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Component tests of a LOX/methane full-expander cycle rocket engine: Injector and regeneratively cooled combustion chamber

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Abstract

JAXA and IHI have been conducting research to develop a high performance methane rocket engine such as specific impulse (Isp) of 370 secs, and a multi-element injector and a regeneratively cooled combustion chamber were designed. This study conducts firing tests to verify these components. As the results, multi-element injector shows characteristic velocity efficiency high enough to satisfy the target Isp. Then, the heat transfer characteristics of the combustor wall and regenerative cooling are obtained. Through these component tests, we successfully demonstrate the performance of the components and confirm the feasibility of the high performance methane engine.

1. Introduction

Research and development of liquid oxygen (LOX)/methane rocket engines has been expanding, since there are a few advantages of methane as rocket propellant over hydrogen. For example, liquid methane (LCH4) can be stored at similar temperature as LOX, so that a thermal insulator can be simplified, and an evaporation rate of the fuel can be reduced. Also, LCH4 is denser than liquid hydrogen (LH2) so that a propellant tank can be smaller and lighter. Moreover, methane is inexpensive. Therefore, methane could be a good candidate for a next generation rocket engine propellant suitable for a variety of applications such as a reusable booster engine and a deep space transport [1]. On the other hand, LOX/methane engine is not able to produce high specific impulse (Isp) compared to LH2. There are several activities to regarding methane engine research and development conducted by national agencies such as LUMEN [2], VEGA-E [3] and Prometheus [4]. Also, there are various rocket engine developed by private companies such as Raptor by Space X and BE-4 by Blue origin.

In Japan, an LNG rocket engine with a thrust of 107 kN called LE-8 were developed, and research activities to develop high Isp methane engine have been continued. In 2014, a parametric study [5] set a reference engine system to be competitive among the other methane engines as shown in Fig. 1, and target performance of the reference engine is determined such that thrust as 30 kN, Isp as 370 secs and mixture ratio (MR) as 3.3 (Table 1). In order to obtain high Isp, a full expander cycle has been chosen, as a schematic of the engine cycle is shown in Fig. 2. Then, various element tests such as single-element injector tests [6] and regenerative cooling heat transfer test [7] have been conducted to establish database to realize the reference engine.

Utilizing the results obtained by the past research activities, major components of the reference engine were designed and manufactured in order to validate performance of the components and verify feasibility of the reference engine system. The selected components are a multi-element injector, a regeneratively cooled combustion chamber, a single-shaft LOX/methane turbopump and four electrically actuated valves, that are a thrust control valve (TCV), a thrust bypass valve (TBV), a main fuel valve (MFV) and a main oxidizer valve (MOV) Test campaigns of the electrically actuated valve and the LOX/methane turbopump have been conducted, and results are presented in elsewhere [8,9]. This paper focuses on the validation of the remaining components; the multi-element injector and the regeneratively cooled combustion chamber.

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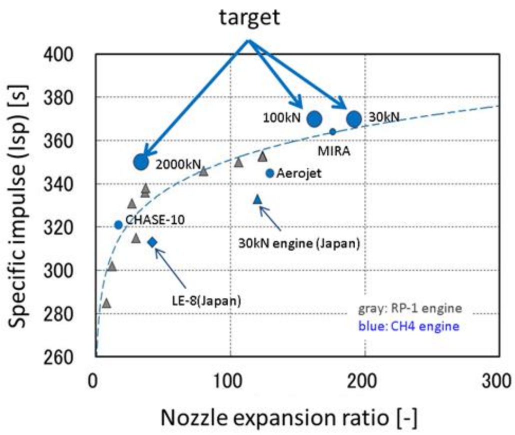

Figure 1. Isp of hydrocarbon rocket engine [5]

Table 1. Reference Engine Specification [5]

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)

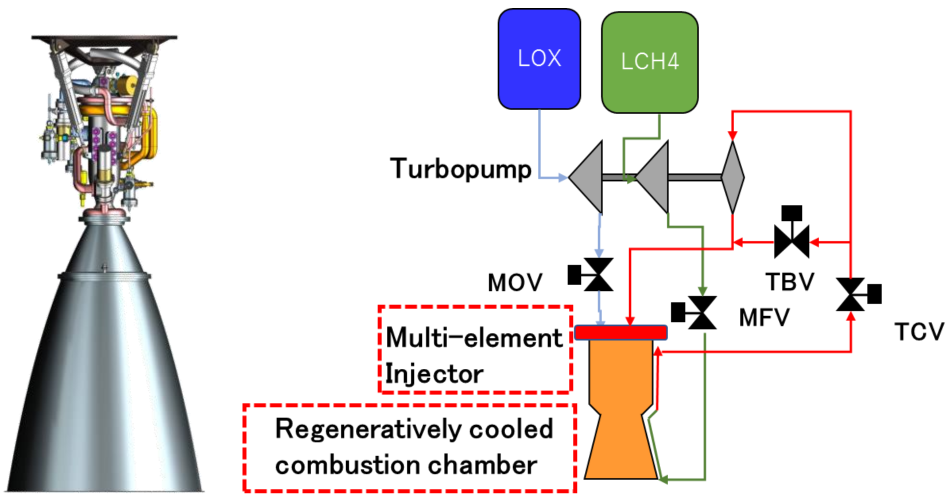

Figure 2. Schematic of the reference engine (left) and an engine cycle of the reference engine (right). Blue, green and red lines indicate LOX, LCH4 and GCH4 respectively. Components in red dashed boxes are scopes of this paper.

2. Experimental Setups

As discussed in the previous section, the performance of the multi-element injector and the regeneratively cooling chamber is validated by conducting firing tests at Aioi test site owned by IHI. This section describes the components and the experimental setups.

2.1 Experimental configurations of the multi-element injector

The multi-element injector is designed to have 36 co-axial LOX/GCH4 elements as shown in Fig. 3. The shape of the co-axial element is same as m-type2 that showed the best characteristic velocity (C*) efficiency in the past study [6].

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A porous plate manufactured by additive manufacturing is installed as a faceplate to enhance transpiration cooling and avoid damage of the injector. Also, a water cooled calorimetric chamber with 16 annular cooling channels is attached to obtain the heat flux profile in axial direction as shown in Fig. 4.

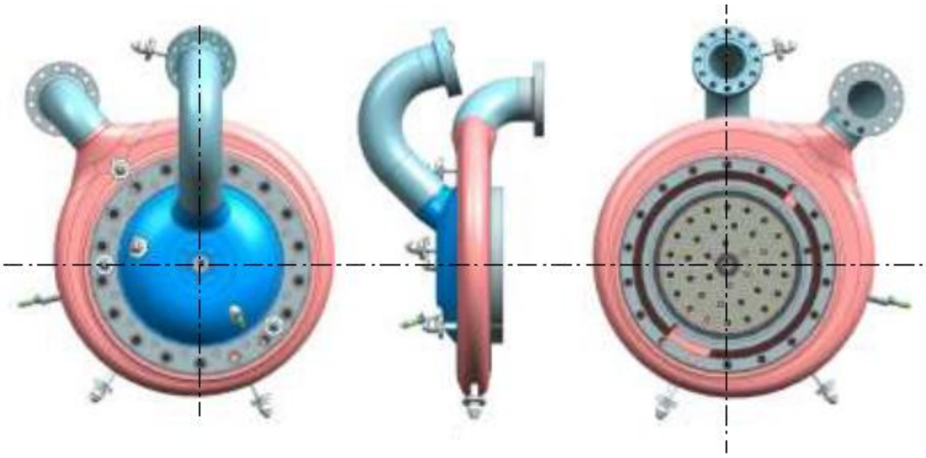

Figure 3. Schematic of the multi-element injector.

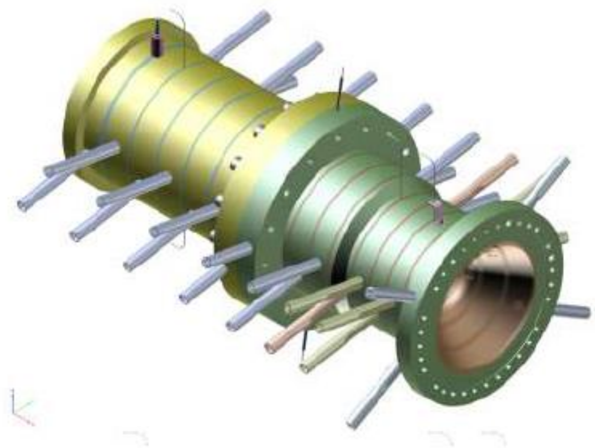

Figure 4. Schematic of the water cooled calorimetric chamber

Even though the reference engine is the full expander cycle, multi-element injector firing tests are conducted in simplified open configuration as shown in Fig. 5. The turbopump pressurize LOX and LCH4, and the turbine is driven by gas methane (GCH4) provided from a high pressure GCH4 tank. LOX is led to the injector and burned with the GCH4 provided also by the GCH4 tank. LCH4 pressurized by the turbopump is simply sent to a vent stack. Cooling water is pressurized by a water pump up to 4 MPa to avoid evaporation within the cooling channels. NV900G, MFV2 and MFCOV are valves attached on the test facility and used instead of engine valves to control an engine sequence. An actual experimental configuration at the test stand is shown in Fig. 6.

DOI: 10.13009/EUCASS2019-223

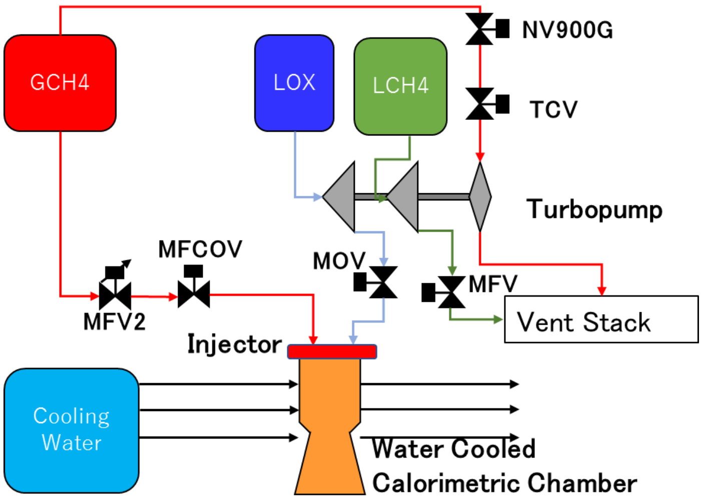

Figure 5. Flow diagram of the multi-element injector firing test. Red, blue, green and black lines indicate GCH4, LOX, LCH4 and cooling water, respectively.

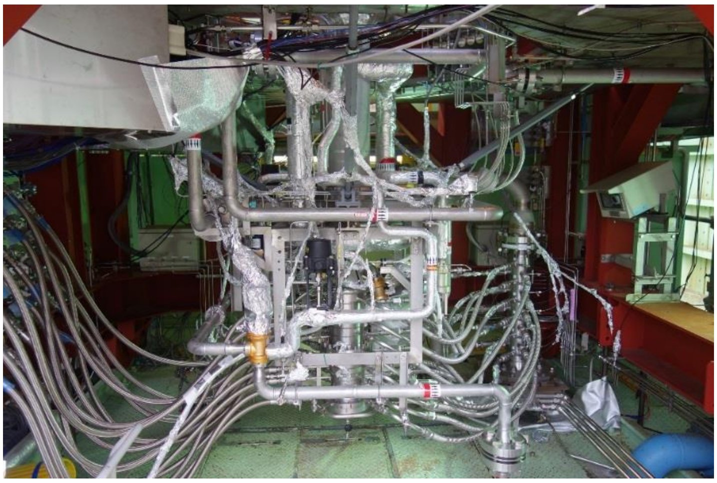

Figure 6. Experimental configuration of the water-cooled calorimetric chamber

2.2 Experimental configurations of the regeneratively cooled combustion chamber

The second series of the firing tests is carried out with the same injector and the regeneratively cooled combustion chamber with cooling channels in an axial direction. An amount of heat gain and pressure loss of methane is measured under different test conditions. A schematic of the regeneratively cooled combustion chamber is shown in Fig. 7. LCH4 pressurized by the turbopump is sent to the coolant inlet manifold, obtain heat within the cooling channels, exhausted from the coolant outlet manifold.

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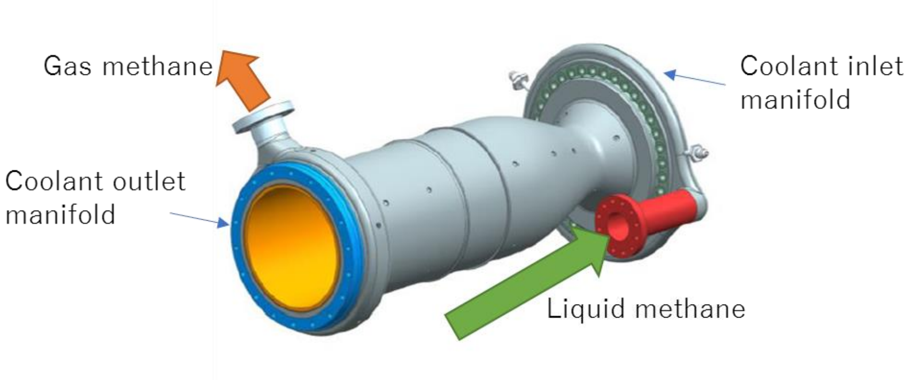

Figure 7. Schematics of a regeneratively cooled combustion chamber

Figure 8 shows a flow diagram of an experimental configuration of the regeneratively cooled combustion chamber. Overall, the configuration is similar to the multi-element injector firing test, but the difference is that the LCH4 pressurized by the turbopump is sent to the cooling channel of the combustion chamber, and then methane is sent to the vent stack. With such the open configuration, it is possible to control the amount of coolant independently from the fuel injected to the combustion chamber, whereas they are essentially identical if a close engine cycle as in Fig. 2 is applied. A snapshot of a firing test is shown in Fig. 9. As a typical methane engine, a blue exhaust plume is clearly observed.

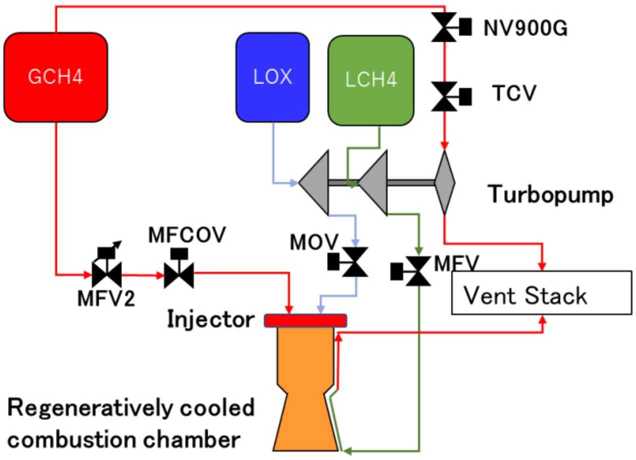

Figure 8. Flow diagram of the regeneratively cooled chamber. Red, blue and green lines indicate GCH4, LOX and LCH4, respectively.

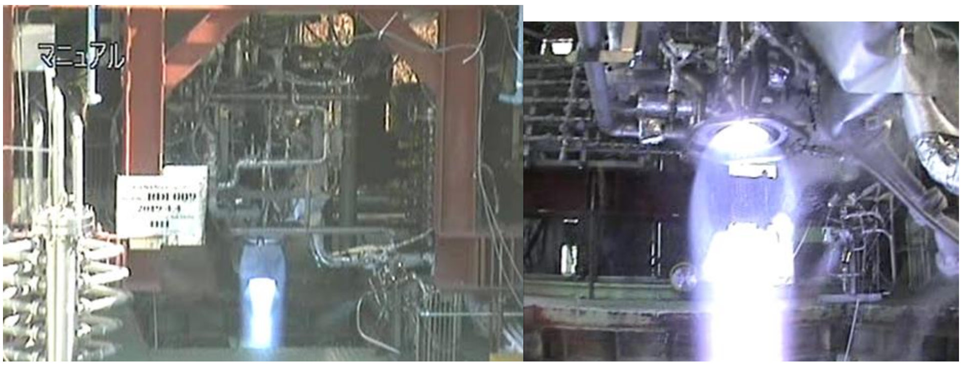

Figure 9. Front view (left) and bottom view(right) of the regeneratively cooled combustion chamber firing test.

DOI: 10.13009/EUCASS2019-223

3. Experimental results

3.1 Results of the multi-element injector firing test

Five firing tests with accumulated burning time of 111 secs are performed, and operating points are indicated by combustor pressure and mixture ratio (MR) as shown in Fig. 10 and Table 2. In order to validate the capabilities of multi-element injector, a wide range of combustion pressure are tested.

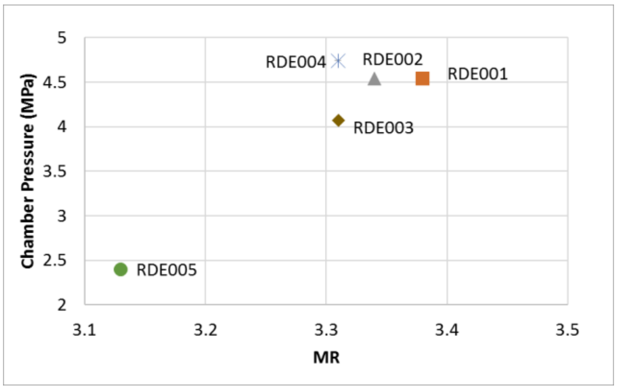

Figure 10. Operating points of the injector firing tests

Table. 2 List of the operating points of the injectors firing tests

Test Number	**Chamber Pressure [MPa]**	Mixture Ratio **[-]**
RDE001	4.54	3.38
RDE002	3.02	3.34
RDE003	4.07	3.31
RDE004	4.74	3.31
RDE005	2.40	3.13

The test results show high C* efficiency equivalent to Isp of 370 secs is successfully obtained at the desired operating point of the reference engine at RDE004. Since GCH4 is provided by the pressure tank as in Fig. 5, the temperature of burned GCH4 is around ambient temperature or lower. However, within the reference engine cycle, GCH4 temperature is higher due to regenerative cooling, and also the injection velocity of GCH4 become larger, so that C* efficiency is expected to be improved [10]. Thus, the target (Isp of 370 secs) set as high performance engine is likely to be achieved for the reference engine configurations.

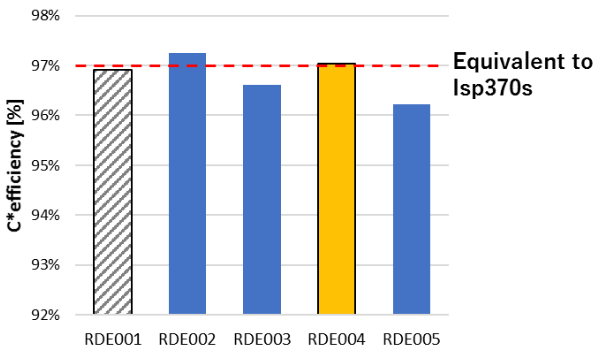

Figure 11. C* efficiency of the multi-element injector test. C* efficiency is reached targeted value at a desired operating point (RDE004). C* efficiency of RDE001 is temporal since it is a short firing test.

Also, combustion stabilities of the multi-element injector are examined. Strong pressure fluctuations are not observed in all five firing tests. For example, Figure 12 shows the pressure fluctuations of the highest (RDE004) and the lowest (RDE005) chamber pressure. Even though a few peaks can be seen close to 2T mode, an order of the fluctuation is less than 0.01MPa and not significant.

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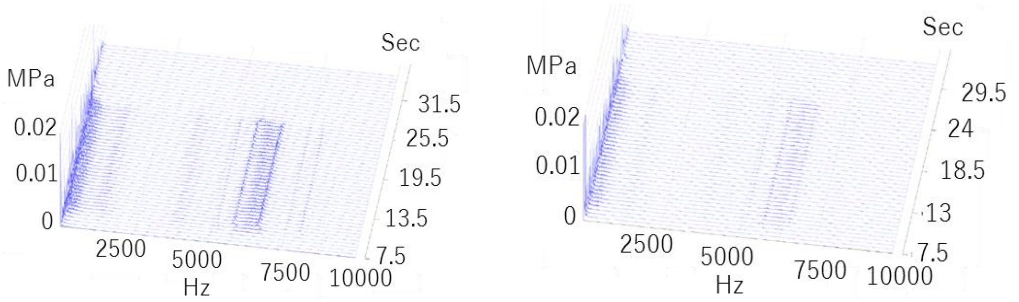

Figure 12. Water fall plots of pressure fluctuations at the highest (left: RDE004) and the lowest (right: RDE005) chamber pressure

Heat flux profiles are measured by the water cooled calorimetric chamber as shown in Fig. 13. The horizontal axis is the axial location of the relative throat position, and the vertical axis is the normalized heat flux. As typically seen, the maximum heat flux is observed around the throat. The heat flux at the vicinity of the injector is relatively small due to the transpiration cooling from the porous faceplate. By obtaining heat flux profiles with different operating points, it is possible to improve our heat flux prediction model applied to determine the heat gain in the regeneratively cooled combustion chamber.

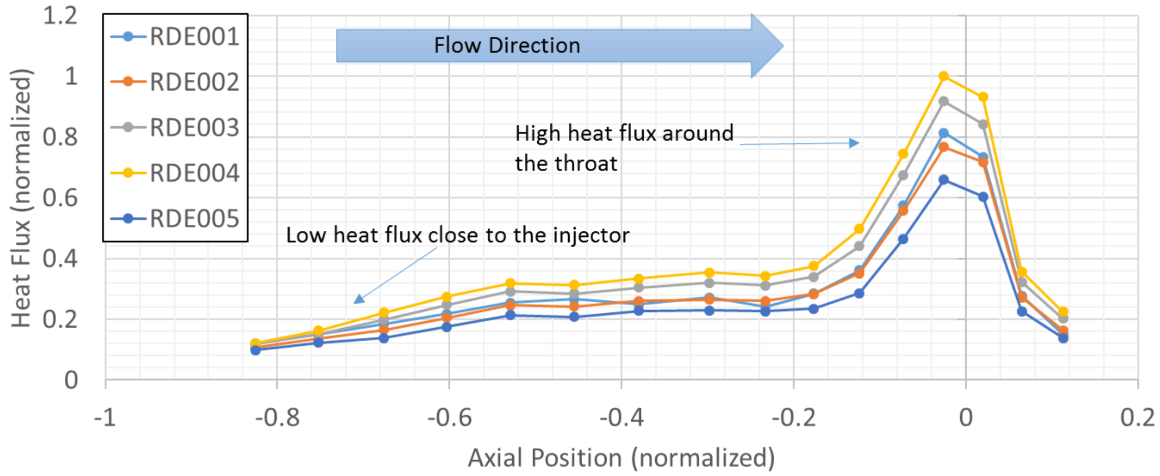

Figure 13. Axial heat flux distributions with different test cases. The vertical axis is normalized by the maximum heat flux measured, and the axial position is normalized by the total length of the water cooled calorimetric chamber, and the throat position is set at zero.

3.2 Results of the regeneratively cooled combustion chamber tests

Four firing tests with accumulated firing time of 102 secs of the regeneratively cooled combustion chamber are conducted as listed in Table 3, and the operating points are shown in Fig. 14. Before the experiments, the maximum acceptable temperature of the outer surface of the combustion chamber is determined in order to avoid critical damage. The first test case, RDE006, is set to have high ratio of coolant methane mass flow to burned methane mass flow (Qc/Qb) to prevent a damage on combustion chamber. By accumulating data on the combustion chamber, heat transfer models of the coolant are improved. Finally, the temperature profile of combustion chamber can be predicted precisely as shown in Fig. 15, and it is able to conduct the firing test with Qc/Qb=1.0 without exceeding the temperature limit. Thus, the regeneratively cooled combustion chamber is shown to be operative with the full-expander cycle. Even though the highest heat flux is seen around the nozzle throat, the highest wall temperature is observed at the parallel section upstream of the throat. The reason is that because the direction of the coolant is up-path and the coolant temperature at the throat is still low.

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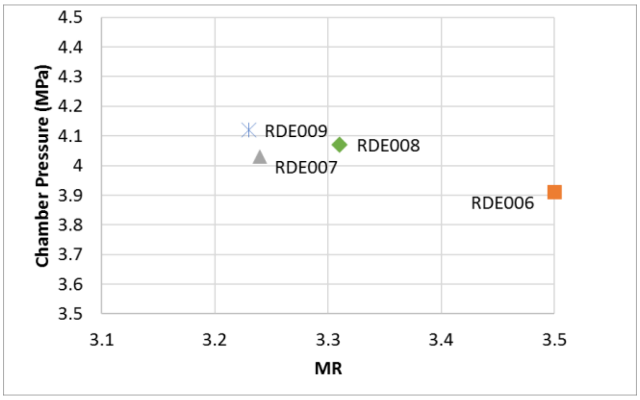

Figure 14. Operating points of the regeneratively cooled combustion chamber test

Table 3. List of the operation points of the regeneratively cooled combustion chamber

Test Number	Chamber Pressure[MPa]	Mixture Ratio[-]	Mass flow ratio of coolant/burned methane (Qc/Qb)
RDE006	3.91	3.5	1.27
RDE007	4.03	3.24	1.14
RDE008	4.07	3.31	1.17
RDE009	4.12	3.23	1.0

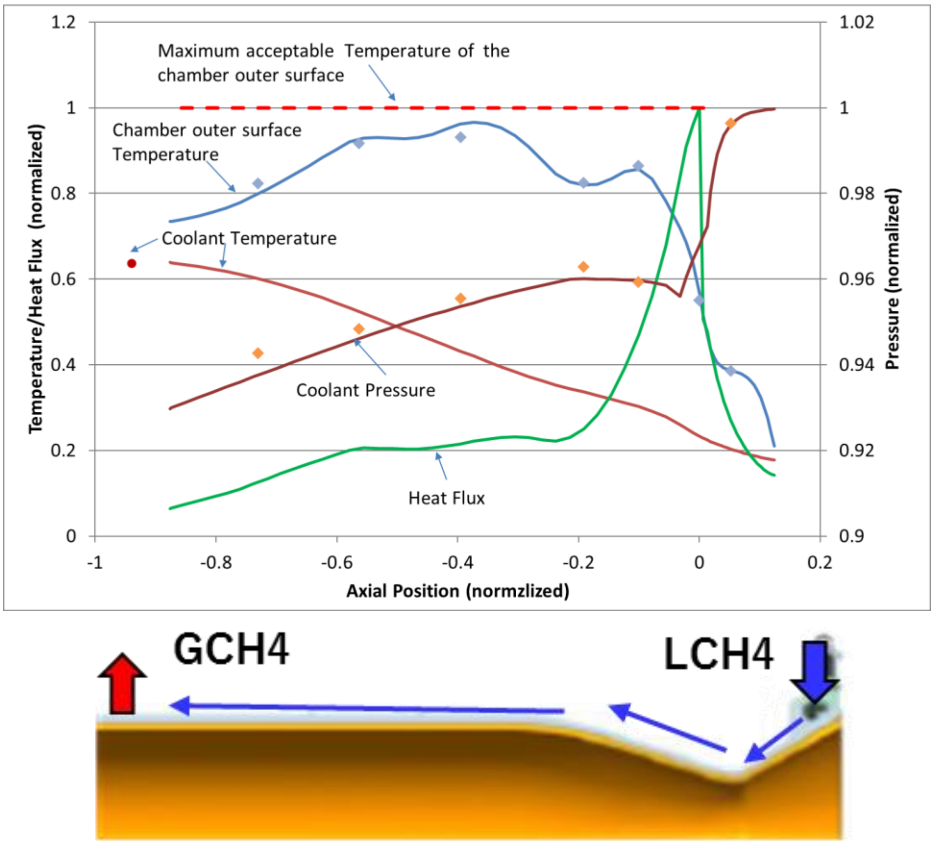

Figure 15. Temperature, heat flux and pressure profiles of the regeneratively cooled combustion chamber of RDE009. Solid lines are predicted profiles, and dots are measured quantities in the experiment. Temperature is normalized by the maximum acceptable temperature of outer surface of the chamber, and the pressure is normalized by the coolant pressure at the inlet manifold. Heat flux is normalized by the maximum heat flux.

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4. Conclusion

In order to achieve a high-performance LNG engine with Isp 370 secs, JAXA and IHI have established the research plan and conducted element studies as described in the past work [5,6,7]. Based on the database established, the major components of the reference engine were designed and manufactured, and component test are conducted in this study. The multi-element injector shows the high C* efficiency that is equivalent to Isp of 370 secs as an engine system. Also, the heat flux profiles with different combustion pressure are obtained by the calorimetric chamber. Also, no strong combustion instability is observed. The characteristics of the regenerative cooling is obtained, and the temperature of the combustor wall can be precisely predicted to avoid the temperature limit, and the combustion chamber is verified to be operative for the closed cycle. As a result, JAXA and IHI demonstrate the performance of the major components and successfully verify feasibility of the high performance methane engine along with corresponding paper [8,9]. For future work, we plan to connect all components as a full expander cycle and run firing tests to demonstrate the engine system.

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