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Component tests of a LOX/methane full-expander cycle rocket engine: Electrically actuated valve

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Abstract
This paper describes the design and the experimental result of the cryogenic propellant valves which are actuated by the electric motor. Through three years of a development term, the valve experienced several elemental tests to investigate its characteristics, and it was modified as required. In order to validate valve function, demonstration flow tests were carried out. As a result, the valve could be demonstrated its function under high pressure. Then, the valve was applied to the engine firing test series, and it was shown that the valve worked well under both ambient and cryogenic conditions during the firing test.

1. Introduction

In Japan, research and development have been conducted on a regenerative cooling LOX/methane rocket engine in order to achieve higher performance than so far demonstrated [1].
In 2016, based on a system study, many types of LOX/methane shear co-axial injectors for the main combustor were designed and then the firing tests of single injector element were performed under high pressure condition [2]. The test results showed that several promising candidates of injector element design had high performance expected [3].
In 2018, Multi-element firing tests were conducted with the selected element designs for the purpose of confirming the performance. The cofiguration of the firing tests was engine-like test bench such as, the multi-element injector installed on a regenerative-cooled combustion chamber with propellant valves, and propellant supplied by a shingle-shaft LOX/methane turbopump, similar to the expander cycle engine of 30kN-class thrust [4-5].
Targeted engine requires thrust control or varying engine oeprating point (the mixture ratio and the combustion pressure) during engine firing operation. In order to realize those operations, cryogenic propellant valves which were actuated by electric motors were newly developed.
The valves have the function of propellant flow control as well as shut-off function. By equipping such valves, the engine can change the operating point easily during firing operation without replacing conventional trimming orifices. In addition, since the valves are actuated by the electric motor, the engine system does not need any pneumatic system for them, that means the engine system can become much simplified.
This paper describes the development and test of the prototype cryogenic propellant valves actuated by an electric motor which can be used as a flow control valve as well as a simple shut-off valve.

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2. Requirements for valves

2.1 Target engine

This research activity is carried out as part of the research of 30 kN-class LOX/methane full expander engine, in order to investigate feasibility of high performance methane engine. The vacuum Isp of the engine will be reached 370s with nozzle expansion ratio of 210.
The engine has function of continuous throttling anticipated to be adopt to future transportation system such like lunar lander. Engine throttling is conducted as following steps.

1) In order to control combustion pressure by increasing or decreasing turbine bypass flow rate, the turbine bypass valve (TBV) installed at turbine bypass line is operated.
2) In order to maintain coolant pressure above critical pressure, the thrust control valve (TCV) installed at outlet of regenerative cooling is operated.
3) In order to control mixture ratio in the combustion chamber, the oxidizer propellant valve (MOV) installed at main oxidizer line is operated .

Therefore, the engine need flow control valves in turbine bypass line, outlet of regenerative cooling and main oxidizer line in addition to shut-off valve in main oxidizer line and main fuel line. However, it is not preferred to install flow control valve and shut-off valve in same line (main oxidizer line) because it lead to increasing engine mass and complicating engine system. The purpose of this activity, then, was determind to develop of the valve with two functions that are flow control and shut-off function.
Based on the above, four valves shown in Fig.1 were planned to be developped. The requirement of functions of each valves are as follows.

MOV (1) Shut-off main oxidizer line
(2) Control flow rate of oxidizer
MFV (1) Shtuoff main fuel line
TCV (1) Control coolant pressure in regenerative cooling channel
TBV (1) Control turbine bypass flow rate

Table 1: Engine specification.

Item	Value
Thrust, vacuum	30 [kN]
Isp,vacuum	370(eps=210) [-]
Propellant	LOX/methane
Throttling	50 to 100 [%] (Continuous)

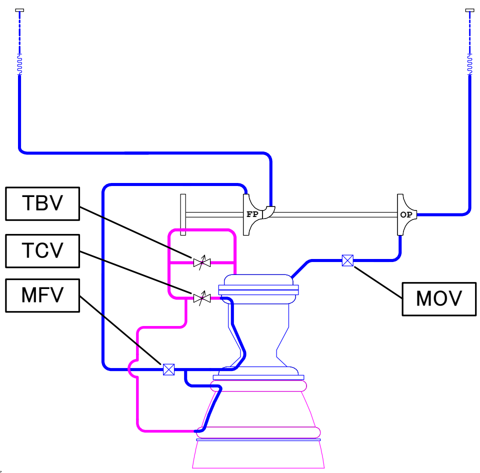

Figure 1: Engine system diagram with nozzle extension

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3. Valve development

3.1 Performance requirements

In accordance with aforementioned functional requirements and engine target, performance requirements of valves were determined as shown in Table 2. To develop the valves efficiently, common design was applied to MOV, MFV, and TCV, except for Cv value. TBV was designed separately, since TBV could be downsized than other valves due to smaller Cv requirement.

Table 2: Valve requirements.

	Operating pressure [MPaG]	Cv	Remarks
MOV/MFV	13	17.9	For shut-off and flow control
TCV	13	24	For flow control
TBV	13	2.5	For flow control

3.2 Valve design

Valve configuration is shown in Fig.2. The main features of the valve design are summarized as follows:

- Poppet type valve, which could control mass flow rate easily, was selected.
- Bellows was adopted for sealing the fluid firmly to meet the non-leak requirement.
- The actuator of the valve has unique system to generate high thrust, which consists of stepping motor, HarmonicDrive® speed reducer and 3D toggle[6-7].
- Stepping motor generates and transmits torque to HarmonicDrive®.
- HarmonicDrive® amplifies and transmits torque to 3D toggle.
- 3D toggle transduces torque to axial thrust and moves poppet stem.

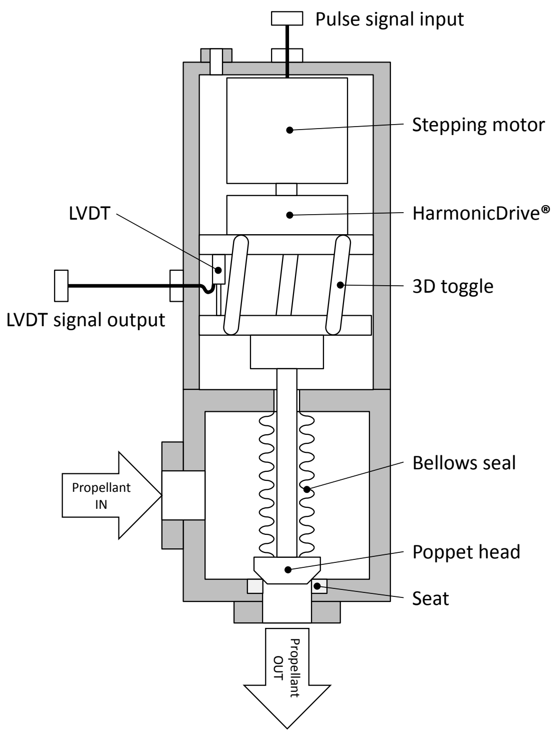

Figure 2: Valve configuration.

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Stepping motor

Stepping motor is a simple structure motor which is consisting of a coil and a permanent magnet. It is not required a brush for rectification of current such as used for DC motor, and also it does not need a hole sensor which is used for brushless DC motor. Therefore, the motor can actuate the valve with robustness in the operation since the motor does not have the components functionally sensitive to cryogenic condition.

HarmonicDrive® speed reducer

HarmonicDrive® was used for the valves as a speed reducer. HarmonicDrive® has backlash free and high accuracy positioning control characteristics, therefore it is appropriate for flow control valves. In addition, it can realize high reduction ratios with small sized and light weight, then the total valve size including motor can be downsized

Toggle

To transduce motor torque to thrust, 3D toggle was applied. In general, the size of the actuator of shut-off valve tends to be large as the shut-off power depends on the actuator size. To avoid that, the valve actuator was designed to generate bigger power at shut-off phase by adopting 3D toggle which consisted of the toggle structure as shown in Fig.3.

As shown in Fig.4, by adopting 3D toggle, the velocity of axial displacement is getting to zero, when the toggle arm is moving to close direction (upright) and approaching full close, and the motor torque can be transduced to thrust totally. Hence, axial thrust at valve close can be increased without increasing motor torque. For this, motor can be downsized and also electric power can be reduced.

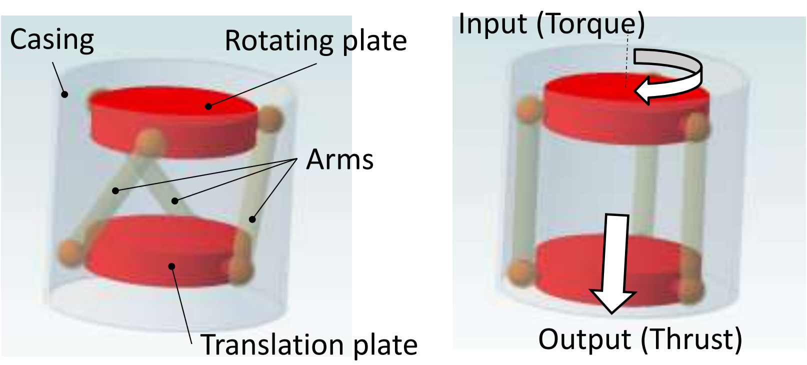

Figure 3: 3D toggle configuration.

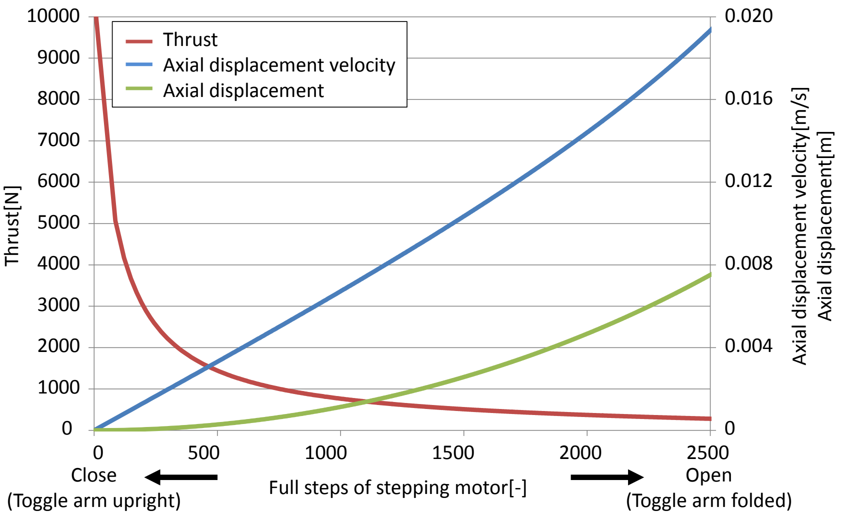

Figure 4: Thrust profile of 3D toggle (example).

Latch function

The valve has latching mechanism. When the 3D toggle arms pass over the top deadpoint of toggle arms, the valve is in latch condition, which makes the valve keep close condition by latch mechanism in case without electric power.

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Positioning sensor

To detect poppet head position, a linear variable differential transformer (LVDT) is installed to the actuator. In general, stepping motor uses the encoder as a positioning sensor, measuring the rotation of the motor. However, by using LVDT, poppet head position can be detected directly.

The design summary is shown in Table 3. The design optimization was done with IHI Total Design Management (IHI-TDM) [8]. IHI-TDM is an optimal design method including robustness.

Table 3: Design summary of MOV/MFV/TCV and TBV.

Item	MOV/MFV/TCV design result	TBV design result
Operating pressure	13[MPaG]	13[MPaG]
Leakage	Ambient : less than 1[sccm] Cryogenic : less than 60[sccm]	Ambient : less than 1[sccm] Cryogenic : less than 60[sccm]
Operating temperature	MOV/MFV : 77 to 333[K] TCV : 77 to 450[K]	77 to 450[K]
Proof pressure	Operating pressure×1.5	Operating pressure×1.5
Burst pressure	Operating pressure×2.5	Operating pressure×2.5
Cv (Flow capacity)	MOV/MFV : 17.9 (Water : 4.3[L/s]@288.75[K], 0.1[MPaD]) TCV : 24 (Water : 5.7[L/s]@288.75[K], 0.1[MPaD])	2.5 (Water : 0.6[L/s]@288.75[K], 0.1[MPaD])
Operating cycle	Ambient : More than 500 times Cryogenic : More than 500 times	Ambient : More than 500 times Cryogenic : More than 500 times
Mass	Less than 4.0[kg]	Less than 2.0[kg]

The pictures of the valve assemblies are shown in Fig.5.

Figure 5: Pictures of MOV and TBV.

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4. Test result

4.1 Flow test

A series of flow tests of TCV with methane gas were performed in IHI AIOI test site in order to verify valve function and investigate Cv characteristics. In this section, TCV test results with high pressure condition are presented.

Test condition
Test condition is shown in Table 4. Methane gas supply pressure, 5 and 8 MPa were selected which were operating points of the firing test. The valve opening position was transitioned from 100% to 10%, in steps of -10% during a test, in order to evaluate Cv value at every opening position.

Table 4: Test condition.

Parameter	Value
Fluid	Gaseous methane
Opening range	10 - 100 [%]
Supply pressure	5, 8 [MPaA]

Flow test configuration
Test configuration is shown in Fig.6. Methane gas is provided from the high pressure storage tank. The pressure regulator in downstream of the storage tank regulates the methane gas to a test pressure condition. When starting a test, the shut-off valve in upstream of TCV is opened, then methane gas flow to TCV.

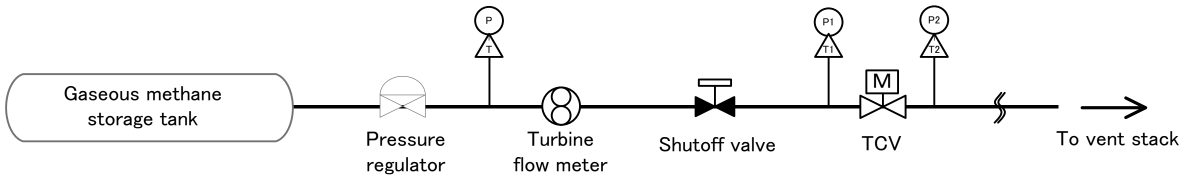

Figure 6: Test configuration.

Test result
Command and answer historys of the valve poppet position are shown in Fig. 7 (at supply pressure of 5 MPa) and Fig.8 (at supply pressure of 8 MPa), with upstream pressure P1, downstream pressure P2 and differential pressure DP. Open command was from 100 % to 0 %, moving in steps of -10% after 5 seconds steady state operation.
It was confirmed that at all position, the operation was stable and the valve opening position changed smoothly following the command. Finally, differential pressure reached approxmately 7.8 MPa between valve inlet and outlet in the case of supply pressure 8 MPa. From these results, the valve showed that it could work properly under high differential pressure condition.

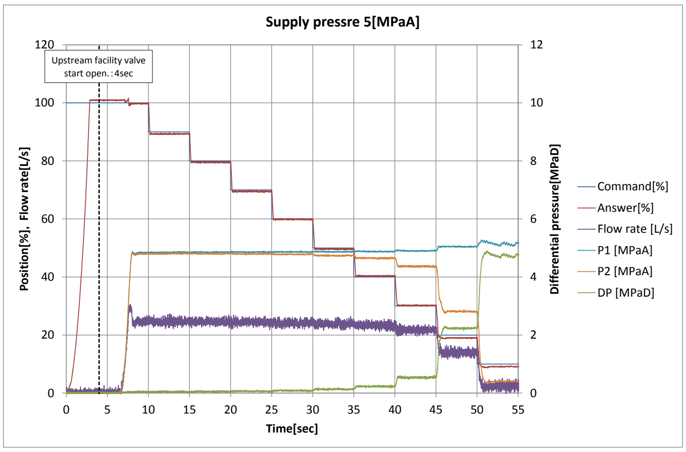

Figure 7: Command / answer history of flow test (supply pressure 5 MPa).

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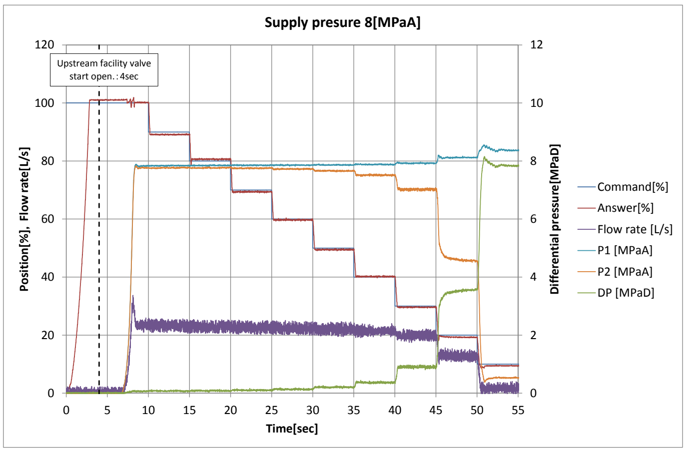

Figure 8: Command / answer history of flow test (supply pressure 8 MPa).

4.3 Firing test result

After the flow test, the valves were applied to the engine firing test. Test configuration is shown in Fig. 9. MOV and MFV were mounted on main oxidizer and fuel line respectively, TCV was mounted on turbine driving gas line. Due to the firing test constrain, MOV/MFV were used as shut-off valve and TCV was kept full open condition. Time historys of MOV/MFV and TCV during the firing tests are shown in Fig. 10, 11 and 12. MOV/MFV and TCV were properly working under high pressure and cryogenic condition in the firing test series, thereby it was succeeded to control operating point during the firing test by controling those valves. A picture of the firing test is shown in Fig.13.

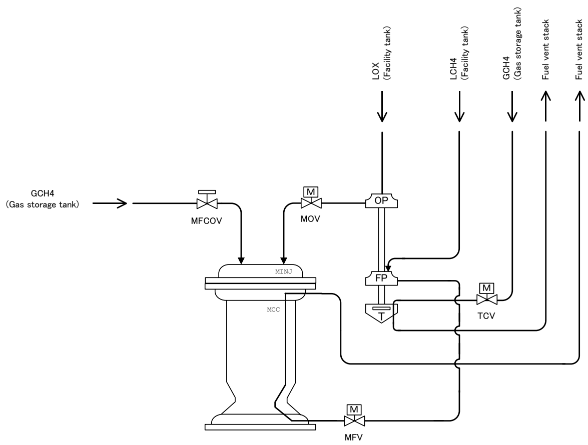

Figure 9: Firing test configuration.

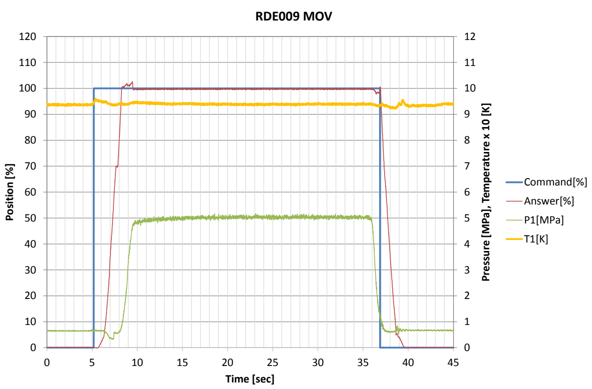

Figure 10: Command / answer history of MOV in firing test (RDE009).

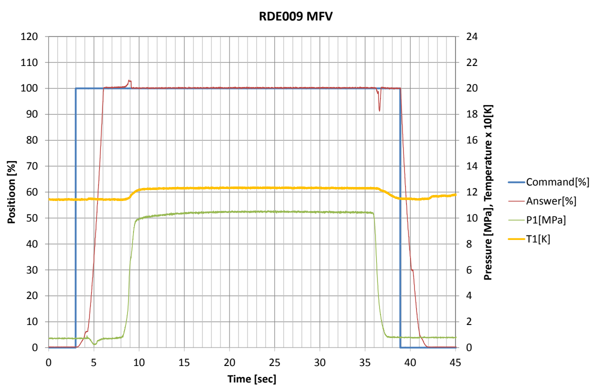

Figure 11: Command / answer history of MFV in firing test (RDE009).

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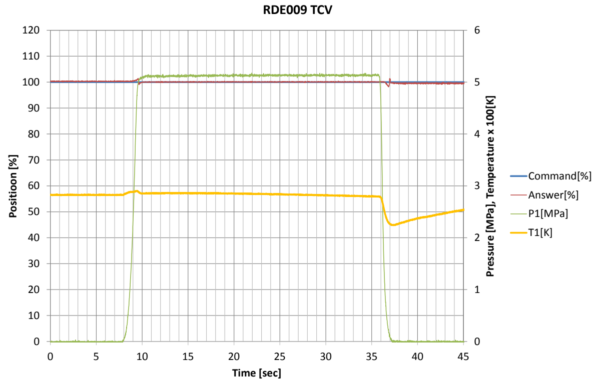

Figure 12: Command / answer history of TCV in firing test (RDE009).

Figure 13: Picture of firing test (RDE009).

5. Future work

From the test results, basic functions for valve, such as shut-off and flow control, under high pressure and cryogenic condition were confirmed. Since the valves are prototype model, additional modification can be expected such as mass and cost reduction. Future works with high priority are to realize faster traveling time for throttling operation and capability for more deep and long applicability of space environment.

6. Conclusion

In this activity, the valves which have both shut-off and flow control function, were designed based on the engine system requirements and prototype model production and testing were done. The valve functions were tesed in flow test, as a result, it was confirmed that the valves worked properly as designed. Finally, the valves were used in firing test and could be properly operated under high pressure and cryogenic condition.

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