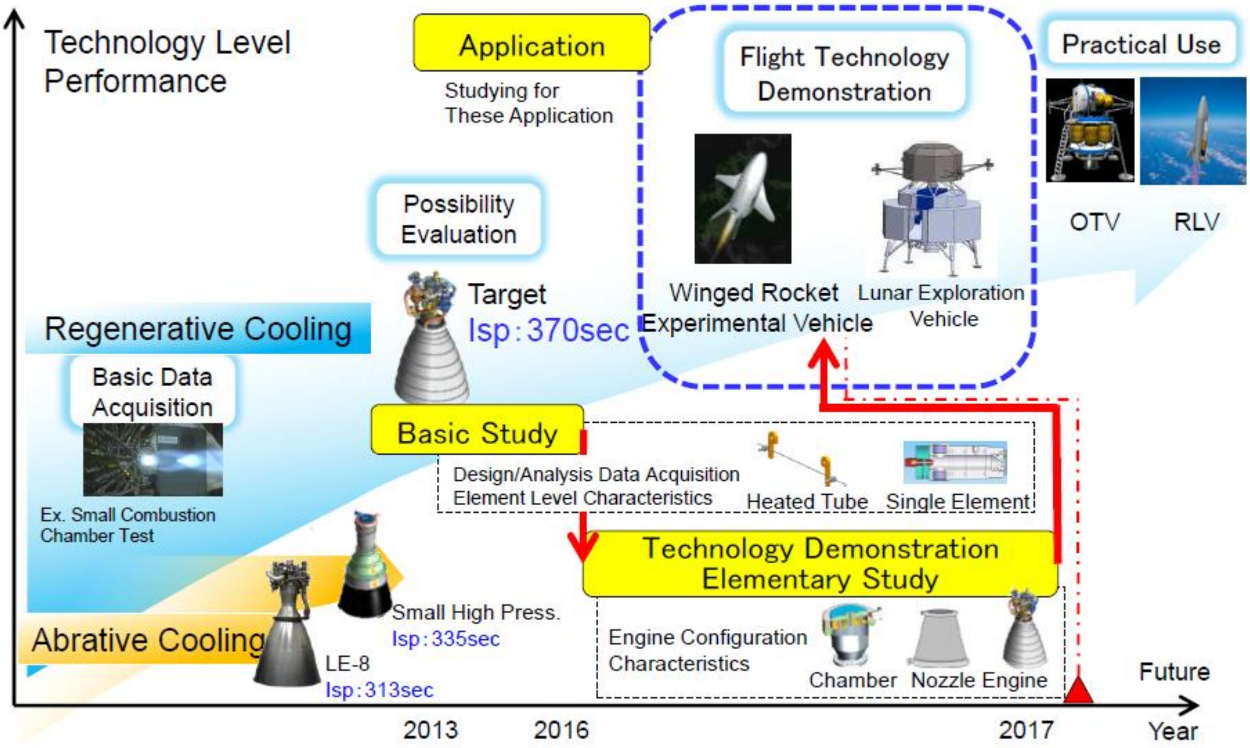


Figure 14 Status and Future Vision of LOX/Methane Engine Research

9. Conclusion

The research and development status of high performance LOX/Methane regenerative engine is shown in this paper. The 30kN full expander cycle reference engine is designed to be expected to apply future small precursor mission. The engine components are designed based on the result of element test such as regenerative heat transfer test and injector single element test.

The sub-scale firing tests which consist of multi element test, regenerative cooling test, engine system test are planned to be conducted in JFY2017 to evaluated the Isp 370 sec engine performance.

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