DOI: 10.13009/EUCASS2025-002
11TH EUROPEAN CONFERENCE FOR AERONAUTICS AND SPACE SCIENCES (EUCASS)

BLDC-Motor-Driven Multipurpose Control Valve for Liquid Rocket Engine of KSLV-III

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Abstract
This paper presents the development of a BLDC-motor-driven multipurpose control valve for a liquid rocket engine (LRE). This valve satisfies all requirements for the next-generation engine of Korea Space Launch Vehicle III to launch a lunar lander by 2032. The low-cost and low-weight space launch vehicle is essential in the new space era. The multipurpose control valve has the flow control and shut-off functions. Thus, it is helpful for reducing the weight and cost of the LRE.

Nomenclature

BLDC	=	Brushless direct current	*GFV*	=	GG fuel shutoff valve
CC	=	Combustion chamber	*GOCV*	=	GG oxidizer control valve
CFCV	=	CC fuel control valve	*GOV*	=	GG oxidizer shutoff valve
EMA	=	Electromechanical actuator	*MFV*	=	Main fuel shutoff valve
GG	=	Gas generator	*MOV*	=	Main oxidizer shutoff valve
GFCV	=	GG fuel control valve	*MPCV*	=	Multipurpose control valve

1. Introduction

The new space era began when SpaceX launched the reusable Falcon 9 vehicle and dominated the commercial satellite launch industry. Since then, reusability and low cost have become important factors for the development of new space launch vehicles worldwide. In particular, a simple system design is essential for developing low-cost vehicles. Several space vehicle developers have attempted to adopt electric-motor-driven valves instead of conventional pneumatic valves for cost and weight reduction [1-3]. Since 2015, the European Space Agency has been developing a next-generation engine (PROMETHEUS) that is reusable and inexpensive. The engine consists of only four main valves in its propellant lines, all of which are driven by electric motors and have the flow control and shut-off functions [1]. We refer to these valves as multipurpose control valves (MPCVs).

Korea Space Launch Vehicle II (KSLV-II) (Nuri) was successfully launched in 2022. Its engine contains seven main valves (three shut-off valves and four control valves) in the propellant lines, as shown in Fig. 1 [4]. The control valves are driven by BLDC motors and only have the flow control function [5]. If the control valves are replaced with MPCVs, then the three shut-off valves (GOV, GFV, and MFV) and the solenoid valves and pilot pipes required to operate the shut-off valves can be eliminated, thus reducing the engine weight and cost.

The development of KSLV-III began in 2023 to launch a lunar lander by 2032. KSLV-III is composed of two stages. The 1st stage comprises five engines with 100 tonf of thrust each. The 2nd stage consists of two engines with 10 tonf of thrust each. Kerosene and liquid oxygen are used as the propellants. All LREs are “closed cycle engines” with an oxidizer-rich preburner. Figure 2 shows a simplified scheme of the 2nd stage engine under development. In this engine, the CFCV and MFV are installed in the fuel line of the thrust chamber. This study develops an MPCV that can replace the CFCV and MFV (Fig. 2), thus reducing the weight and cost of the LRE. The MPCV shown in Fig. 3 is developed based on previous studies [5,6]. The left side of Fig. 3 shows the flow part of the MPCV, and the right side shows the electromechanical actuator (EMA) driven by a BLDC motor. The main specifications of the MPCV are listed in Table 1.

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Table 1: Specification of MPCV

Specification	Unit	Value
Flow diameter	mm	25.85
Medium	-	Kerosene
Flow rate (Nom.)	kg/s	6.65
Pressure (Max.)	MPa	23.5
Control range	Kv	3~13
Motor power	watt	70
Gear ratio	-	100:1
Maneuvering time	sec	< 1.0
Weight	kg	3.25

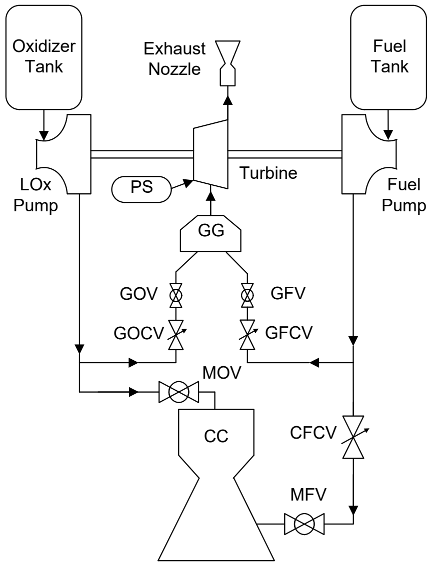

Figure 1: Scheme of KSLV-II 75 tonf LRE

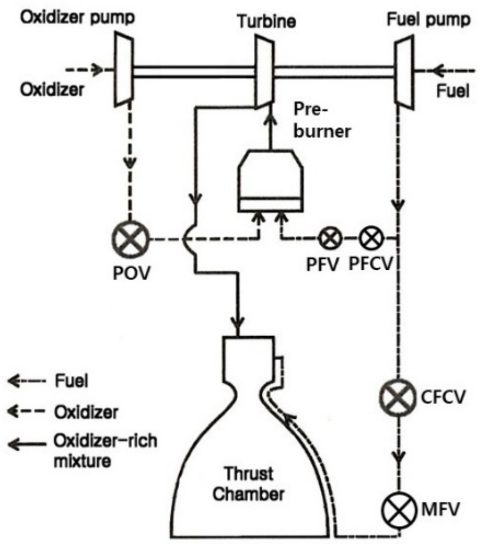

Figure 2: Scheme of KSLV-III 10 tonf LRE

2. Design of MPCV and Controller

2.1 MPCV

Figure 4 shows the conceptual configuration of the MPCV. The MPCV comprises a flow control component and EMA. The flow control component is composed of a shaft, sleeve, and plunger, as shown in Fig. 4(a). The sleeve moves horizontally in accordance with the rotation of the driving shaft connected to the EMA, and the flow area between the sleeve and plunger is changed to adjust the flow rate of the propellant. The above operational mechanism is the same as that of the control valve for the engine of KSLV-II [5]. Seals A and B are newly added for the shut-off function. The seals block the propellant flow when the sleeve moves to the end of the right side and contacts the plunger. Mechanical-spring-energized seals are used. The MPCV is an inline coaxial valve. This valve has a thin sleeve, which results in a small flow-induced force that acts on the end tip of the sleeve. Therefore, the required power of the EMA is considerably small compared with other types of valves such as ball and globe valves.
The EMA comprises a BLDC motor with a brake accessory, harmonic drive for speed reduction, potentiometer, and other components, as shown in Fig. 4(b). The potentiometer measures the rotational angle of the shaft. Therefore, the signal from the potentiometer is used to control the position of the shaft or sleeve. The primary specifications of the throttle valve are listed in Table 1.

2.2 Controller for MPCV

The controller is fabricated using industrial electronic elements to obtain the maximum flexibility because an onboard controller is not yet available. Therefore, the requirements of the electronic controller are compatible with a laboratory environment. Figure 5 shows the controller. The controller can simultaneously control the three throttle valves. It

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controls the speed and current of the motors and the valve position. It comprises an embedded real-time controller (cRIO 9024) and three motor drivers (amplifiers). In addition, the controller can acquire data about the motor status and the pressure and flow rates of the hydraulic lines in a test facility to control the MPCV according to a control algorithm.

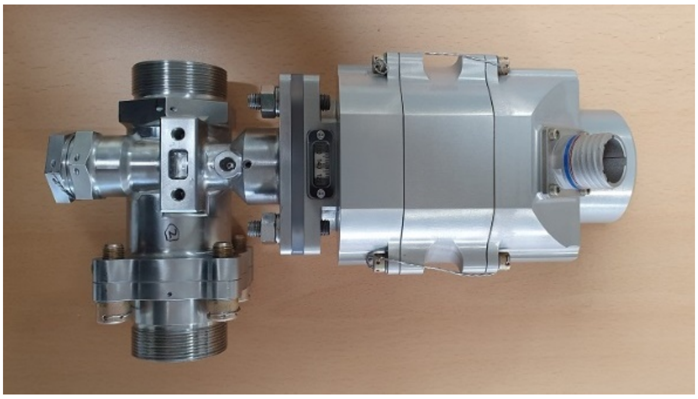
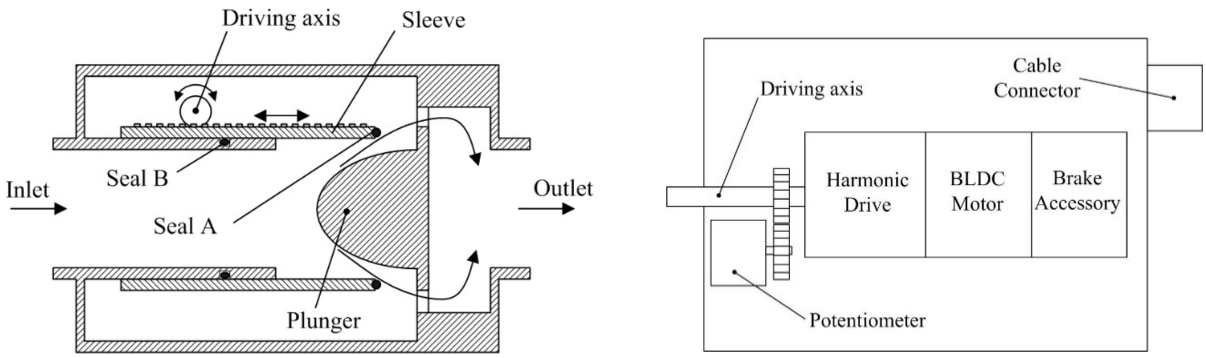


Figure 3: Multipurpose Control Valve



(a) Flow control part (b) EMA

Figure 4: Conceptual configuration of MPCV

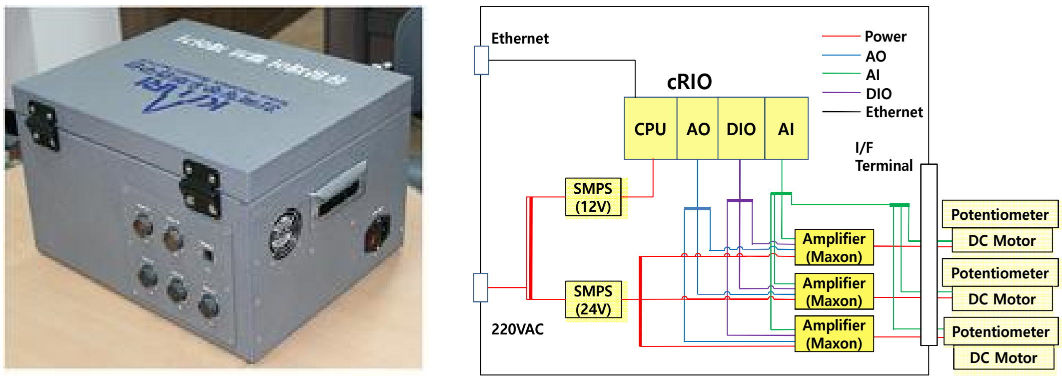


Figure 5: Controller for MPCV

A computer communicates with the controller via TCP/IP. It provides control orders to the controller and obtains data from the controller at a sampling rate of 100 Hz. The control S/W is programmed using LabVIEW, and the S/W architecture comprises host_vi, RT_vi, and FPGA_vi, as shown in Fig. 6.

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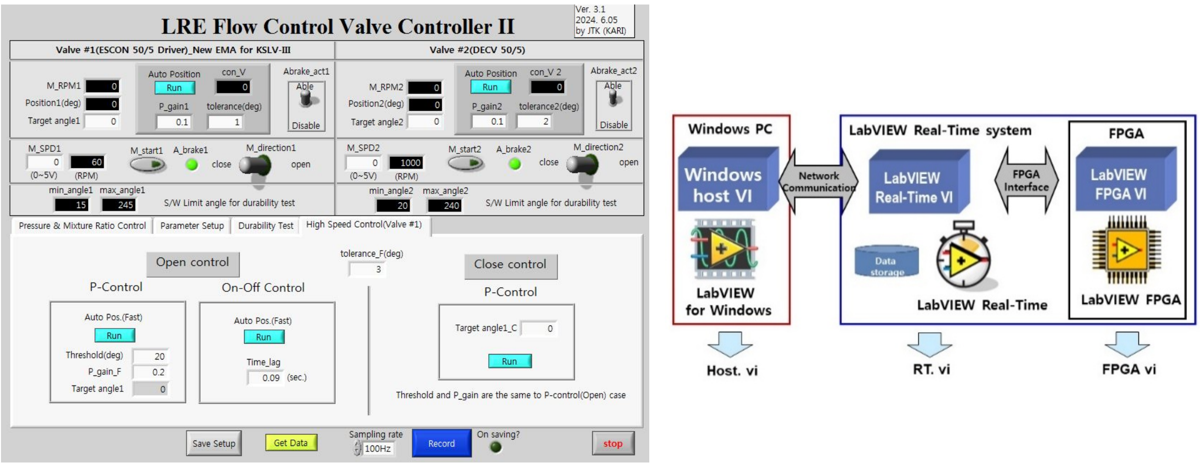

Figure 6: GUI and architecture of control S/W

3. Development Test

3.1 Flow Characteristic Test

Figure 7 shows the experimental results for the inherent flow characteristics of the MPCV along the valve position (angle of the driving axis). The test is performed using the setup shown in Fig. 8. The flow coefficient, K_v, is defined based on the plunger profile shown in Fig. 4(a), as follows:

$$K_v = Q\sqrt{\frac{G}{\Delta P}} \tag{1}$$

where Q is the flow rate (m^3/h), G is the specific gravity, and ΔP is the pressure drop (bar).

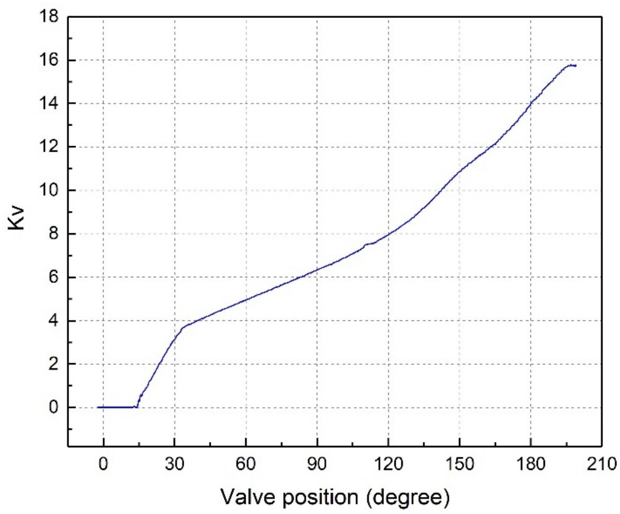

Figure 7: Inherent flow characteristics of MPCV

3.2 Pressure Proof and Leakage Test

A pressure proof test is performed at 28.2 MPa using GN_2. No permanent deformation or leakage occur during the test. Leakage tests are successfully performed using GN_2 at room temperature, as shown in Fig. 9. There is no internal leakage through seal A when the valve is closed at an inlet pressure of 2.0 MPa. Furthermore, the leakage of a drain

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port is 0.15 cm^3/s, which is less than the allowable limit of 0.5 cm^3/s, when the valve is open at an inlet pressure of 25.8 MPa.

Figure 8: Flow and maneuvering test setup

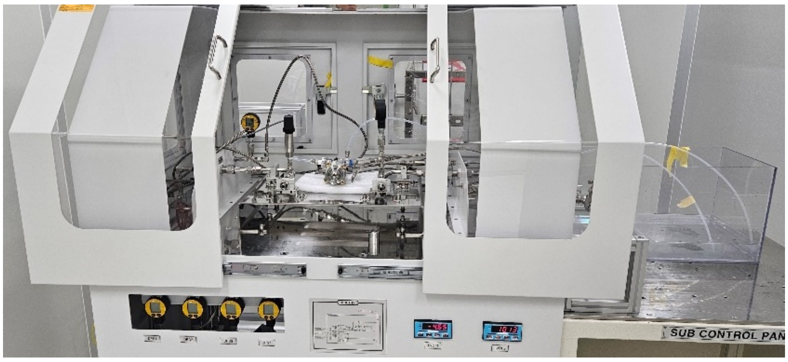

Figure 9: Proof and leakage test

3.3 Maneuvering Test

The MPCV has the flow control and shut-off functions. Therefore, the MPCV requires a short maneuvering time for the shut-off function. For example, the maneuvering time of the shut-off valves with a pneumatic actuator for the engine of KSLV-II is approximately 7–45 ms. However, the MPCV cannot achieve such a short maneuvering time because it is driven by an electric motor. This can only be achieved using higher motor power, which increases the weight. Thus, there must be a suitable tradeoff between the maneuvering time and weight. Recently developed MPCVs [2,3] have maneuvering times of 1–1.5 s.

The MPCV used in this study can manipulate the rotational speed of the motor from 0 RPM to 7,000 PRM. For fast valve opening and closing during engine start up or shut down, a proportional control algorithm is used so that the BLDC motor can rotate at the maximum speed of 7,000 RPM during the initial period of the operation. The motor speed significantly decreases when the valve position is close to a target position.

The maneuvering test is performed under an inlet pressure of 0.5–4 MPa and atmospheric outlet pressure, as shown in Fig. 8. In this test, the initial and target valve positions are set as 0° and 145°, respectively, where a valve position of 0° indicates that the MPCV is closed. Figure 10(a) shows the transient valve positions. The final valve positions are 145°–146° within a tolerance of 1°, regardless of the inlet pressure. In addition, the maneuvering time is approximately 0.52 s faster than the cases reported in literature [2,3]. Figure 10(b) shows the command voltage released to the motor driver (amplifier) for motor speed control, where 0–5 V corresponds to 0–7,000 RPM. The maximum speed command (5 V) is given at 1.5 s, and the command voltage considerably decreases starting from approximately 1.85 s to stop the motor using the proportional control algorithm. The motor rotational speeds shown in Fig. 10(c) increase at the beginning of the valve opening. However, they show deeper valleys at approximately 1.65 s in accordance with the higher inlet pressures. This is because the flow-induced force that acts on the end tip of the sleeve increases with the inlet pressure. Therefore, the motor current increases with the inlet pressure, as shown in Fig. 10(d), such that the motor power can overcome the flow-induced force and open the closing element (sleeve) of the MPCV.

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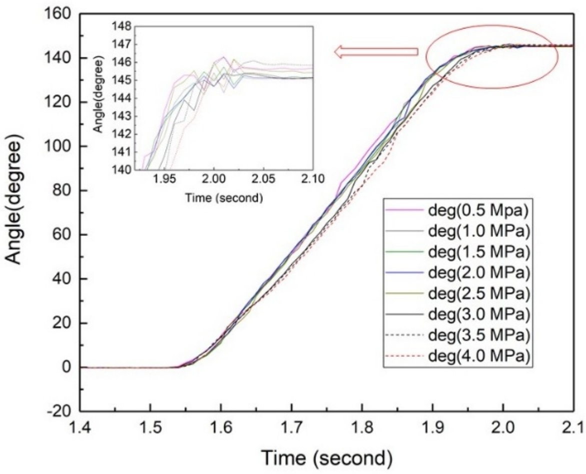
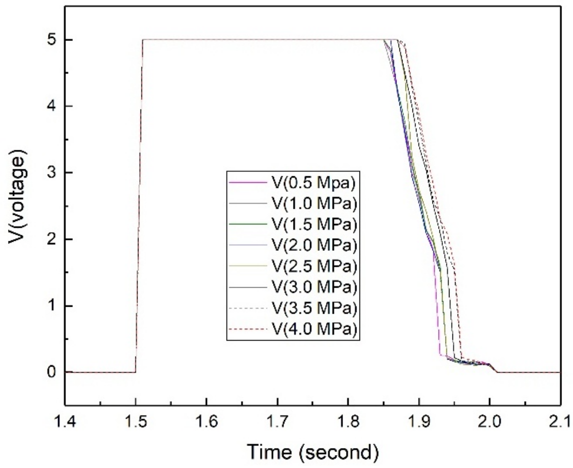
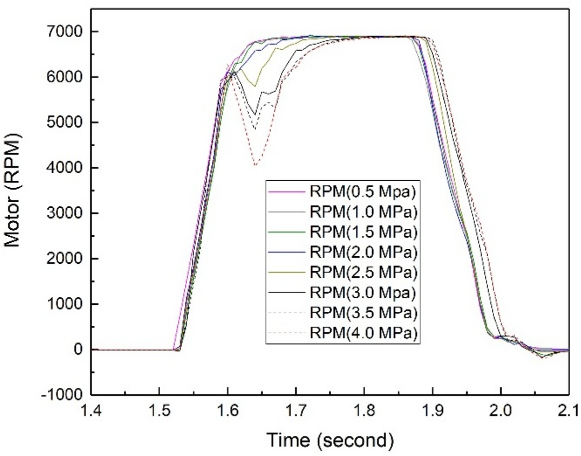


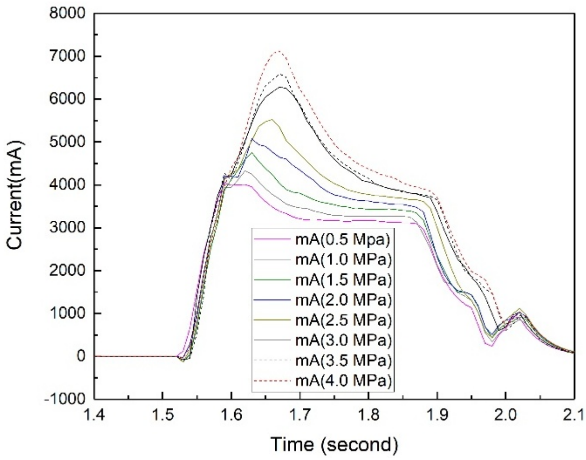
(a) Valve position



(b) Command signal for motor speed control



(c) Motor rotational speed



(d) Motor current

Figure 10: Maneuvering test results

3.4 Vibration Test

The vibration tests of the MPCV are performed along the x, y, and z axes, as shown in Fig. 11. After and during all vibration tests, such as random and sinusoidal tests, the MPCV operates normally and does not show any damage.

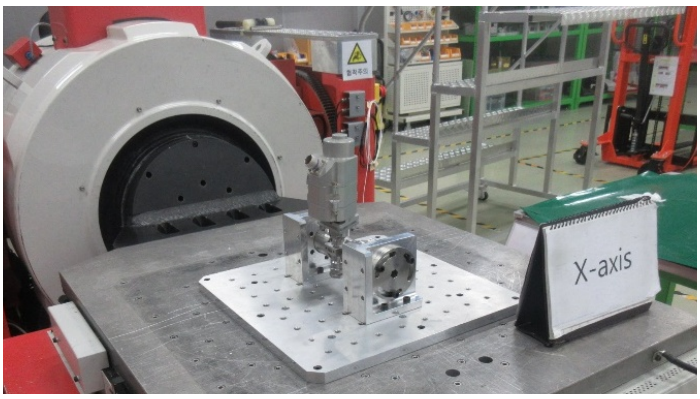


Figure 11: Vibration test

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3.5 Durability Test

Durability tests are performed at room temperature and a motor speed of 7,000 RPM under the following conditions:

- 140 cycles under atmospheric pressure.
- 70 cycles under 23.5 MPa.

Leakage tests are successfully conducted after each durability test. The leakage is within the allowable limit.

3.6 Cryogenic Test (Feasibility Study)

The MPCV is designed and developed to operate at room temperature. However, a feasibility study is performed to prove the flexibility of the valve at cryogenic temperatures such as 77 K. All seals are replaced with cryogenic seals. A cryogenic leakage test is performed using GHe in a LN_2 submersion container, as shown in Fig. 12. There is an internal leakage of 8.2 cm^3/s, which is less than the allowable limit of 20 cm^3/s under the valve-closed condition at an inlet pressure of 0.6 MPa. Moreover, the leakage of the drain port is 2.9 cm^3/s, which is less than the allowable limit of 5 cm^3/s. Note that the leakage of the internal and drain ports exceeds the allowable limits when the pressure is higher than 2 MPa. The reasons for this are as follows: The materials of the valve body and moving parts are different because the valve is designed for room-temperature usage. Therefore, the difference in the thermal expansion coefficients between the materials results in excessive leakage at cryogenic temperatures. This problem can be solved by selecting the appropriate materials for cryogenic applications.

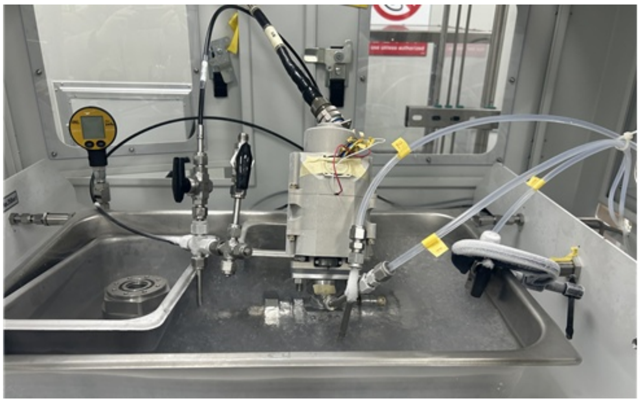

Figure 12: Cryogenic test

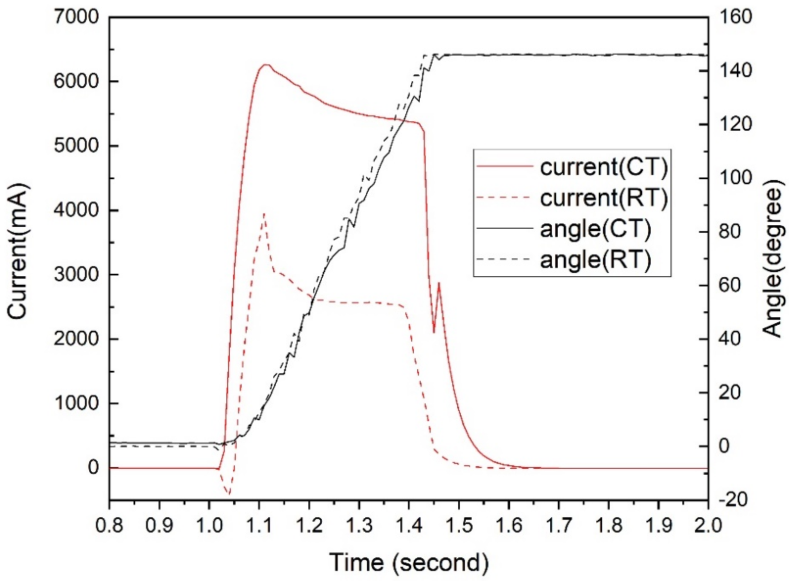

Figure 13: Maneuvering test results under room and cryogenic temperature

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A functional test is performed during the cryogenic leakage test without any problems. A maneuvering test is performed under atmospheric pressure. In this test, the initial and target valve positions are set as 0° and 145°, respectively. Figure 13 shows the test results obtained at room temperature (RT) and the cryogenic temperature (CT). The final valve positions (angles) are similar regardless of the temperature. In addition, the maneuvering times are similar owing to the proportional control algorithm, although the maneuvering time at room temperature is 0.02 s shorter than that at the cryogenic temperature. The motor current at the cryogenic temperature is approximately two times higher than that at room temperature. This is because the friction forces at the cryogenic temperature are higher than those at room temperature.

4. Conclusions

This paper described the development of an MPCV driven by a BLDC motor for the potential replacement of the MFV and CFCV in the 2nd stage engine of KSLV-III. The development tests satisfied all the required specifications. In particular, the maneuvering time was 0.52 s, and it remained almost constant regardless of the valve inlet pressure. The design and development technologies of the MPCV proposed in this study can be successfully used for weight and cost reduction in KSLV-III and future Korea space launch vehicles.

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