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Development of a cryogenic high-pressure pump for compact FGSS high-pressure skids

Fuel Injection & Gas Admission and Engine Components

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ABSTRACT

Currently, 300 bar high-pressure gas supply skids for LNG fuel gas supply systems (FGSS) used in liquefied natural gas (LNG) fueled ships employs two cryogenic high-pressure pumps, including one spare pump. The key management component of the cryogenic high-pressure pump is a cold-end, which pressurizes cryogenic LNG to 300 bar. The cold-end has the shortest maintenance period and is the part most prone to issues. The reason for having a spare pump in the existing high-pressure gas supply skid is to ensure an immediate replacement with a spare cold-end when necessary. This study's cryogenic high-pressure pump is designed with two combinations of four cold-ends in a single pump, allowing them to serve as backups for each other. The cam/roller drive mechanism enables cut-off of the non-operational cold-end combination. A separately designed cut-off device was devised, and to design this structure, the cam/roller drive mechanism's structure and lubrication analysis were performed. Additionally, vibration of the entire pump according to cold-end combinations was evaluated. A prototype was manufactured, and the design was validated through performance and durability tests. Currently, demonstration tests are ongoing in conjunction with engines at an engine test facility. The operational structure of the cryogenic high-pressure pump developed through this study has been validated, and lineup model development is underway according to ship types.

1 INTRODUCTION

Climate change is an unavoidable reality. While CO_2 emissions have declined in most sectors of developed countries since 1990, emissions from international shipping have increased by 34%. According to the International Maritime Organization (IMO)'s 4th GHG study, international shipping emissions rose by 20% between 2012 and 2018 [1]. In response, IMO adopted a strategy in 2018 to cut carbon intensity by 40% by 2030. Furthermore, the 2023 IMO GHG Strategy strengthened the goal of achieving net zero greenhouse gas emissions by or around 2050. Measures like carbon taxes, emission trading, and fuel regulations are under discussion. Technologies such as slow steaming and wind-assisted propulsion can reduce emissions by up to 30%, but achieving over 50% reduction requires shifting to low-carbon fuels like liquefied natural gas (LNG), hydrogen, methanol, or ammonia [2].

Given these targets, LNG is being reconsidered as an environmentally friendly fuel due to its lower environmental impact. In the maritime industry, LNG is gaining increasing importance as a marine fuel, largely driven by the IMO's stringent regulations aimed at reducing air pollutant emissions. Additionally, the supply chain and cost issues of alternative fuels remain key discussion points. Given this background, the demand for LNG-fueled ships continues to rise, making the development of efficient, safe, and competitive fuel gas supply systems (FGSS) a critical challenge for shipbuilders.

This study develops a cryogenic high-pressure pump for the FGSS of LNG-fueled ships as shown in Figure 1. The pump is designed to discharge LNG at cryogenic temperatures, 300 bar pressure, and 85% efficiency. A reliable structure for high-pressure, cryogenic conditions was designed and validated through experiments. This paper outlines key design considerations and presents prototype test results for verification.

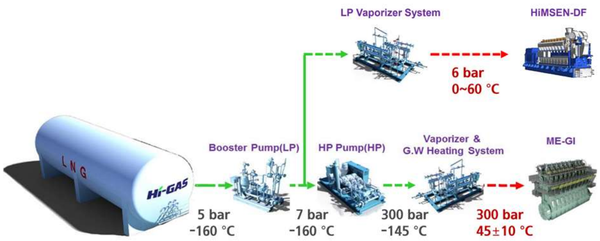


Figure 1. FGSS for ME-GI engine

2 PUMP DESIGN

The current 300-bar high-pressure gas supply skid for LNG-fueled propulsion ships employs two cryogenic high-pressure pumps, including a standby pump. The critical component of the cryogenic high-pressure pump is the cold-end, which pressurizes LNG at cryogenic temperatures (below -130°C) to 300 bar. This part has the shortest maintenance cycle and the highest failure rate. The necessity of a standby pump in the existing high-pressure gas supply skid underscores the importance of having readily replaceable spare cold-ends.

In this study, we developed a cryogenic high-pressure pump that integrates two cold-ends into a single pump, allowing them to serve as mutual backups as shown in Figure 2. The pump is designed with a cam/roller drive mechanism that can cut off the non-operating cold-end combination.

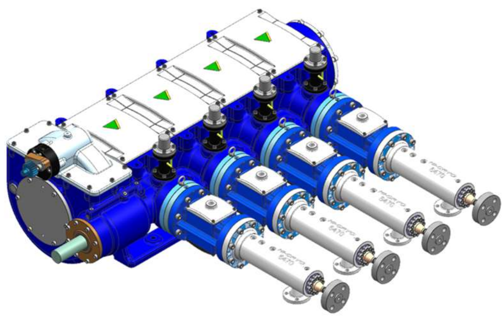


Figure 2. Pump external view

This unique structure enables the pump to be configured as needed, as illustrated in Figure 3.

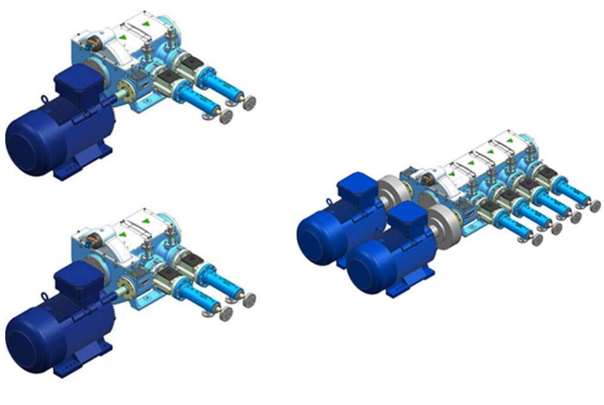


Figure 3. Separated vs. Integrated configuration

We designed and implemented a separate cut-off device, analyzing the structure and lubrication of the cam/roller drive mechanism to achieve this design. Additionally, we evaluated the pressure pulsation and overall vibration of the pump based on the cold-end combination.

The design complies with ISO Standard specifications, 24490 and 13710. The cold-end of the pump has obtained product design approval from the classification society, ABS.

2.1 Fundamental design

The cryogenic high-pressure pump developed in this study is a reciprocating piston type, driven by an electric motor. This pump maintains a constant pressure of 300 bar across the entire operating speed range, with the flow rate varying according to speed. For the prototype, a duplex operation mode was adopted, considering the cold-end configuration. Designed for application in container ships, the piston diameter, stroke, and pump speed were optimized to achieve a maximum discharge flow rate of 10 m³/hr. The performance curve is shown in Figure 4.

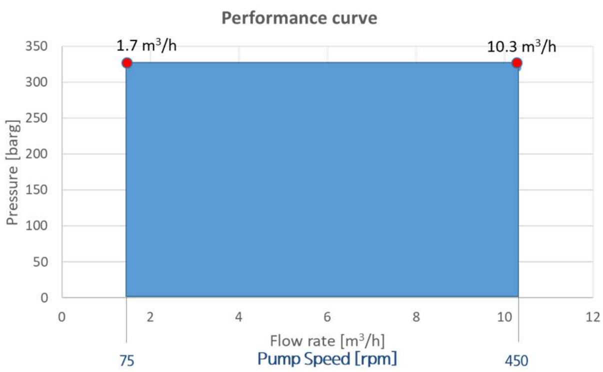


Figure 4. Performance curve

The fundamental design specifications were analytically verified through 1D simulation as shown in Figure 5, and structural loads were analyzed. Additionally, 1D simulation was conducted to account for potential leakage from the pistons of individual cold-ends, determining the maximum flow rate that meets target efficiency. Based on this, the cryogenic seal design for the pistons was optimized. The high-pressure pump skid system was analyzed to evaluate pressure pulsations that might occur due to different cold-end combinations.

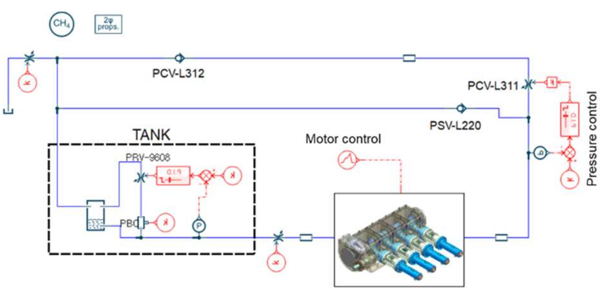
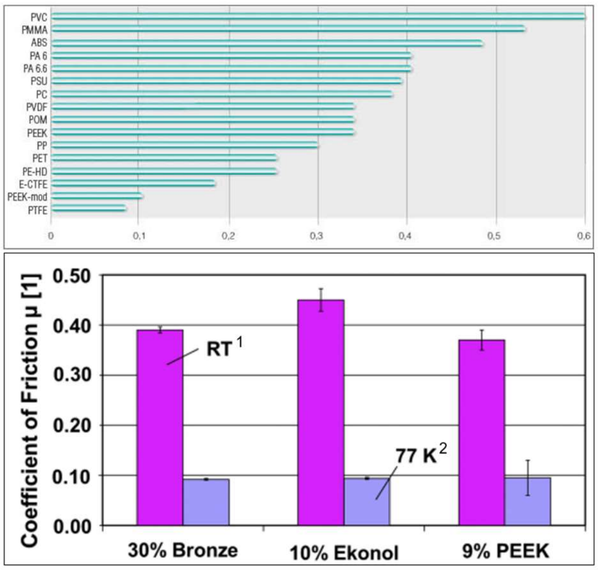


Figure 5. 1D simulation model

2.2 Cryogenic sealing system

Since LNG is stored at a cryogenic temperature of around -163°C, the design of cryogenic seals is crucial. These seals block vapor and heat transfer that occur as LNG vaporizes, ensuring stable fluid movement within the pump while maintaining a proper seal. In this study, cryogenic seals made of PTFE-based materials were applied to the pump. The PTFE-based material maintains its mechanical strength and chemical resistance even in cryogenic environments. Additionally, it offers significant advantages in terms of friction, particularly under cryogenic conditions where the coefficient of friction is reduced by over 70% as shown in Figure 6.



[1] Room temperature, [2] -196.15 °C

Figure 6. Frictional properties of PTFE-based material: Coefficient of friction [3][4]

The specifications and arrangement of the cryogenic seals were reviewed to meet the allowable leakage rate of the cold-end piston derived from the fundamental design. Additionally, the maximum load acting on individual seals was evaluated through multi-body dynamic analysis. Computational Fluid Dynamics (CFD) and heat transfer analyses were conducted to assess temperature and pressure conditions, which served as criteria for the seal design.

The sealing system of the cold-end piston was based on the fundamental hydraulic piston system, as shown in Figure 7. As illustrated in Figure 8, the specific specifications (clearance, width and number) of the seal were designed to meet the target requirements for the leakage rate.

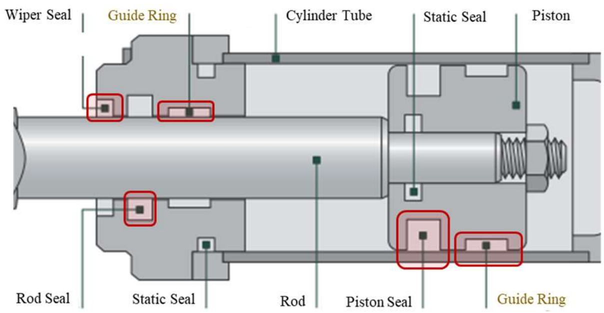


Figure 7. Sealing system of hydraulic piston

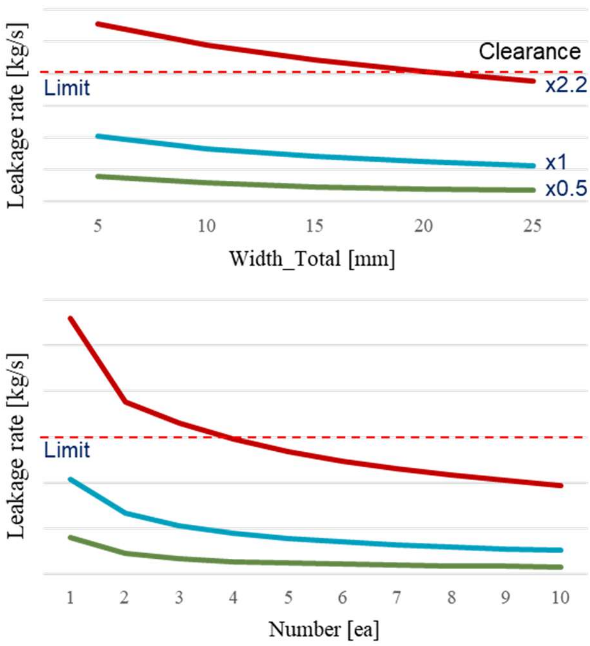


Figure 8. Design review of cryogenic seals

2.3 Cold-end driver design

One of the key components of the pump is a cam/roller drive mechanism with a cut-off function. This mechanism enables interaction between the cam and roller, facilitating stable pressure increase. Furthermore, the cam/roller structure plays a critical role in ensuring smooth fluid flow, thereby enhancing pump efficiency. In this study, a cam profile was designed to minimize the maximum torque acting on the cam.

To ensure a stable cam/roller design, structural analysis and multi-body dynamic analysis were performed. The design criteria for the pump structure and drive mechanism were aligned with those of Hyundai HiMSEN H32 engine, aiming for standardization. The cam/roller mechanism meets both static and fatigue strength requirements, while dynamic analysis of the roller drive confirmed stability, including the mitigation of surging within the internal spring.

It was confirmed that the roller drive remained dynamically stable at maximum speed, 450 rpm as shown in Figure 9.

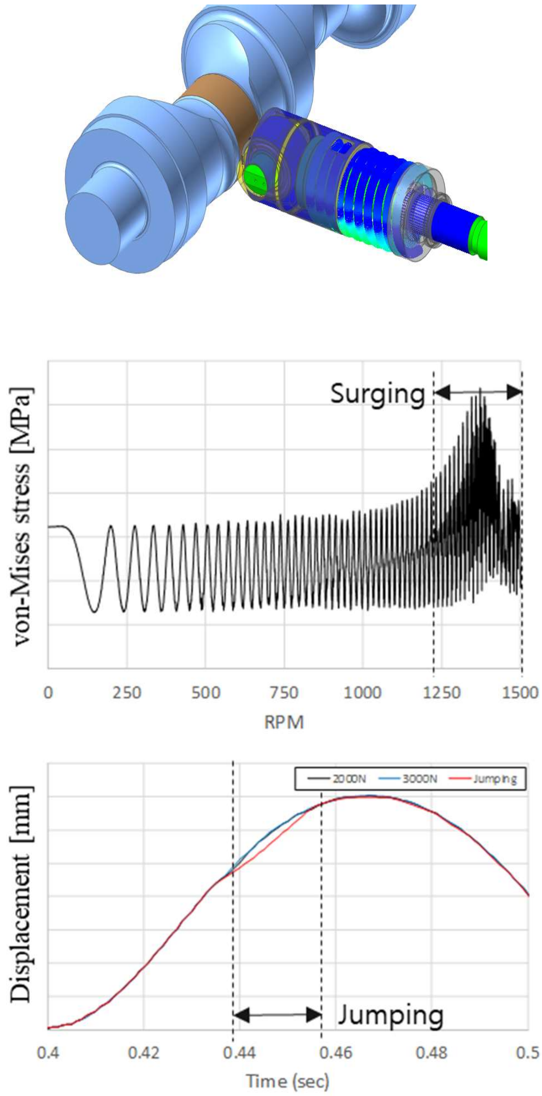


Figure 9. Multi-body dynamic analysis results of roller drive and spring

2.4 Bearings and lubrication system

Bearings are crucial components that enable smooth operation of the pump's rotating parts with minimal friction. The journal bearings used in the pump camshaft are identical to those in Hyundai HiMSEN H32 engine class, which have been validated in existing engines.

However, unlike power generation engines that operate at consistently high speeds, the high-pressure pump of FGSS operates at variable and relatively lower speeds. Therefore, lubrication analysis was conducted as shown in Figure 10. We confirmed that the thickness of the oil film tends to increase as the oil groove width decreases and derived a design improvement plan, leading to enhancements in lubrication performance during low-speed operation. A 10°C reduction in lubricant supply temperature resulted in a 35% increase in minimum oil film thickness (MOFT), and after design improvements, the MOFT increased by more than twofold. The lubrication performance at the pump's minimum speed, 75 rpm and high-level temperature of lubricant was confirmed to meet the design criteria (MOFT) established from the HiMSEN engine [5].

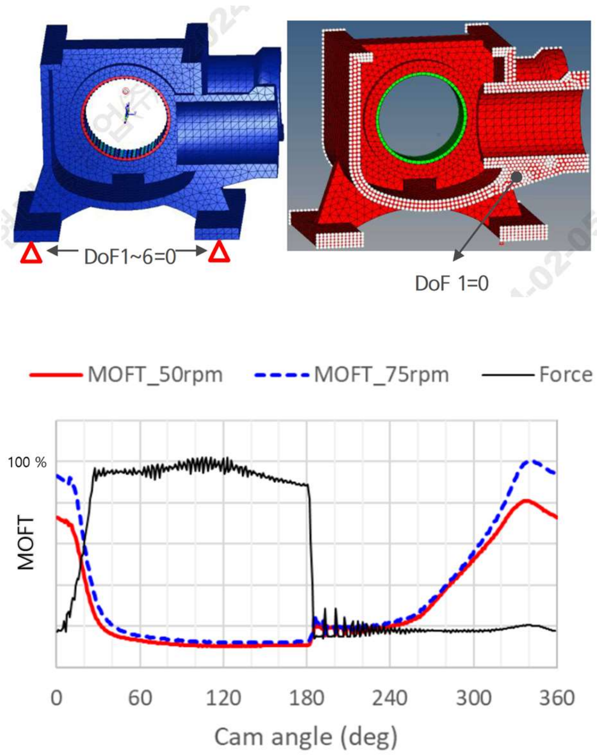


Figure 10. Lubrication analysis results of journal bearings at pump min. speed

A 1D hydraulic system simulation was performed to determine the specifications (oil volume, circulation rate, supply pressure and flow rate) of the lubrication oil supply system as shown in Figure 11. The external piping from the oil tank to the pump, internal flow paths within the pump, and orifice sizes at key lubrication oil supply locations were modeled to evaluate pressure and flow rate of lubrication oil.

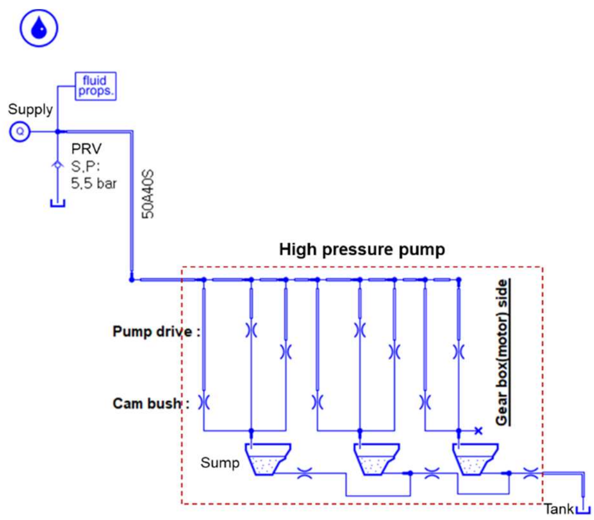


Figure 11. 1D hydraulic system simulation model of lubrication oil supply system

3 PROTOTYPE TEST

3.1 Test skid and facility

For this study, a separate pump skid was fabricated for prototype demonstration, and its performance was verified using liquid nitrogen and LNG as shown in Figure 12. The pump was also installed in an actual engine test facility to conduct performance and durability tests in conjunction with the ME-GI engine.

A centrifugal low-pressure pump, capable of pressurizing the test fluid to 10 bar before entering the high-pressure pump from the cryogenic fluid storage tank, was installed. The pump's performance and efficiency were evaluated based on supply pressure. Additionally, a net positive suction pressure (NPSP) test was conducted.

The experiment utilized equipment capable of real-time measurement of the pump's operating characteristics. The temperature, pressure, and discharge flow rate of the test fluid were measured and analyzed according to pump load (speed) to assess efficiency. Furthermore, vibrations in the pump drive and cold-end, as well as noise levels around the pump, were measured to collect data.

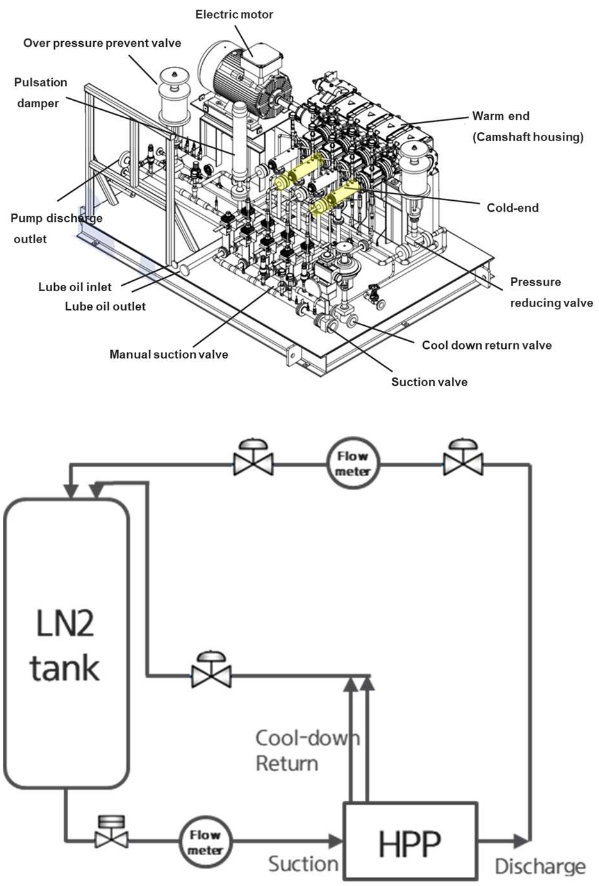


Figure 12. Pump skid and facility diagram for LN2 prototype test

3.2 Test results

The pump demonstrated stable operation under cryogenic and high-pressure conditions. The seal and bearing systems maintained their sealing and lubrication performance as designed, and the pump performance met the intended objectives. Additionally, the cam/roller drive mechanism effectively managed pressure fluctuations, ensuring stable performance. The actual pump testing is shown in Figure 13.

Figure 13. Pump test view

Test results confirmed that the designed pump successfully achieved the target performance, a maximum discharge flow rate of 10 m³/hr. The pump discharge flow rate ranged from a minimum of 1.5 m³/h to a maximum of 10.3 m³/h as shown in Figure 14. And the pump efficiency reached 85%, operating stably at a fluid temperature of -163°C. It provided a stable fuel supply without pressure fluctuations, even at a discharge pressure of 300 bar. Notably, the pump-maintained lubrication performance and operated normally at low speeds.

The pump efficiency varied from a maximum of 88% to a minimum of 65%, depending on pump speeds. Efficiency decreased in the low-speed range (<25% load), likely due to a reduced suction flow rate, which led to decreased cooling flow for the cold-end and increased internal heat loss as piston reciprocation slowed.

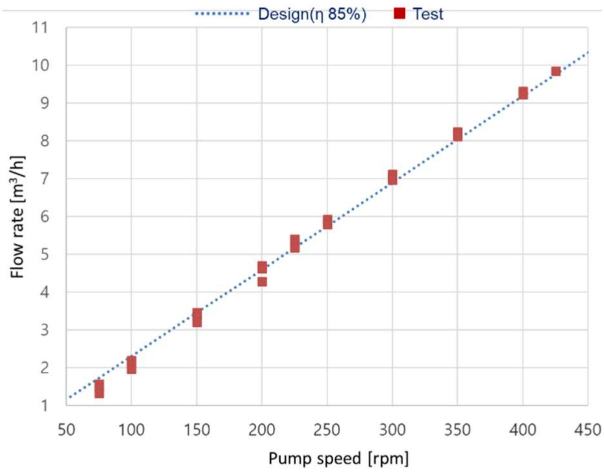


Figure 14. Pump performance test results (discharge flow rate)

A durability test was conducted under full-speed continuous operation to assess the fatigue life of structural and drive components. For structural and drive components, the test met the 10^7 cycles requirement, corresponding to infinite life for steel materials. The condition of the major components was inspected through disassembly after the durability test.

Subsequently, engine-linked tests were performed to evaluate stability under various operating conditions, and ongoing tests are being conducted to determine the lifespan of key wear components such as cryogenic seals of the cold-end and journal bearings. The wear of these components is being monitored over operating time. Based on accumulated data, a lifespan prediction chart will be developed in the future.

4 CONCLUSIONS

Performance Achievement: The cryogenic high-pressure pump developed in this study successfully achieved the target performance of maintaining a fluid temperature of -163°C, a discharge pressure of 300 bar, and an efficiency of 85%. The pump demonstrated stable LNG fuel supply from the FGSS system to the engine, exhibiting excellent performance even in cryogenic environments without pressure fluctuations or instability in fluid flow.

Innovative Design: The design, which integrates two cold-ends into a single pump and employs a cam/roller drive mechanism, proved effective in maintaining stable operation and managing pressure variations. The use of high-durability materials for the seals and bearings ensured reliable performance under extreme conditions.

Comprehensive Testing: The pump's durability and efficiency were validated through extensive testing, including full-speed continuous operation and engine-linked tests. These tests confirmed the pump's ability to perform reliably under various operating conditions.

Practical Application: The successful completion of the lineup design and ongoing prototype testing indicate that the pump is well-prepared for practical application in LNG-fueled propulsion systems. This study contributes to the advancement of cryogenic pump technology, providing a reliable solution for stable and efficient LNG fuel supply in marine applications.

5 DEFINITIONS, ACRONYMS, ABBREVIATIONS

IMO: International Maritime Organization

LNG: Liquified Natural Gas

FGSS: Fuel Gas Supply System

MOFT: Minimum Oil Film Thickness

NPSP: Net Positive Suction Pressure

6 REFERENCES AND BIBLIOGRAPHY

[1] Faber J et al. Fourth IMO GHG Study 2020. London, UK: International Maritime Organization; 2021.

[2] Park, H.C, et al. 2023. Methane emission reduction technologies for medium-speed dual-fuel engines, Paper of CIMAC Congress 2023, Busan, Korea, No. 433.

[3] https://www.macplas.co.nz/mechanical-properties/

[4] K. Friedrich, Polymer composites for tribological applications (2018)

[5] Lee, H, et al. 2023. Tribology in engine parts design considering the characteristics of operating regime, Paper of CIMAC Congress 2023, Busan, Korea, No. 324.

7 CONTACT

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