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Development of Liquid Oxygen/Liquid Methane Pressurization Systems for Launch Vehicles

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Abstract
The Small Launcher Research Division (SLRD) of the Korea Aerospace Research Institute (KARI) is developing advanced propulsion technologies using liquid oxygen and liquid methane. SLRD's focus is on two vehicle systems: a Vertical Takeoff and Vertical Landing (VTVL) demonstrator, and the upper stage of a two-staged Small Launch Vehicle (SLV). SLRD have designed and built a reusable operation platform for short-duration flights to demonstrate and verify the landing propulsion system's capabilities. The VTVL demonstrator uses a pressure-fed cycle with gaseous nitrogen as the pressurant gas. The engine operates at a pressure of 30 bars, while the propellant tanks are pressurized at 60 bars. The upper stage of the SLV features a liquid oxygen-liquid methane expander cycle rocket engine with an autogenous pressurization system. Tests have been conducted to investigate heat transfer and pressurization abilities using cryogenic propellant tanks.

1. Development of pressurization system for VTVL

KARI and HanyangEng Co. Ltd, are developing a vertical takeoff and landing (VTVL) demonstrator to validate the core technologies of a reusable launch vehicle. The VTVL is equipped with 1-tonf thrust liquid rocket engine using liquid oxygen and liquid methane as propellants. The engine is a pressure-fed engine.

1.1 Propulsion system of VTVL

Propulsion system of the VTVL consists of an oxidizer tank, a fuel tank, two pressurized gas storage tanks, various valves, pipes/tubes and control & measuring devices [1].
The propellant tanks, with an internal diameter of 350 mm, is manufactured in a hemispherical shape by spin forming Inconel 718 material, welded, and insulated. Pressurant is gaseous nitrogen and charged at 270 bar in two 130 liter composite tanks. The combustion chmaber and injector head are both made of Inconel 718 by additive manufacturing, and a torch igniter is used for its ignition. This combustion chamber is regeneratively cooled using both liquid oxygen and liquid methane. The performance of the thrust chamber has been verified through hot fire tests at a ground mobile test facility located in KARI.
The shutoff valves for propellant supply in VTVL are pneumatically operated, and the flow control valves are a combination of a ball valve and a servomoter. The attitude control system of VTVL consists of a thrust vector control device for pitch and yaw with a rotational angle of ±5°, and a roll control device using four 40N thrusters mounted on the outer skin of the VTVL demonstrator. Structural strength tests, leakage tests, cold flow tests and ignition tests of the VTVL have been conducted and flight tests will be in the second half of this year.

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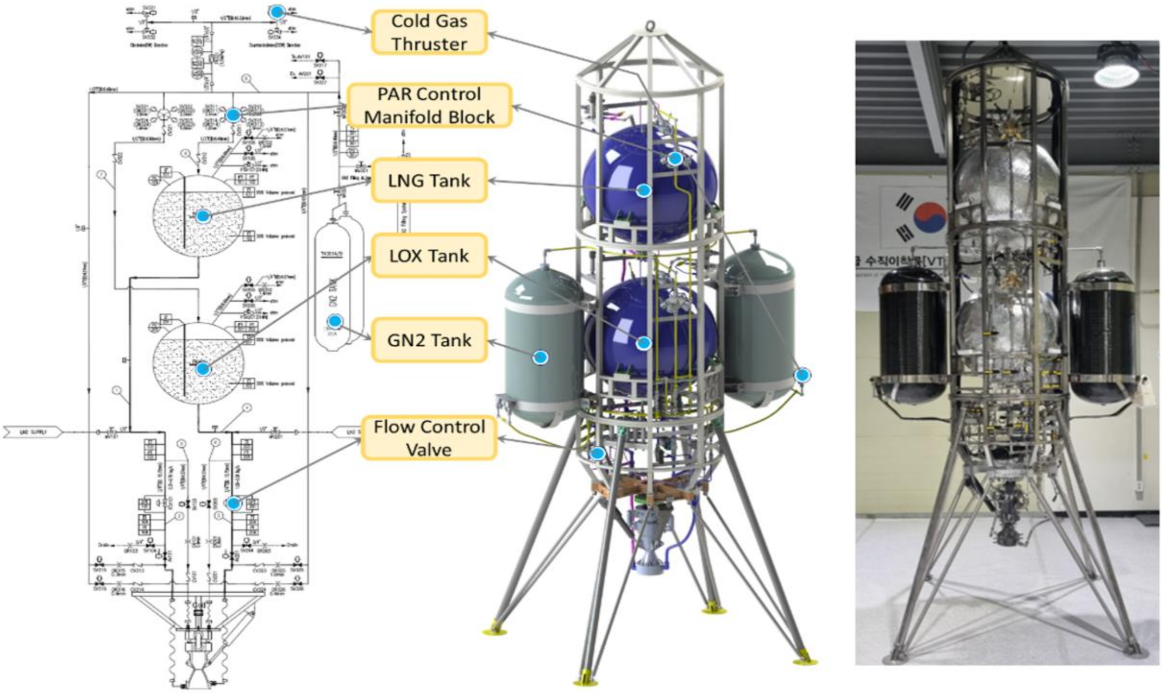

Figure 1: Propulsion system configuration of VTVL demonstrator

The performance and specifications of VTVL and its major components are provided in Table 1.

Table 1: VTVL Performance and the specifications of the main components [2]

Category	**Specification**	
VTVL	Thrust	1 tonf
	Flight time	< 60 sec.
	Propellant mass flow rate	3.34 kg/s
	Combustion chamber pressure	3.0 MPaA
Propellant tank	Type	Spherical
	Material	Inconel 718
	Capacity	179.6 Liter
	Working temperature	111 K (for LOX) 139 K (for LNG)
	Working Pressure	6.0 MPaA
Nitrogen storage tank	Type	Carbon Composite
	Material	Liner: Al. Reinforce material : Carbon
	Capacity	130 Liter
	Working Pressure	27.0 MPaA

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1.2 Pressurization system of VTVL

To achieve a combustion pressure of 30 bar, the ullage volume the the propellant tanks is pressurized to 60 bar using gaseous nitrogen. Flow control valves are installed in the supply pipes at the bottom of the propellant tanks to adjust the thrust by regulating the flow rate of the propellants. During the operation of the rocket engine, the storage pressure of the pressurized gas continuously decreases due to the supply of pressurized gas to the propellant tanks and RCS thrusters. In order to maintain a constant pressure within the propellant tanks, a pressure control system has been implemented.

The pressure control system for the propellant tanks consists of pressurized gas storage tanks, solenoid valve assemblies, and supply pipes. By setting the desired internal target pressure of the propellant tank, the four solenoid valves and the propellant tank vent valves open and close based on signals from pressure sensors installed on the upper dome of the propellant tanks. This allows for the adjustment of the amount of pressurized gas in the propellant tank ullage volume. The composition of the pressure control system is shown in Fig. 2.

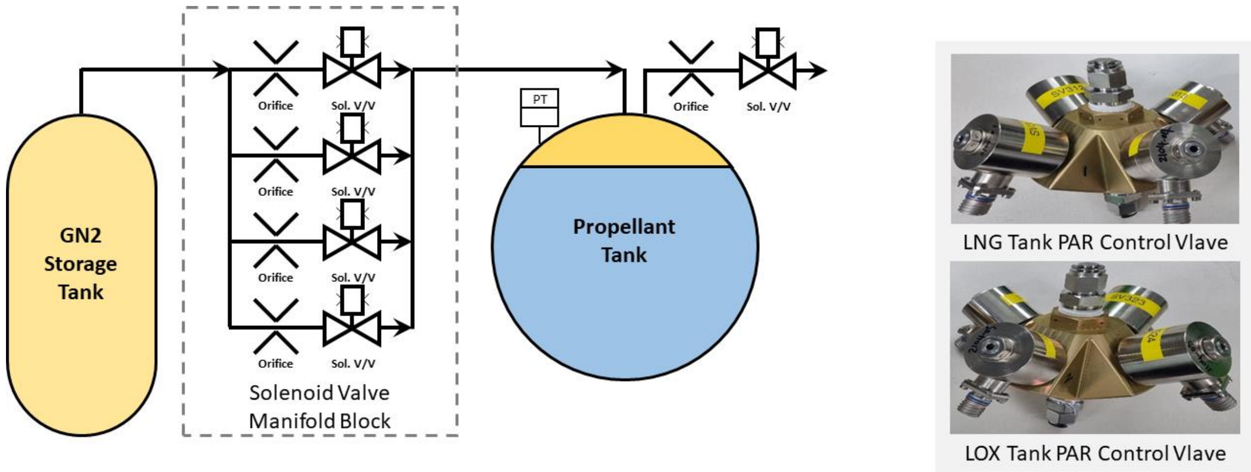

Figure 2: Configuration of the pressure control system [2]

The solenoid valves assembly of the pressure control system for the propellant tanks is combined with orifices with different cross-sectional areas. The system operates by changing the total cross-sectional area through the opening and closing of some of the four valves to supply the target flow rate, even when there are changes in the front pressure of the valves. The characteristics of the individual cross-sectional area ratio of the orifice applied to the four valves and the achievable cross-sectional area ratio through different valves combinations are shown in Figure 3.

The cross-sectional areas of the solenoid valves and orifices were selected to enable linear implementation of the cross-sectional area ratio for 16 cases based on the combination of the four valves. In this context, when all valves are closed, and no flow is supplied, it is considered as 0 %, and when all valves are opened, achieving the maximum cross-sectional area, it is considered as 100 %. When the pressure of the gas in front of the valves are lowered to 80 bar, the cross-sectional area capable of maintaining the propellant tank pressure at 60 bar is considered as 100% of the maximum cross-sectional area.

The flow coefficient of the solenoid valves was determined by measuring the values obtained from the gaseous nitrogen flow test in the development stage. To calculate the required flow rate of the pressurized gas, the supply flow rate of the propellant and the temperature of the ullage volume inside the propellant tank must be considered. The supply flow rate of the propellant is adjusted through the propellant flow control valve to achieve the target value. The temperature of the ullage volume is difficult to predict due to the complex heat-mass transfer characteristics inside the propellant tank, so the temperature change in the ullage volume was confirmed through cold flow tests. During the operation of the VTVL demonstrator, as the pressure of the gaseous nitrogen storage tank decreases, the temperature of nitrogen also decreases. When considering the density of gaseous nitrogen supplied to the solenoid valves, the polytropic expansion process of the gaseous nitrogen storage tank was also considered.

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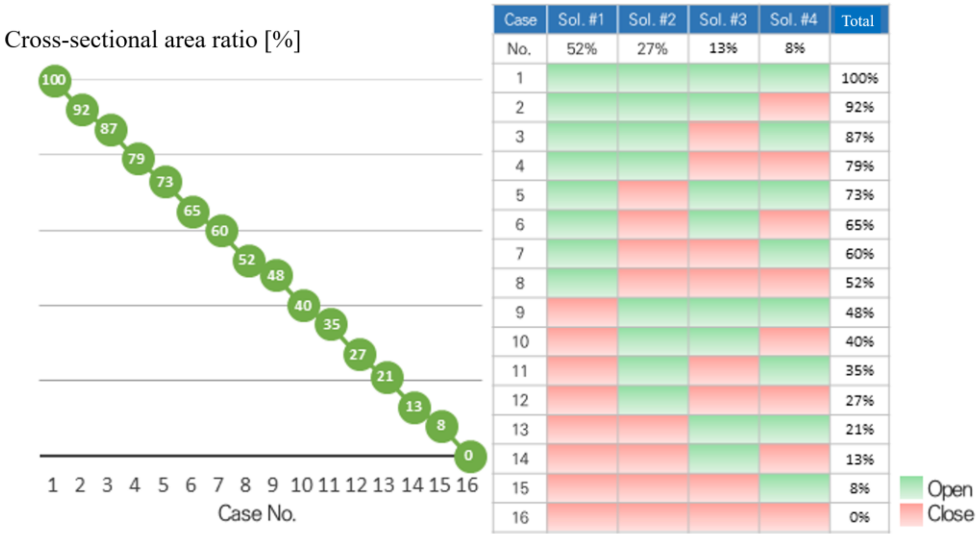

Figure 3: Achievable cross-sectional area ratio using solenoid valves assembly [2]

The ullage pressure control tests of the propellant tank were conducted to confirm that the ullage pressure of the tank remains constant when the flow rate of propellant from the tank to the combustion chamber changes. Figures 4 and 5 represent the pressure control tests results of the LOX tank and LNG tank, respectively. The tests show that the ullage pressure of the tank is maintained at a constant level by gradually reducing the opening percentage of the propellant flow control valve.

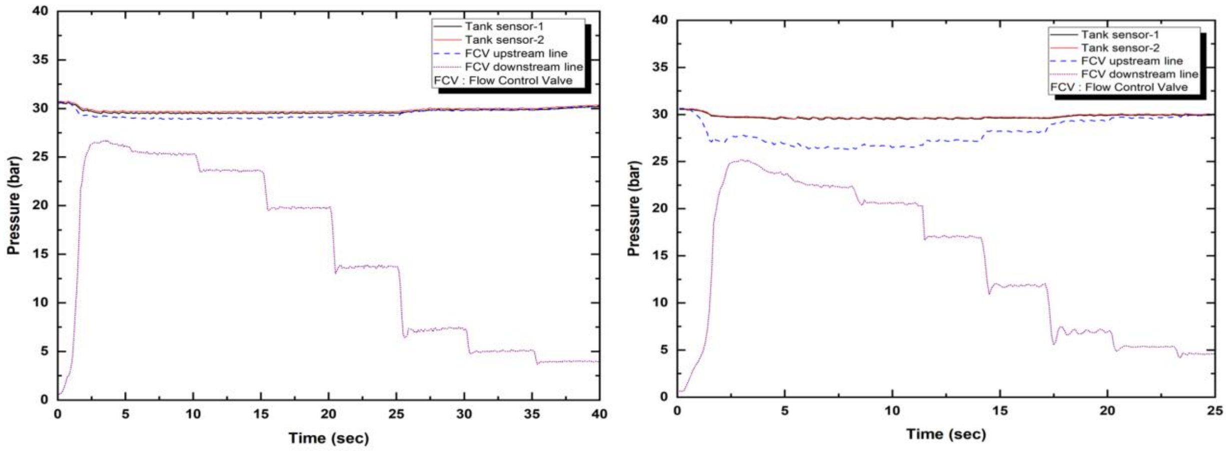

Figure 4: Pressure control test results (left: LOX tank, right : LNG tank)

1.3 Flight test

To conduct performance tests of the demonstrator, a test facility was built at an outdoor test site. The test facility consists of a vertical test stand, propellant and pressurized gas supply/discharge equipment, and a control room. Fig 5 (left) represents a vertical test stand for ground firing tests, which is designed and constructed to provide a working platform for inspection and repair of the demonstrator. Underneath the working platform, there is a flame deflector capable of spraying water to reduce noise generated during fire tests and ensure facility protection and fire prevention. The demonstrator has a takeoff weight of 762 kg, a maximum flight time of 65 s, and a thrust control range of 70~100 %. The demonstrator will be used to perform a mission of ascending vertically to 15 m, horizontally moving for 10 m, and vertical descending/landing.

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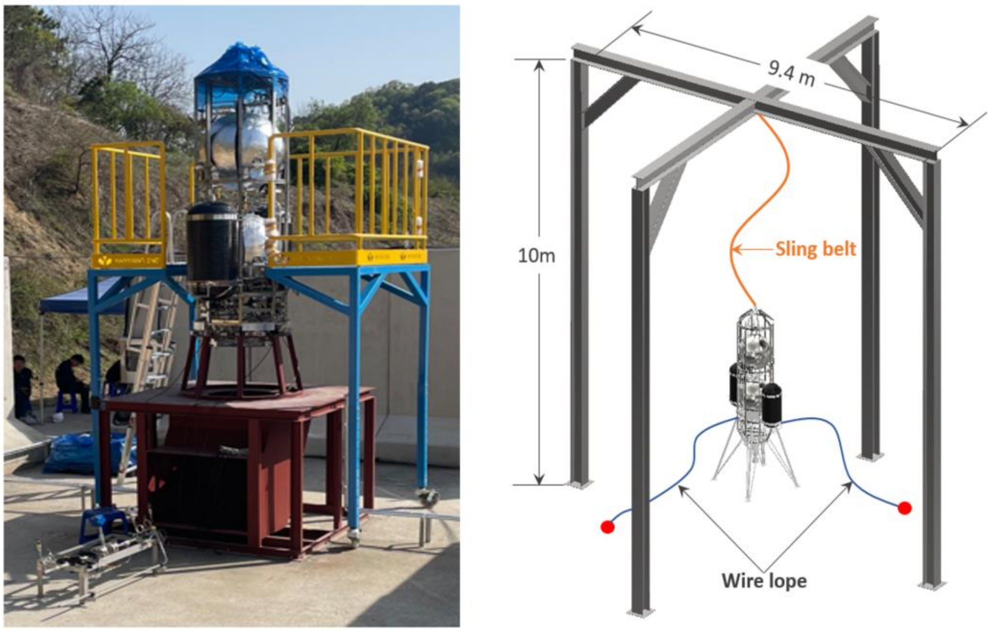

Figure 5: Preparation of vertical fire test facility and tethering flight test scheme [3]

2. Development of Pressurization system for the upper stage of SLV

The SLRD of KARI is developing a 3-ton class liquid rocket engine to be used in the upper stage of a small launch vehicle capable of delivering a 500 kg payload to a 500 km sun-synchronous orbit. The upper stage propulsion system uses liquid oxygen and liquid methane as propellants.

2.1 Configuration of the upper stage

The design drivers for the two-stage small launch vehicle are high reliability, high performance, low cost and low development risk. To satisfy these positive characteristics, a common bulkhead is used for the propellant tanks, and a combination of the expander cycle rocket engine and autogenous pressurization system is selected. The oxidizer tank and fuel tank have volumes of $3.5m^3$ and $2.8m^3$, respectively, with a diameter of 2.0 m. The total estimated mass of the common bulkhead tanks is 260 kg. Figure 6 illustrates the configuration of the upper stage and the common bulkhead propellant tanks.

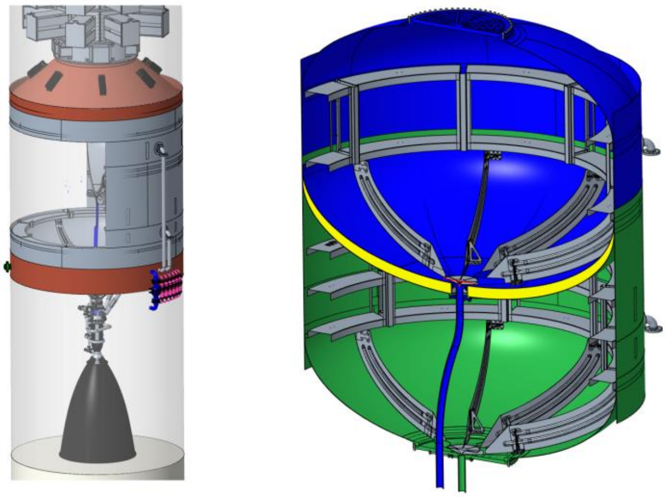

Figure 6: The upper stage of the small launch vehicle

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2.2 Pressurization system for upper stage

The basic structure of the autogenous pressurization system in the upper stage of the small launch vehicle is shown in Figure 7. The fuel tank is pressurized using gaseous methane heated through the regenerative cooling channels, while the oxidizer tank uses gaseous oxygen heated in a heat exchanger. The flow rate of the pressurizing gas is controlled by a combination of three solenoid valves and orifices. The diameter of each orifice hole is determined to correspond to the rated flow rate, small flow rate, and emergency flow rate of gas respectively.

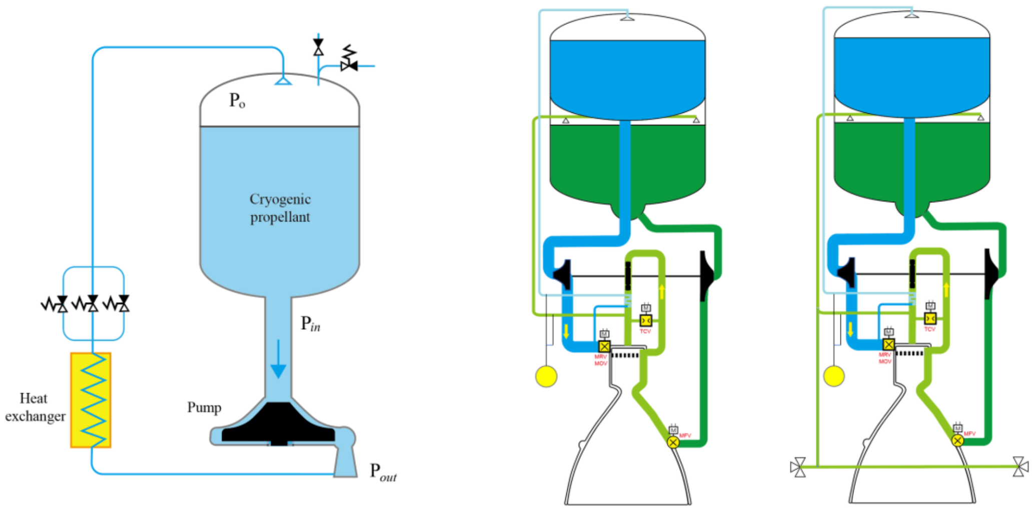

Figure 7: architecture of autogenous pressurization system

2.3 Research & Development activities of autogenous pressurization system

Prior to the development of the autogenous pressurization system, research experiments are being conducted to evaluate the pressurization capacity of the pressurizing gases. As shown in table 2, experiments with seven combinations of pressurant and propellant were planned. Among them, experiments with three combinations (cases of A, B, C) were conducted in 2022, and the remaining combinations are scheduled to be conducted in the second half of 2023. The main objective of the experiments is to determine the mass flow rate of the pressurant gas that maintains the same pressure in the ullage volume of the propellant tank when the liquid propellant discharge volume flow rate is constant.

Table 2: The combination of pressurant gases and simulated propellants

	Pressurant gas	**propellant**
A	gaseous nitrogen	water
B	gaseous nitrogen	liquid nitrogen
C	gaseous helium	liquid nitrogen
D	gaseous helium	liquid oxygen
E	gaseous oxygen	liquid oxygen
F	gaseous helium	liquid methane
G	gaseous methane	liquid methane

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The configuration of autogenous pressurization simulation test stand is shown in Fig. 8, and consists of a propellant tank, a pressurized gas supply system, a propellant discharge system, and a control & measurement system. The volume of the propellant tank is 0.3 m^3, and it is made of A240-304 material.
The wall of the tank is covered with a 100 mm thick layer of urethane to minimize heat transfer from the external environment. Insulation of the tank is important to achieve the purpose of the experiments.
In order to measure the level of propellant, a level sensor has been installed in the tank, and to verify the supply conditions of pressurized gas, a mass flowmeter, pressure sensors and temperature sensors were installed in the gas supply line, while a turbine flowmeter was installed in the propellant supply line.
The gas distributor is designed with multiple holes to minimize sloshing of the propellant.
A level sensor and a heat exchanger have been installed. The level sensor can measure the level of about half the tank height, and the heat exchanger can't increase 'constantly' the temperature of the supplied gas. So these devices are in need of improvement.

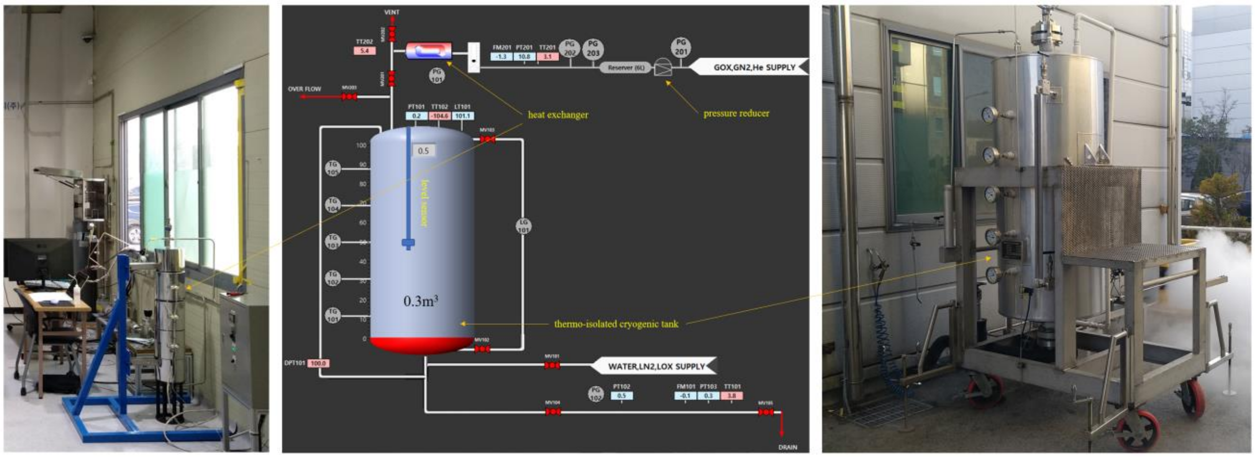

Figure 8: Test setup with the thermal insulated tank

2.4 Results of the experiments

The experiments were conducted under the conditions of A, B, and C as specified in Table 2.
Assuming that the ideal propellant has the same temperature as the supplied pressurized gas and there is no mass transfer, the flow rate of the pressurized gas filling a 10 liter/min volume is 1.05 g/s.
When filling the tank with water and charging it with 10 liter/min of the ullage volume with gaseous nitrogen, it consumed 1.32 times more gaseous nitrogen compared to the ideal case.
By comparing the experimental results of case A and case B, we can assess the intensity of condensation of the gaseous nitrogen in the liquid nitrogen. Considering that the water temperature was 15 ℃ and the temperature of LN2 was -185 ℃, the ratio is calculated as (273+15)/(273-185) = 3.27. This means that, based solely on the temperature difference, approximately 3.27 times more pressurized nitrogen gas is required in case B compared to case A.
With the experiments of case B and case C, we can experimentally compare the pressurization capabilities of gaseous helium and gaseous nitrogen. The molar mass of helium is 4 kg/kmol, while the molar mass of nitrogen is 28 kg/kmol. When comparing based solely on molar mass, the mass flowrate of nitrogen gas required to fill the same volume at the same pressure is 7 (=28/4) times greater than that of gaseous helium. In the experiment, gaseous nitrogen was consumed approximately 7.2 time more compared to gaseous helium, yielding results that are closely similar to the ratio based on molar masses. It is believed that this result is due to the short duration of the experiment, which did not provide enough time for gaseous nitrogen to condense into liquid nitrogen.

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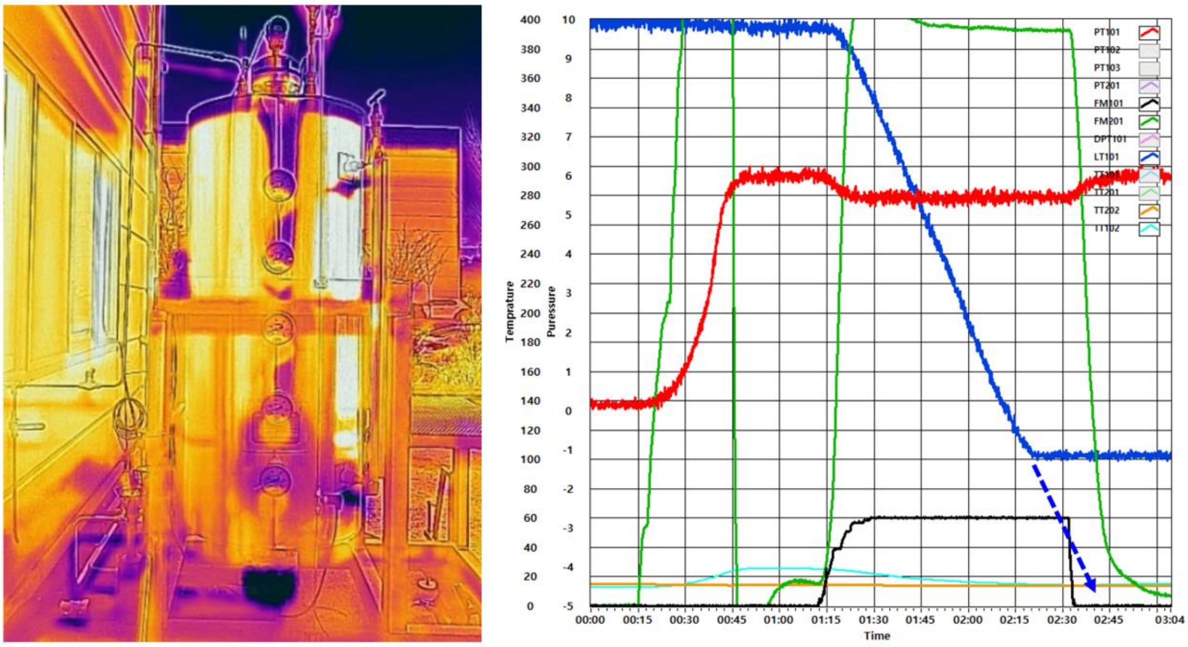

Figure 9: Autogenous pressurization simulation experiment [4]

Table 3: Pressurization capacity of gaseous nitrogen under ideal condition

	Pressurant	**Simulated propellant**	**Filling volume rate**		**Pressurant mass flow**	
			liter / min	m^3 / min	kg/min	g/sec
0	GN2	Ideal fluid	10	0.01	0.063	1.05

Table 4: Pressurization capacities of gases under real conditions

	Pressurant	**Simulated propellant**	**Pressurant mass flow** (SLPM)	**Real gas mass flow** (considering gas factor)	**density**	**Pressurant mass flow** (g/sec)
1	GN2	Water	66.7	66.7	1.251	1.39
2	Helium	LN2	133	184.8	0.378	1.16
3	GN2	LN2	400	400	1.251	8.34

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2.5 Future tasks and plans

In the second half of 2023, the simulated tests of the autogenous pressurization system will be conducted using real propellants (liquid oxygen and liquid methane). Thes tests are expected to provide information on the effect of autogenous pressurization on the payload transportation efficiency and cost-effectiveness of the autogenous pressurization system versus helium pressurization.
In addition to that, there are plans to conduct research on propulsion systems for space transporatations that utilize autogenous pressurization and expander cycle rocket engine.
The purpose of this research is to compare with research results about the space transportation systems using hydrogen peroxide-kerosene and nitrous oxide-ethane combinations as propellants, which began in Korea several years ago.

3. Summary and Conclusions

Development of the pressurization system for VTVL using liuqid oxygen and liquid methane as propellant has been carried out. And fundamental research is currently underway to develop autogenous pressurization system for upper stage of the small launch vehicle. The research results from these studies can also be used as basic data for the development of resuable rockets, space transportation systems, and air launch systems.
Research on pressurization systems for various rocket systems such as VTVL, upper stage for small launch vehicle, and space transportation system, as well as air launch is expected to amplify the synergy in research and facilitate the accumulation of advanced technology effectively.

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