CIMAC CONGRESS 25
ZURICH, MAY 19 – 23, 2025

2025 | 056

Development of supply and safety system for hydrogen in two-stroke marine diesel engine

Safety Aspects of New & Alternative Fuels

Ryosuke Ishibashi, Mitsui E&S Co., Ltd.

Johan Sjöholm, MAN Energy Solutions SE
Michael Kryger, MAN Energy Solutions SE
Hiroyuki Sato, RIKEN KEIKI Co., Ltd.
Hisako Kato, Mitsui E&S Co., Ltd.

ABSTRACT

The GHG emission reduction target set by the IMO necessitates the application of carbon-free fuels like ammonia and hydrogen in the marine sector. This is currently one of the main challenges for industry and in particular for the ICE development. However, there are currently no operation results and few calculation results using hydrogen in two-stroke marine diesel engine. This work aims to clarify the applicability of hydrogen to the engines mentioned above.

In order to achieve this, MAN Energy Solutions (MAN-ES) and Mitsui E&S (MES) collaborated on converting one cylinder of the MES test engine, 4S50ME-T, to operate on hydrogen while the remaining three cylinders ran on diesel oil. The combustion principle and engine design, including the engine control system, were based on a ME-GI engine, which is a dual-fuel engine operating in diesel mode with high pressure gas injection at around TDC and a small diesel pilot directly injected into the combustion chamber. This paper will present the supply and safety systems used in these experiments and the results thereof.

To meet the requirements of a ME-GI fuel gas supply system, a four-stages gas compressor solution was used to supply high-pressure hydrogen gas to the engine via the gas valve train which had a double block bleed valve system intended for hydrogen operation.

And to comply with safety requirements of ME-GI and the IGF code, a mechanical ventilation system in double wall pipes was applied at the MES testbed which was regarded as the engine room. Moreover, nitrogen was used as a ventilation medium for ensuring the safety of the testbed in case a large amount of hydrogen leaked. However, it had been known that the hydrogen gas detectors commonly used in the industry today had a fundamental problem that they are unable to detect the hydrogen gas under the inert gas environment. Therefore, the prototype of gas detector which could be used under the nitrogen environment and which could be directly inserted into the outer pipe was newly developed by RIKEN-KEIKI.

As a consequence of the combination the engine and supply system, high pressure-hydrogen could be stably supplied to the engine up to the full engine load. And during the hydrogen test period, the gas compressor showed good performance without the pressure pulsation and showed good followability against the engine load variation. No hydrogen leakage from the supply system nor the engine was found during hydrogen operation. Moreover, the changeover sequence from hydrogen mode to diesel mode went smoothly at any engine load. This showed the hydrogen engine system using ME-GI including high pressure gas supply system had a great potential to apply in maritime sector. It will be necessary to increase the flow capacity of the supply system for applying to marine engines, whereas safety functions which were introduced in this paper are considered to be sufficient for hydrogen-fueled vessels.

1 INTRODUCTION

The IMO's GHG reduction strategy, adopted in 2023, sets a target of net-zero GHG emissions by 2050 [1], and efforts are being made to switch from conventional fossil fuels to carbon-neutral fuels such as hydrogen and ammonia. While ammonia is considered the preferred fuel for large two-stroke engines, hydrogen utilization is considered unsuitable for large engines due to its low energy density and storage difficulties.

However, in Japan, the development of a hydrogen propulsion system package is being promoted through a project using the Green Innovation Fund [2]. Meanwhile, Mitsui E&S, as the top engine manufacturer in Japan, has been developing not only hydrogen-fuelled engines but also supply system and gas valve train for hydrogen. This paper presents the newly developed hydrogen supply system and safety measures and describes the results of the coordinated operation of two-stroke marine diesel engine and the supply system.

The supply and safety equipment are very important development elements to enable stable and safe hydrogen operation. There are two options of pressure boosting devices in the hydrogen supply system: liquid pumps or gas compressors. The advantages and disadvantages of liquid pumps and gas compressors are listed in Table 1. The gas compressor was adopted in this development to speed up engine development and to ensure operational stability due to its easy controllability and high durability. This compressor is a prototype developed by Kaji Tech CORPORATION, a group company of Mitsui E&S.

Table 1. Comparison of hydrogen boosting device

	Liquid Pump	Gas Compressor
Motor Power	Low	High
Footprint	Small	Large
Availability	Low	High
Controllability	Low	High
Durability	Unknown	High

To verify the stability of the hydrogen supply system in demonstration testing of two-stroke marine diesel engine, one cylinder of Mitsui four-cylinders test engine, 4S50ME-T9.7, had been converted to be hydrogen fuelled, based on the MAN B&W two-stroke dual fuel engine (ME-GI) with a view to its early application in marine engines. Its specification is shown in Table 2. The gas valve train (GVT) is a double block-and-bleed system for high-pressure hydrogen, and nitrogen was used as the ventilation medium for the double wall piping ventilation system, a safety device, to ensure robust safety in the case of a hydrogen leak.

Figure 1. 4S50ME-T9.7

Table 2. Specification of 4S50ME-T9.7

Specification	
Output (kW/cylinder)	1780
Engine speed (-)	117
Pmax (MPa)	20
Pi (MPa)	2.1
Bore x Stroke (mm x mm)	500 x 2214

2 HYDROGEN SUPPLY SYSTEM

Figure 2 and Table 3 show the detailed diagram and specification of the hydrogen supply system respectively used in this study. The main components are shown in Figures 3 to 8.

LH_2 tank has a double shell construction and the perlite vacuum insulation system. The internal pressure of the tank is maintained at 0.84 MPa when not in use. If the internal pressure exceeds 0.84 MPa, hydrogen gas is released to the atmosphere. There are three air-heated vaporisers. HX1 vaporises the liquefied hydrogen and raises its temperature to near atmospheric temperature, while HX2 raises the temperature of boil off gas (BOG) to near atmospheric temperature. HX3 is responsible for maintaining the tank pressure at a predetermined level to ensure the pressure at the compressor inlet. During system operation, both the hydrogen gas and the BOG heated by HX1 and HX2 are supplied to the compressor.

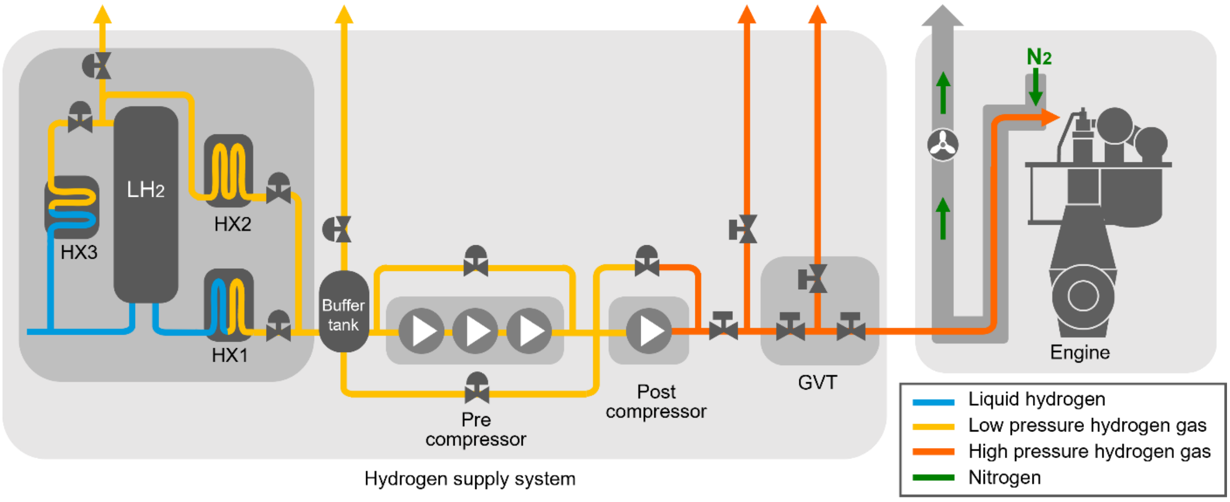

Figure 2. Detailed diagram of hydrogen supply system

Table 3. Specification of hydrogen supply system

Specification	
Tank Capacity (m^3)	47
Storage Pressure (MPa)	0.84
Pressure at Compressor inlet (MPa)	0.60
Pressure at Compressor outlet (MPa)	Max. 35.0
Maximum flow rate to engine (Nm^3/h)	1000

The compressor is made up of two reciprocating units. The pre compressor consists of three cylinders. The hydrogen supercharged by the pre compressor can be boosted by the single-cylinder post compressor to a maximum pressure of 35 MPa. Both compressors have spill-back valves to control hydrogen pressure and the flow rate. And in case of an emergency, all hydrogen in the compressor is discharged to the atmosphere via the buffer tank. In this study, all excess hydrogen generated during engine operation was discharged to the atmosphere.

The GVT is a valve unit that controls the start and stop of hydrogen supply to the main engine and, like the conventional ME-GI, uses a double block-and-bleed system.

All equipment of the supply system were made of austenitic stainless steel, which is resistant to hydrogen embrittlement [3]. Due to the short test duration of this study, the assessment of the hydrogen embrittlement of the material is an item that will continue to be required.

Figure 3. LH_2 Tank

Figure 4. Air-heated vaporizers (HX1, HX2, HX3)

Figure 5. Pre compressor

Figure 6. Post compressor

Figure 7. Buffer tank

Figure 8. GVT

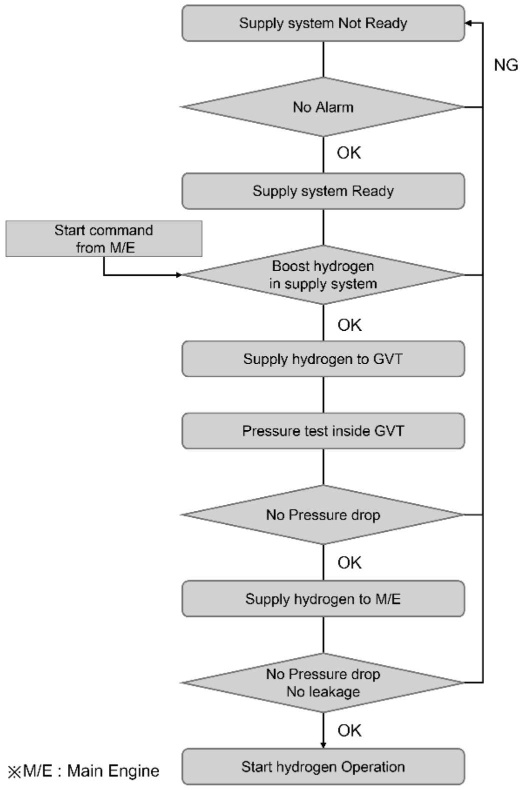

Figure 9. System flow chart

The flow chart of hydrogen supply system is shown in Figure 9. The system is put into operation by a start-up command from the main engine. After start-up is complete, hydrogen is supplied to the GVT when the engine control system (ME-ECS) detects that the compressor discharge pressure has increased to a predetermined pressure. The pressure test of the inside of the GVT is then carried out with hydrogen and the ME-ECS detects that there is no pressure drop, meaning that the hydrogen supply to the engine can be started, and hydrogen engine operation is initiated unless ME-ECS detects any pressure drop or leakage inside the engine.

3 SAFETY SYSTEM

Conventional dual-fuel engines, including ME-GI, require the fuel gas piping in the engine room to be enclosed by double wall pipes or ducts [4], and double wall pipes are generally used on marine two stroke engines. In addition, the inside of the outer pipe must be ventilated a specified number of times per hour with dry air during dual fuel operation. In this study, nitrogen was used as the ventilation medium to further consolidate safety, considering the leakiness and explosive nature of hydrogen. Nitrogen is produced by a generator and is drawn in by a ventilation fan to meet the prescribed ventilation frequency for the volume of the outer pipe. Its frequency was adjusted to 30 times per hour in this test. Moreover, ME-ECS has three flow switches on the inlet of the outer pipe to detect whether the nitrogen is flowing or not. In case of no nitrogen flow in the outer pipe, the main engine cannot be moved to hydrogen operation condition.

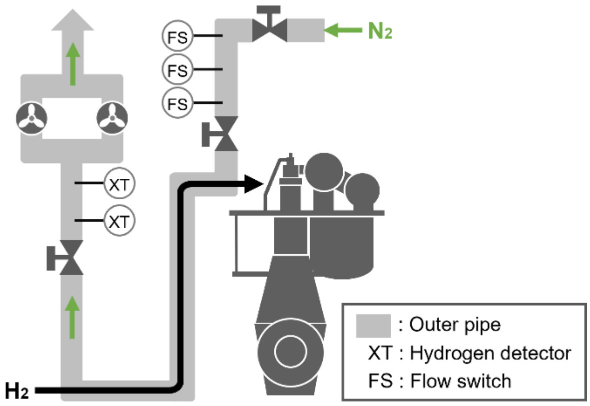

Figure 10. Nitrogen ventilation system

Two hydrogen gas detectors were installed on the outer pipe to detect hydrogen leakage from the inner pipe and engine component. However, as mentioned above, nitrogen was used as the ventilation medium in this study, which means that currently available industrial hydrogen gas detectors cannot be used. The reason for this is that conventional gas detectors are designed for use in an atmospheric environment. Therefore, a gas detector that could be used in a nitrogen environment was strongly needed. RIKEN KEIKI CORPORATION, which has the largest market share in Japan for industrial gas detectors, was currently developing a hydrogen gas detector that could be used in an oxygen-free environment. The specifications and appearance of the sensor under development are shown in the Figure 11, Figure 12 and Table 4. T50 and T90 in the table mean the response time taken for the gas detector to change from a reading of 0 to 50% or 90% of the gas concentration measured in the environment.

This detector is a direct-insertion detector and can be calibrated while installed on the piping. The diagram in Figure 13 shows the detector operating well in a nitrogen environment when supplied with a simulated 40% of the lower explosive limit (LEL) gas of hydrogen while mounted on the piping. The indication errors in this case were within 5%, which met the performance requirement of the indication accuracy by IEC60079-29-1 [5]. The first peak shown by each sensor was due to air accumulation in the calibration volume, which causes a deviation of about 10%LEL when the sensor is used in air.

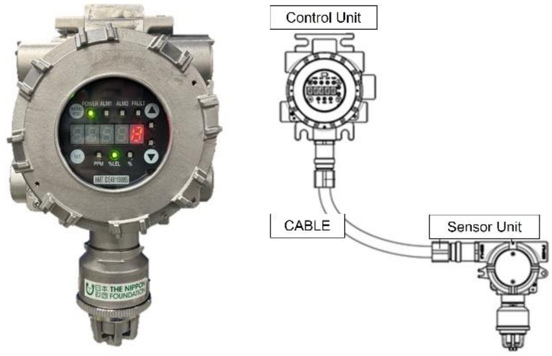

Figure 11. Hydrogen gas detector (RIKEN KEIKI)

Figure 12. Gas detectors on outer pipe

Table 4. Specification of gas detector

Specification	
Type	Thermal conductivity
Detection range (%LEL) in N_2	0-100
T50 / T90 (sec)	8 / 16

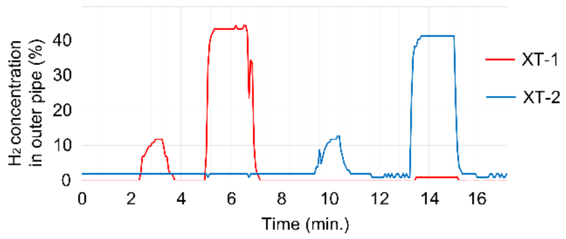

Figure 13. Calibration test of gas detectors

4 RESULTS

4.1 Result obtained from supply system –

Table 5 shows the test conditions of hydrogen engine operation and Figure 14 shows overall pressure history in hydrogen compressors during the test. The maximum pressure required by the engine was 30 MPa, however the pressure at the compressor outlet was biased by the engine load due to pressure losses in the supply pipe to the engine. If the required pressure was 30MPa, the pressure was controlled to be 30.5MPa at the post-compressor outlet.

Table 5. Test Conditions

Load (%)	Speed (RPM)	Hydrogen cylinder (kW)	Other cylinders (kW)
100	117	1780	5340
85	110.8	1513	4539
75	106.3	1335	4005
50	92.9	890	2670
25	73.7	445	1335

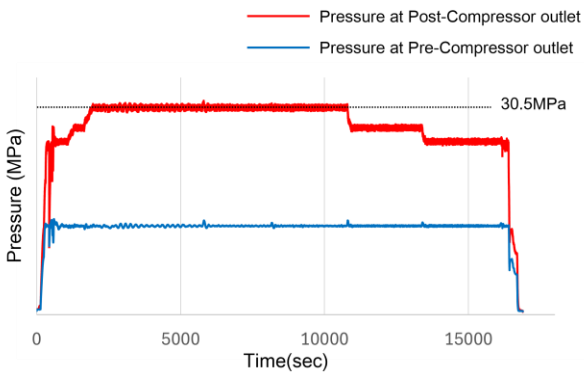

Figure 14. Overall pressure history in hydrogen compressors

Figure 15 shows the start-up pressure history in supply system. After the start-up command from the main engine, the compressor started unloading operation. Load operation was then started when the motor rotation of both compressors was stabilised. After the pressure boost in the system was completed, hydrogen was supplied to the GVT. A sharp drop caused by supplying hydrogen to empty pipes could be observed at this time. When completing the pressure recovery in the system, hydrogen was supplied inside the GVT, and the pressure test was carried out. Once this process was complete, the gas was supplied into the engine. Hydrogen engine operation was initiated as no system pressure loss or leakage was detected during the process.

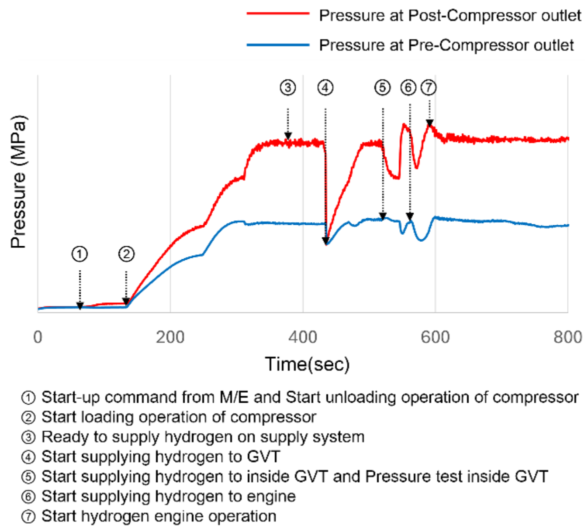

Figure 15. Start-up pressure history in supply system

Figure 16 shows the pressure pulsation of post compressor outlet on the hydrogen engine operating at maximum supply pressure. The maximum pulsation was found to be approximately 1 MPa. It had therefore been confirmed that the hydrogen supply system allows the engine to be operated without any problems.

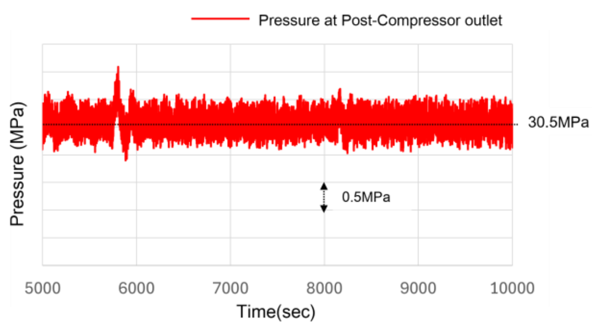

Figure 16. Pressure pulsation at compressor outlet at maximum pressure

4.2 Result obtained from engine –

This section describes the results obtained from the pressure data acquired by the ME-ECS.

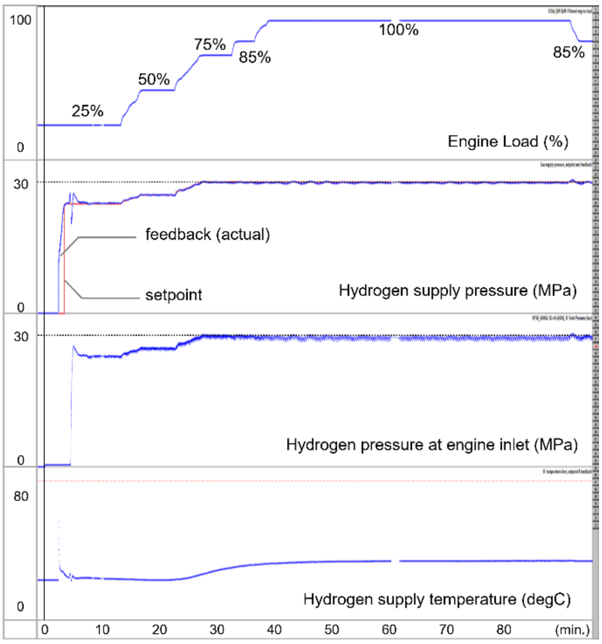

Figure 17. Test history of hydrogen engine operation

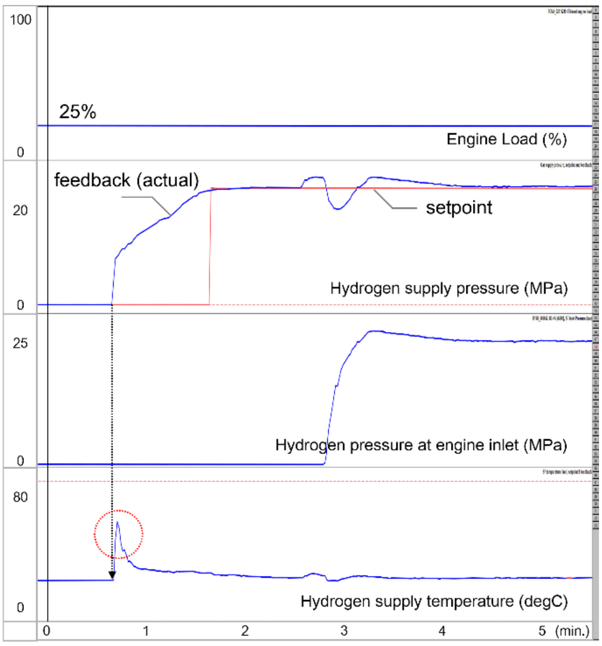

Figure 18. Data history at hydrogen starting-up

Figure 17 shows data history acquired by ME-ECS during the same test period shown in Figure 14. This Figure confirmed hydrogen engine operation could be continued without any problem. The rapid temperature rise shown the area enclosed by the red dashed line in Figure 18 was due to the rapid introduction of high-pressure hydrogen into the empty line to the GVT.

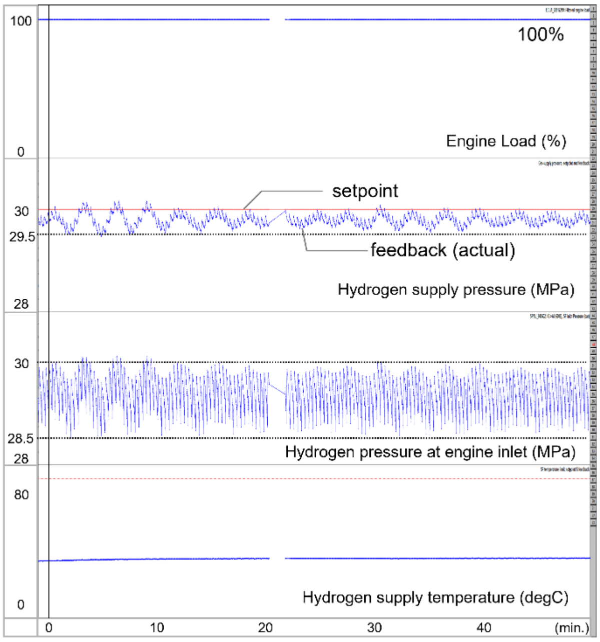

Figure 19. Pressure pulsation at engine inlet at full load

Figure 19 shows the pressure pulsation at 100% engine load. Although the hydrogen pressure pulsation at the engine inlet was slightly higher than that of supply pressure due to the effect of the pulsation of the engine itself, it was maintained at approximately 1.5 MPa, confirming that the engine could be operated in a stable condition.

Figure 20 shows the pressure pulsation at 85%, 75% and 50% engine load. Pressure pulsations at engine inlet are observed to decrease with decreasing engine speed. When the load was changed, an increase in pressure could be observed. However, it was at a level that does not affect the hydrogen engine operation.

Figure 21 shows data history up to the changeover to diesel oil (DO) operation. The changeover was carried out at 25% engine load. Hydrogen operation was changed over to DO operation without abnormal pressure rise.

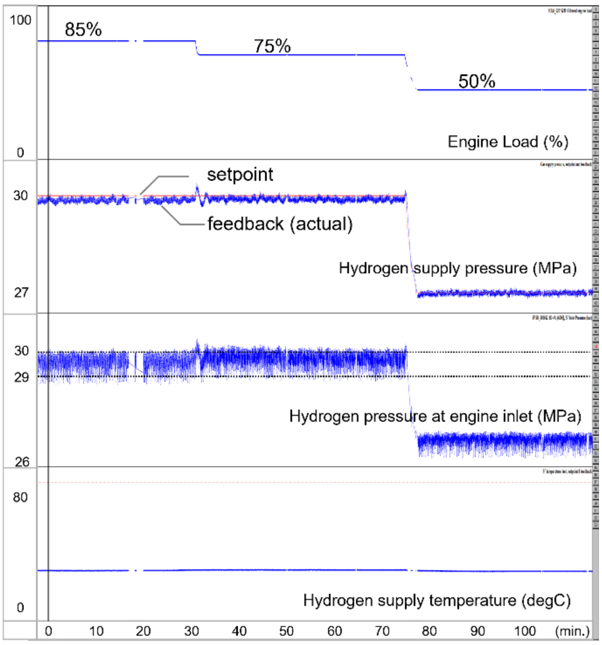

Figure 20. Pressure pulsation at several engine load (85%, 75%, 50%load)

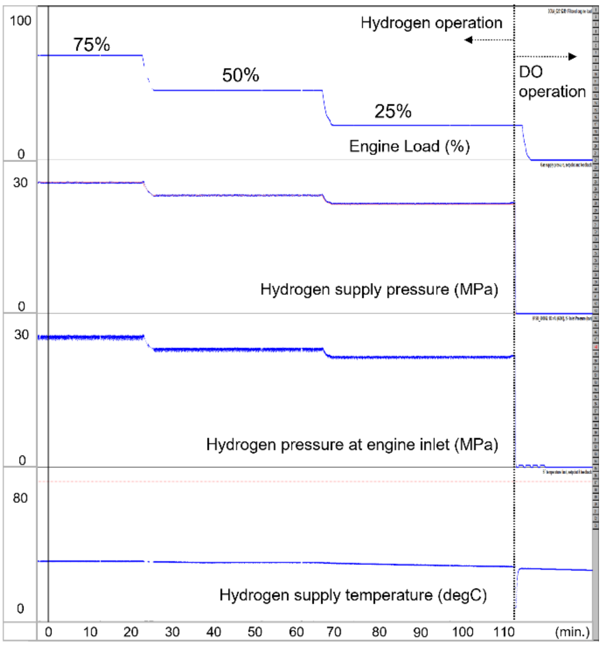

Figure 21. Data history at changing over to DO operation

Figure 22 shows an extract of the data from the hydrogen gas detector mounted on the outer pipe during the test. No hydrogen leaks from the engine occurred during this and the entire test period. In addition, the scavenging air receiver and the crank case were also constantly monitored for hydrogen leaks and no leaks were detected during the entire test period. This proves that the engine based on ME-GI is safe for hydrogen.

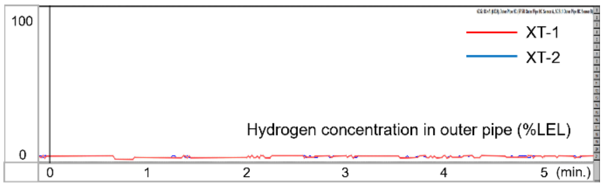

Figure 22 Hydrogen leakage monitoring

5 CONCLUSIONS

The hydrogen supply and safety system developed to date for the marine two stroke hydrogen engine were described, as were the results of coordinated operation of the engine with the system. The results obtained in this study are as follows.

- Gas compressor-based supply system enable stable operation in all load ranges when operated in conjunction with a two-stroke hydrogen engine based on ME-GI.
- The double wall annulus was ventilated with nitrogen during hydrogen operation, creating an oxygen-free situation, which was an effective measure for highly explosive hydrogen.
- Hydrogen gas detectors available under oxygen-free conditions were in good working order and no hydrogen leaks were observed during the entire period of hydrogen operation.
- These results showed the hydrogen engine system using ME-GI including high pressure gas supply system had a potential to apply in maritime sector.
- Hydrogen-brittle resistant materials have been used, but their evaluation is difficult in a short test period. Further evaluation will be needed in actual tests.

6 DEFINITIONS, ACRONYMS, ABBREVIATIONS

ME-GI: MAN B&W two-stroke dual fuel engine

BOG: Boil off gas

GVT: Gas valve train

ME-ECS: Engine control system

LEL: Lower Explosive Limit

M/E: Main Engine

T50/T90: Response time taken for the gas detector to change from a reading of 0 to 50% or 90% of the gas concentration measured in the environment

DO: Diesel oil

7 ACKNOWLEDGMENTS

This study was funded by Ministry of Land, Infrastructure, Transport and Tourism in Japan.

The project to develop the hydrogen gas detector available under oxygen-free conditions is subsidized by the Nippon Marine Equipment Association and funded by THE NIPPON FOUNDATION.

8 REFERENCES AND BIBLIOGRAPHY

[1] IMO. 2023. 2023 IMO strategy on reduction of GHG emissions from ships, *MEPC 80*, London, MEPC 80/WP.12, Annex 1.

[2] Next-generation Ship Development, *https://green-innovation.nedo.go.jp/en/project/development-next-generation-vessels/*

[3] JA. Lee, 2016, *Hydrogen Embrittlement*, National Aeronautics and Space Administration Marshall Space Flight Center, Huntsville, Alabama

[4] 2016, IGF code, International Maritime Organization

[5] IEC 60079-29-1:2016/AMD1:2020, Amendment 1, Explosive atmospheres – Part29-1: Gas detectors – Performance requirements of detectors for flammable gases