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Cold flow test of pintle injector for variable thrust combustion chamber with servo-valve method

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Abstract
From the Apollo lunar lander to SpaceX's recent Falcon 9 rocket, the pintle injector has proven its utility in a variable thrust combustion chamber. This paper presents the results of a cold flow test conducted on the pintle injector using a servo-valve method for a variable thrust combustion chamber. The piston-sleeve was designed and manufactured to move with a total stroke of 16.75 mm, employing hydraulic pressure from a servo-valve to actuate the double-acting cylinder located at the top/bottom of the piston-sleeve. The pintle core and piston-sleeve are fabricated from UNS S31603 and aluminium, respectively, while the head-part casing is composed of transparent polycarbonate to allow for visual observation of the piston-sleeve's movement. The servo-valve and power amplifier utilized were the 550-0610 model from STAR's (UK) and the SV-200 model from W.E.S.T.'s (Germany), respectively. For the control and data acquisition system, the USB-6211 model from NI's (USA), capable of both analog input and output, was employed. A custom in-house program, developed based on the commercial program LabVIEW, served as the software. Prior to the cold flow test, the functionality and operability of the servo-valve and piston-sleeve were verified by supplying a working fluid (kerosene) to the servo-valve and the double-acting cylinder at the head part. Additionally, a preliminary test was conducted to determine the pressurization conditions for each flow rate (or each piston-sleeve stroke). The cold flow test was carried out using water in a miniature rocket engine test facility (mRETF) in Daejeon. After supplying water under the previously determined pressurization conditions starting from the fully open state of the piston-sleeve, the piston-sleeve was moved to positions corresponding to different flow rates, and the mass flow rate and pressure drop of the pintle and annulus ring orifice were measured. It was confirmed that the mass flow rates matched well with the fully open state (piston-sleeve position: 16.75 mm, total mass flow rate of water: 8.36 kg/s) under conditions of 20% to 90% opening position. Furthermore, it was observed that the pressure drop could be maintained over a wide flow rate range, particularly at lower flow rates.

1. Introduction

Advanced countries in rocket development have pursued thrust control technology for liquid rocket engines beyond the traditional goals of high thrust and high efficiency, aiming for mission diversification and economic operation of launch vehicles, including multiple payloads, space exploration, and reusable launch vehicles. The variable pintle injector is one such thrust control technology that precisely controls fuel and oxidizer injection and combustion processes in the combustion chamber, allowing for variable thrust and performance. Successful examples of its utilization can be seen in the descent engine of the United States' Apollo lunar lander (LMDE), SpaceX's Merlin engine, and China's Chang'E-3 lunar lander engine [1-3].
From 2019 to 2022, the Korea Aerospace Research Institute (under KARI) conducted thrust control combustion tests on a fixed pintle injector assuming booster-class operating conditions. It was confirmed that the simple form of the fixed pintle injector enabled deep throttling at a 5:1 level of thrust control [4-5]. Additionally, two variable pintle injectors capable of maintaining a constant injector pressure under low thrust and low flow rate conditions were designed, fabricated, and subjected to cold flow tests [6-7]. This paper describes the design, fabrication, and cold flow test results of a servo-valve type variable pintle injector.

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2. Design of pintle injector

From 2019 to 2021, the KARI conducted hot-firing tests on a different pintle and annular ring orifices, with eight and four each [4-5]. Based on the design conditions of the pintle and annular ring orifice that exhibited the highest combustion efficiency, a two-row pintle orifice with a blockage ratio of 58% was designed, as shown in Figure 1 and Table 1.

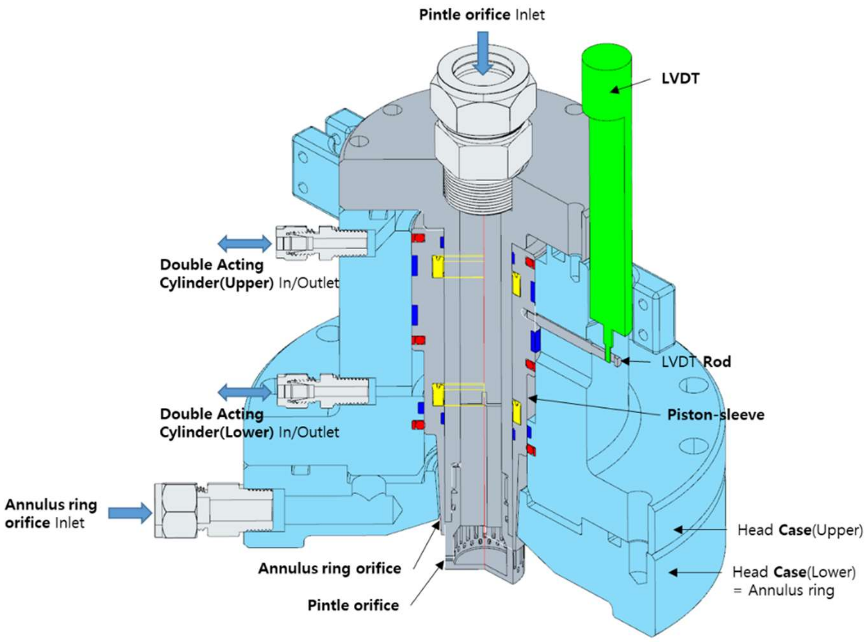

Figure 1: Configuration of the pintle injector for cold flow test

Table 1: Design parameters of the pintle injector

		Pintle orifice	Annulus ring orifice
Mass flow rate [kg/s]		6.16	2.2
Pressure drop [bar]		4.28	4.1
Total momentum ratio (TMR)		1.5	
Blockage factor [%]		58	
Pintle diameter [mm]		33	
Pintle orifice [mm]	1st row	14.5 x 1.0	
	2nd row	1.75 x 1.75	
Number of pintle orifice slit [ea]		22	
Piston-sleeve total stroke [mm]		16.75	
Max. gap distance at annulus ring orifice [mm]		0.7	

The axial travel distance from the start of the 1st row pintle orifice to the end of pintle was designed to be 16.75 mm. The area variation of the pintle and annular ring orifices with respect to the piston-sleeve axial distance is illustrated

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in Figure 2 and 3. The piston-sleeve clearance was designed to be within 0.05-0.15 mm to ensure the proper operation of the piston-sleeve mechanism. To prevent collision between the piston-sleeve and the annular ring casing at a piston-sleeve axial distance of 0 mm, a gap of approximately 1 mm was incorporated into the design.

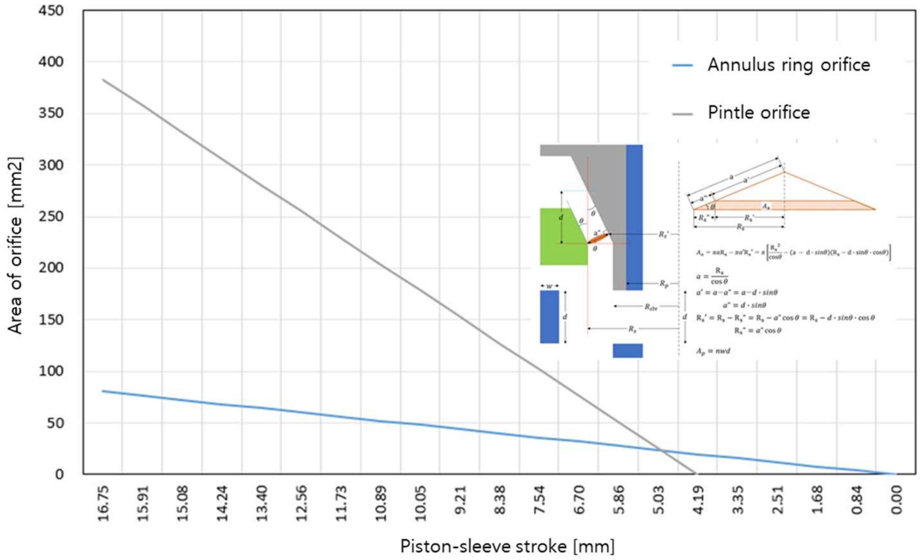

Figure 2: Area of the pintle and annulus ring orifice according to the piston-sleeve stroke

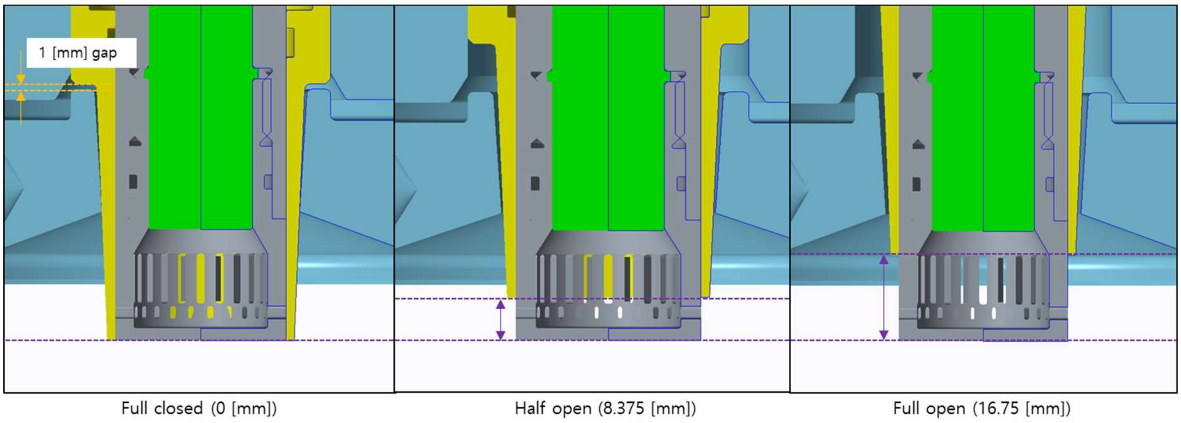

Figure 3: Configuration of the pintle injector with respect to piston-sleeve stroke variations (including the gap between piston-sleeve and annulus ring casing)

The pintle was made of UNS S31603, while the piston-sleeve was fabricated using aluminum. In order to visually observe the movement of the piston-sleeve and internal flow during the cold flow test, the head case and annular ring casing were made of transparent polycarbonate. A double-acting cylinder was incorporated at the top and bottom of the piston-sleeve to allow the hydraulic fluid from the servo-valve to be supplied and discharged, driving the piston-sleeve. Additionally, a Linear Variable Displacement Transducer (under LVDT) rod was installed on the piston-sleeve to provide real-time input of the axial distance, enabling control of the servo-valve.

3. Experimental setup

3.1 Hydraulic

For the cold flow test of the servo-valve type variable pintle injector, water was used, while kerosene was used as the working fluid for the servo-valve. As shown in Figure 4 and 5, a hydraulic line was constructed from the supply line of the mRETF to the pintle injector and servo-valve. The water supply line branched off and connected to the pintle and annular ring orifice inlets using 1" and 3/4" flexible hoses, respectively. The kerosene supply line of the test

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facility was connected to the 'P' port of the servo-valve manifold, and the two actuating ports (A, B) of the servo-valve were connected to the upper and lower double-acting cylinder ports of the pintle injector head, respectively. The return fluid from the servo-valve operation was connected to the kerosene storage tank return line to ensure the circulation of the used kerosene.

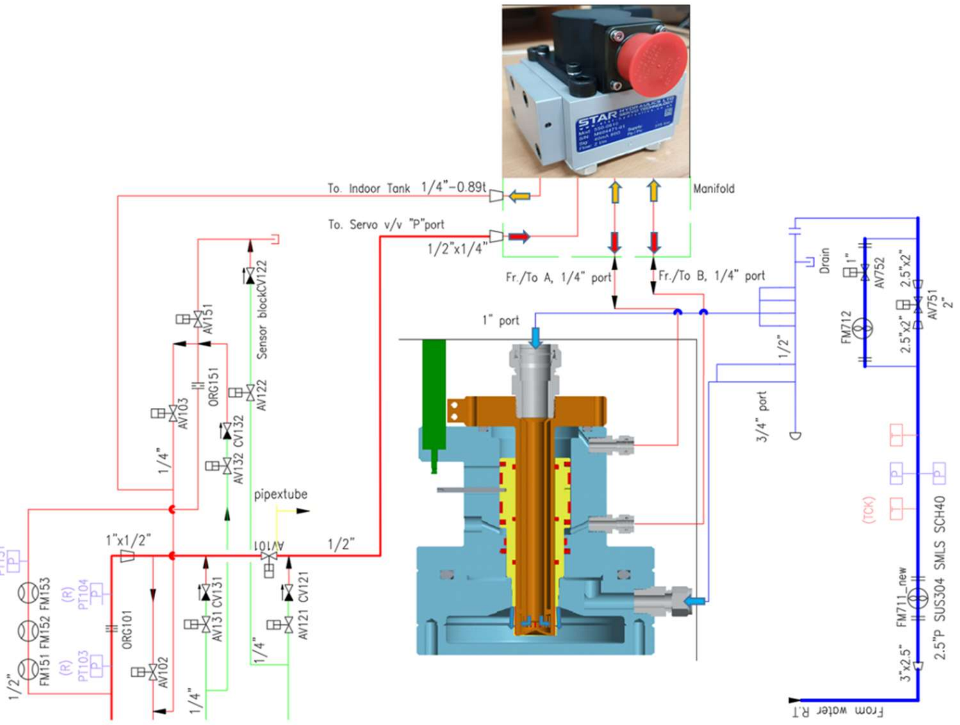

Figure 4: P&ID of the test facility and pintle injector for the cold flow test

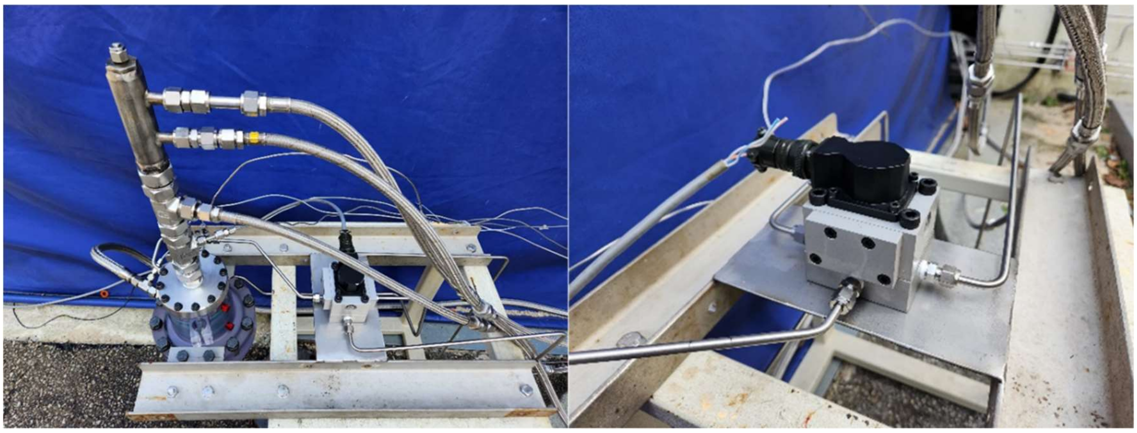

Figure 5: Installation of the pintle injector and hydraulic line at test stand

3.2 Hardware of control and data acquisition system

Figure 6 and 7 illustrate the control and data acquisition system constructed for the cold flow test of the servo-valve type variable pintle injector. The control and data acquisition system hardware consists of the servo-valve, power amplifier, console, DAQ, and sensors (pressure transmitter, flow meter, LVDT).

The servo-valve was the 550-0610 model from STAR's (UK), capable of achieving a discharge flow of 2.1 l/min based on a pressure drop of 70 bar. The voltage signals received from the control and data acquisition system were converted into current signals that the servo-valve can accept and also served as the power supply for the servo-valve using the SV-200 model from W.E.S.T.'s (Germany). This product can output a current ranging from 10 to a maximum of 200 mA with a ±10 V input.

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The flow rate of water supplied to the pintle and annular ring orifices was measured using a turbine flow meter from Hoffer's (USA) installed in the test facility supply line. Pressure was measured by branching off at the inlet of the pintle and annular ring orifices, with one measurement point each, and by branching off in the line where the servo-valve operating fluid is supplied to the upper and lower double-acting cylinders, with one measurement point each, total four measurement points. A displacement sensor (LVDT) was connected to the rod fixed to the piston-sleeve to measure the axial distance of the piston-sleeve in real-time. Using this measurement as a reference, the analog output signal from the DAQ (NI's USB-6211 model) was sent to the servo-valve to control and reach a specific target position.

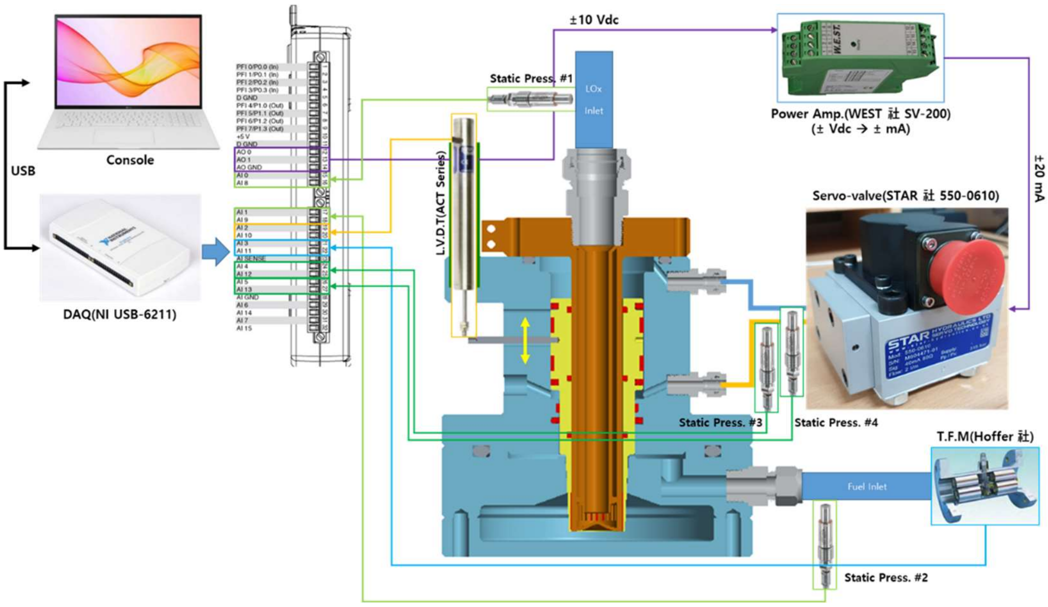

Figure 6: Configuration of control and data acquisition system for the cold flow test

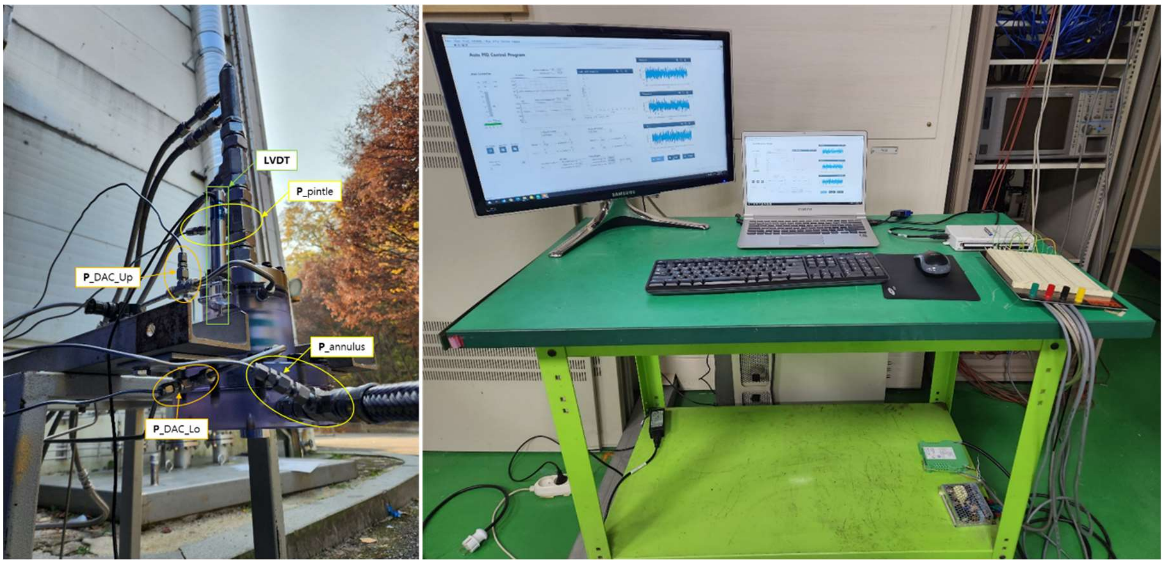

Figure 7: Installation of control and data acquisition system at test facility

3.3 Software of control and data acquisition system

Figure 8 represents the control and data acquisition system software developed for the cold flow test. It was built using National Instruments' LabVIEW software (Ver. 2022 Q3). The software can be divided into several components: on the right-hand side, there is a real-time monitoring graph for the measurement sensors, in the center, there are options to set the sensor gain/offset values, in the top left corner, there are settings for defining control target values and monitoring graphs for reference/control analog output signals, in the bottom left corner, there are

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options for data storage, and finally, in the bottom center, there are settings for control (P/I/D) gain values. Although LabVIEW provides an 'Auto Tune' option, it was not utilized for the cold flow test.

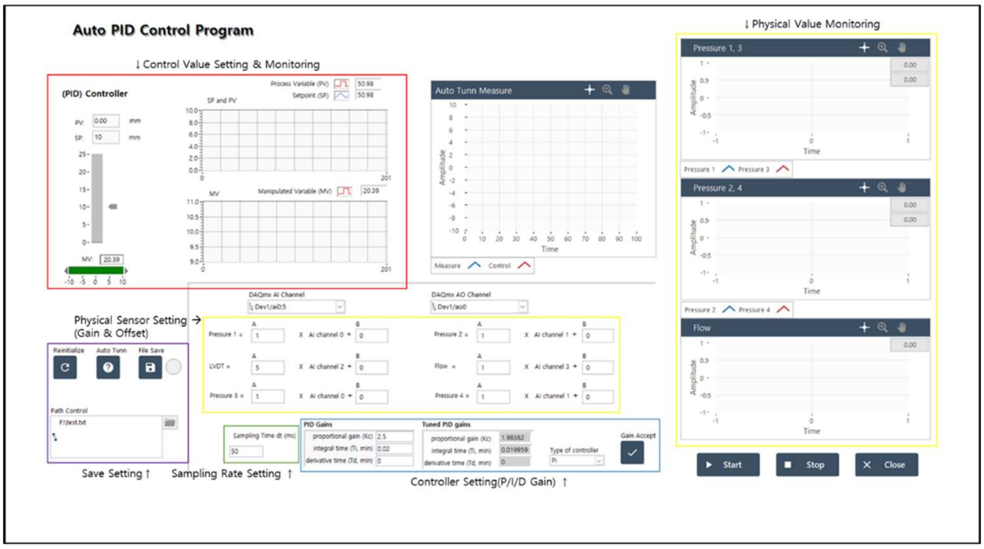

Figure 8: Software of control and data acquisition system for the cold flow test

4. Preliminary test

4.1 Piston-sleeve operation test

After constructing both the hydraulic line and the control and data acquisition system, a piston-sleeve operation (control) test was performed using a servo-valve as shown in Figure 9. During the test, only kerosene was supplied to the servo-valve (including piston-sleeve head top/bottom double-acting cylinders) without supplying water through the pintle and annular orifices. The piston-sleeve's movement was verified by incrementing/decrementing the stroke distance in a step-like manner from 0 mm (fully closed) to 16 mm (almost fully open) with a 4 mm interval. The movement of the piston-sleeve was visually confirmed by slowly controlling it using only the 'P' control with gain 10.

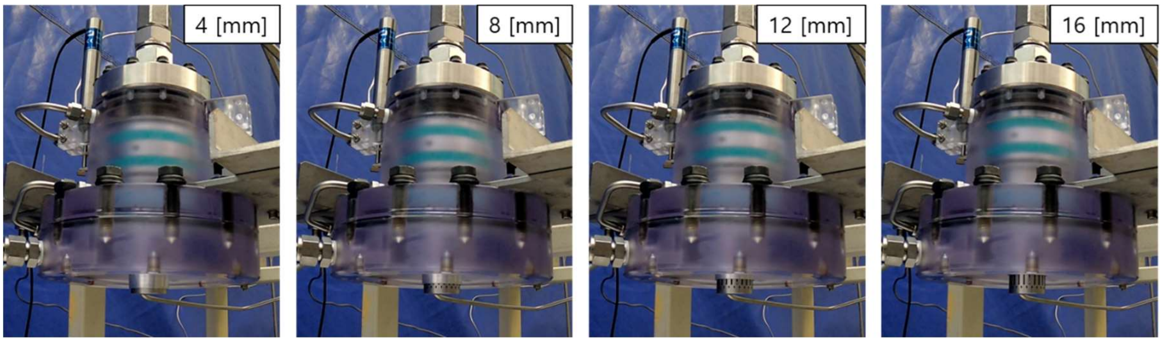

Figure 9: Piston-sleeve operation test

4.2 Cold flow test for exploring the pressurization conditions of the test facility

The test facility is configured as a pressurized system, and it has limitations in real-time control. Therefore, prior to conducting the actual test, a cold flow test was performed to explore the pressurization conditions for each flow rate and determine the pressurization conditions.

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5. Results

5.1 Flow rate and differential pressure

The cold flow test began by supplying water under the pressurization conditions determined prior to the test, with the piston-sleeve in the fully open configuration as shown on the left side of Figure 10 and 11. The piston-sleeve was then moved to different positions corresponding to each flow rate, and the flow rate and differential pressure at the pintle and orifice were measured. Figure 10 and 11 displays a spray pattern of the cold flow test for the variable pintle injector with a servo-valve. Figure 12 and Table 2 represents the volume/mass flow rate and differential pressure results at the pintle and annulus ring orifice based on the piston-sleeve position. It was confirmed that in the low thrust and low flow rate range, as the piston-sleeve opening decreased, the differential pressure increased again, enabling a consistent pressure differential to be maintained.

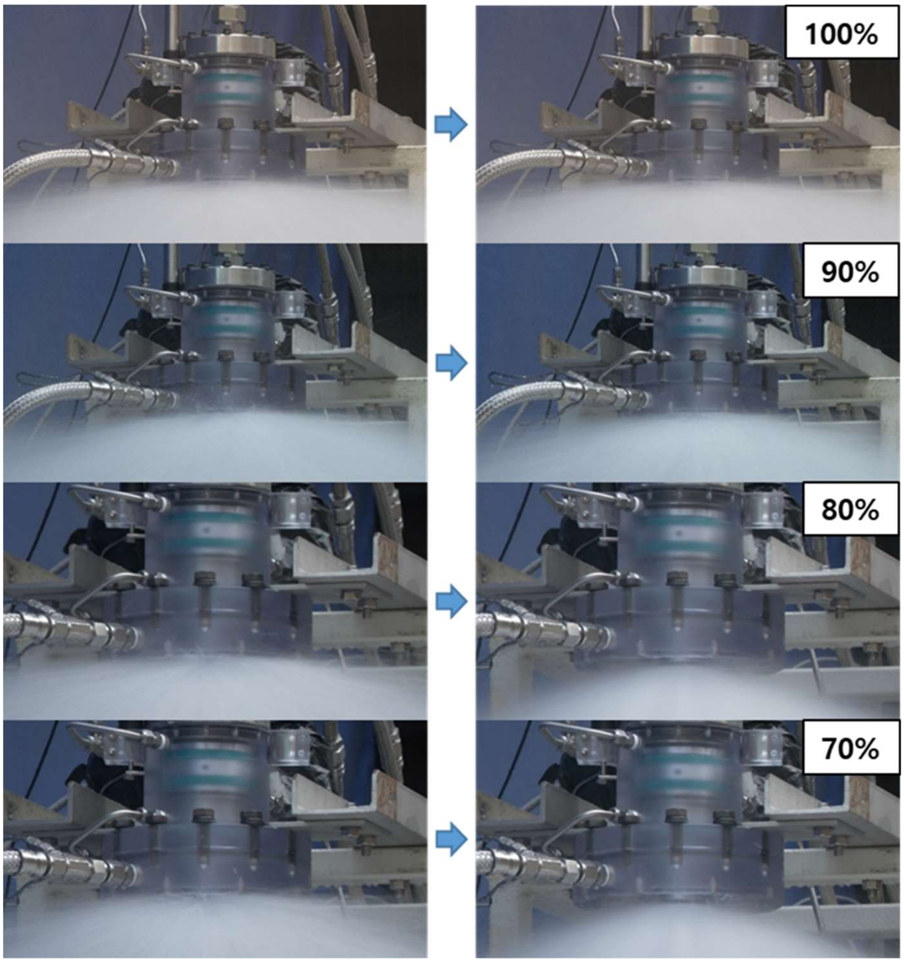

Figure 10: Spray pattern of pintle injector depending on the piston-sleeve position (from 100% to 70%)

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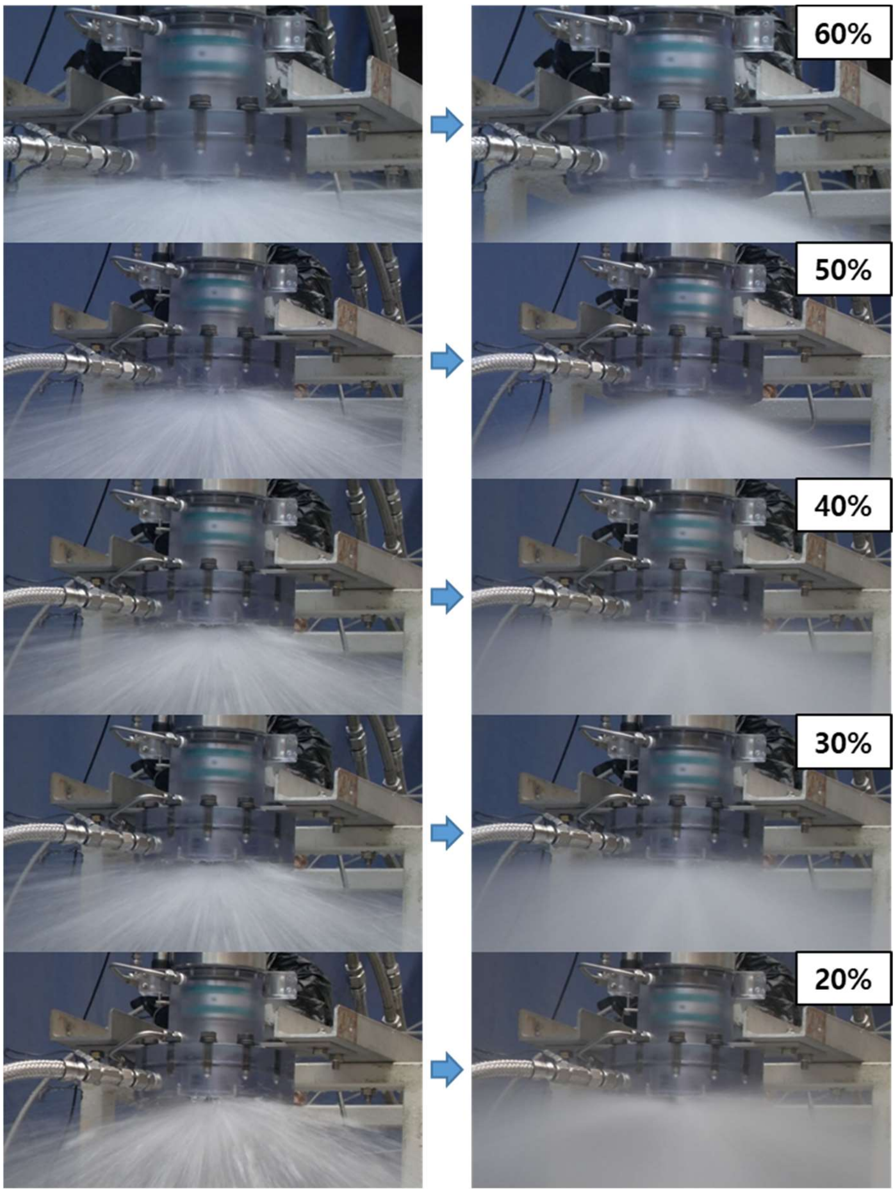

Figure 11: Spray pattern of pintle injector depending on the piston-sleeve position (from 60% to 20%)

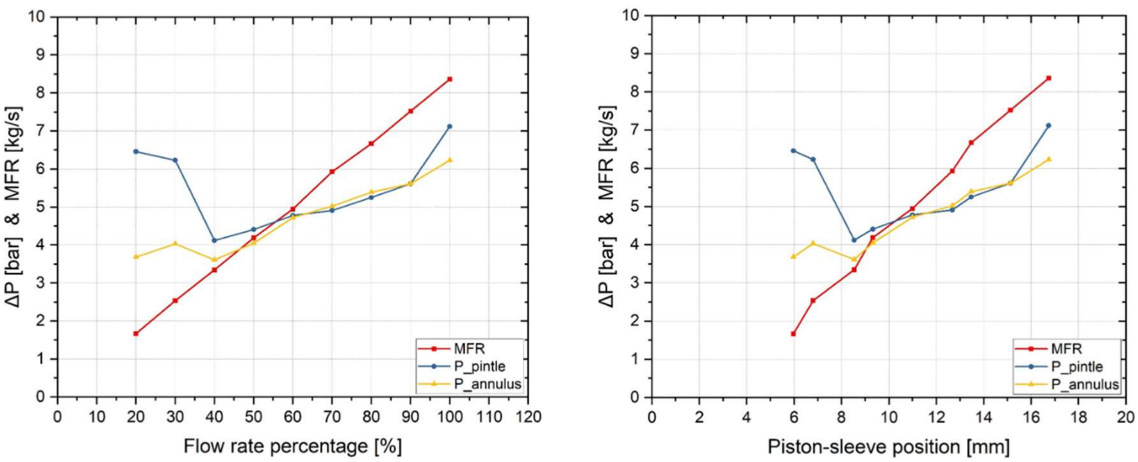

Figure 12: Results of the cold flow test of the servo-valve type pintle injector

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Table 2: Results of the cold flow test of the servo-valve type pintle injector

Flow rate [%]	Piston-sleeve stroke [mm]	Flow rate		Pressure [bar]	
		[lpm]	[kg/s]	P_pintle	P_annulus
100	16.74	501.66	8.36	7.12	6.23
90	15.13	451.47	7.52	5.61	5.61
80	13.47	400.23	6.67	5.25	5.39
70	12.67	355.73	5.93	4.91	5.02
60	10.99	296.71	4.95	4.78	4.72
50	9.32	251.35	4.19	4.41	4.05
40	8.53	200.70	3.35	4.12	3.61
30	6.80	152.04	2.53	6.23	4.03
20	5.97	99.96	1.67	6.46	3.68

5.2 Piston-Sleeve control response

The pintle injector used in this cold flow test was fabricated with a polycarbonate casing for visual inspection of the piston-sleeve movement. As a result, the pressure that can be applied to the upper and lower double acting cylinders of the piston-sleeve, which generate the driving force, was limited to a maximum of 10 bar. In order to fully utilize the superior control performance of the servo-valve used, a pressure of 70 bar or higher is required. However, since this condition could not be met, the focus of this cold flow test was not focus on the dynamic response of piston-sleeve.

6. Conclusion

This paper presents the results of a cold flow test conducted on the pintle injector using a servo-valve method for a variable thrust combustion chamber. It was confirmed that the mass flow rates matched well with the fully open state (piston-sleeve position: 16.75 mm, total mass flow rate of water: 8.36 kg/s) under conditions of 20% to 90% opening position. Furthermore, it was observed that the pressure drop could be maintained over a wide flow rate range, particularly at lower flow rates.

If conditions allow for the fabrication of the pintle injector casing using high-strength materials such as stainless steel in the future, dynamic response analysis will be conducted at that time.

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