ZURICH, MAY 19 – 23, 2025

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Experimental study of dispersion characteristics of ammonia under various humidity conditions

Operators Perspective

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ABSTRACT

In the shipping industry, the use of ammonia, a zero-carbon fuel, is expected to expand in response to the strengthening of GHG regulations. And ammonia fuel is expected to be applied not only to internal combustion engines but also to electric propulsion systems utilizing gas turbines and fuel cells for ship propulsion and power generation. Korean Register has constructed a dedicated engine testbed for the research and development of ammonia engines and post-treatment systems, and subsequently installed ammonia detection sensors and ventilation equipment in the testbed to secure safety against ammonia leakage in closed spaces. Because ammonia has a lower molecular weight than air, the detection sensors and ventilation equipment are installed in the upper part of the testbed. However, when considering the environment in the engine room of a ship operating in a high humidity marine environment, the temperature and humidity are relatively higher than onshore testbeds. Therefore, when ammonia leaks in a humid engine room environment, the high water solubility of ammonia may cause the ammonia to react with moisture and stagnate at the bottom instead of rising to the top. Accordingly, it is necessary to take this into account when installing ventilation systems on ships with ammonia engines. In this study, the actual behavior of ammonia leakage from an enclosed space with high humidity was analyzed experimentally where an ammonia engine is operated in a high-humidity engine room in consideration of actual marine conditions.

In the ammonia engine testbed of KR, the inflow of external air and the outflow of internal air were blocked, and indoor humidity was set for each condition through air-conditioning equipment under the same temperature condition. When ammonia was discharged at the same flow rate from the same leakage section, the diffusion and cohesion tendencies of vaporized ammonia were observed through ammonia detection sensors and IR cameras.

The fuel pipe in the upper part of the engine was selected as the ammonia leakage section to simulate the actual leakage environment. To identify the diffusion tendency of leaked ammonia, ammonia concentrations by phase were measured and recorded in real time by installing ammonia sensors by phase in the lower part of the testbed, lower part of the engine side, upper part of the engine side, and upper part of the testbed.

In addition, IR camera images were examined to identify the amount and condition of ammonia leaked.

In the experiment results, leaked ammonia tended to be aggregated at the bottom of the testbed as the humidity inside the testbed increased. Considering these characteristics, equipment layout based on humidity conditions is important for effective detection and control of ammonia.

The experiment results reflected both physical characteristics and environmental variables. In addition, they are expected to be significantly helpful in optimizing the positions of ammonia detection sensors and ventilation systems in the actual application stage for ships in the future.

1 INTRODUCTION

Global warming and extreme weather events around the world are driving demand for decarbonization strategies across industries. In 2018, the International Maritime Organization also adopted an initial GHG strategy for decarbonizing shipping. The strategy sets targets for reducing international shipping GHG emissions (50 % below 2008 levels by 2050) and for improving energy efficiency. The MEPC's 80th Committee meeting last year adopted a revised 2023 strategy that strengthens the existing targets, with interim targets for 2030 and 2040 to meet net zero by 2050.[1]

In addition, for the implementation of FuelEU Maritime, the European Commission derived GHG intensity thresholds based on MRV data in 2020, which set targets for reducing the GHG intensity limit of energy used by ships in phases every five years until 2050.[2]

A variety of technical and operational measures can be applied to respond to the decarbonization demands on the shipping industry, but ultimately, the transition of propulsion systems from traditional fossil fuels to low-carbon and even zero-carbon fuels is required.

Ammonia, the major zero-carbon fuel for marine applications, is the subject of significant research and development around the world. It is expected to be used not only as a fuel for internal combustion engines in propulsion and power generation systems, but also in gas turbines and electric propulsion systems utilizing fuel cells.

The use of ammonia as a marine fuel requires technical and safety rules, and in this regard, the 9th Sub-Committee on Cargo and Containerized Transport (CCC) has commenced the development of safety guidelines for the use of ammonia as a fuel on ships. At the CCC 10th meeting, interim guidelines, including safety measures for ammonia toxicity, were finalized and approved at the MSC's 109th Committee meeting. Defining exposure limits is difficult at this point due to differences among countries, and three concentration thresholds were agreed upon. Each threshold corresponds to 25 ppm, 110 ppm, and 220 ppm, with local indication, alarm, and safety systems activated at these levels. Regarding toxic areas and spaces, a clear distinction was made between areas and enclosed toxic spaces containing a single point of leakage, and the concentration criteria for determining toxic areas was set at 220 ppm. Additionally, it was established that the boundaries of toxic areas would be set based on the safety distances defined by the IGC Code, while also ensuring that gas dispersion analysis demonstrates that the ammonia concentrations exceeding 220 ppm do not reach non-toxic spaces. The boundary conditions for gas dispersion analysis using commercial software (Star-CCM+, FLACS etc. [3], [4]) should be approved by the administration.

To detect ammonia leaks in enclosed spaces, such as fuel preparation rooms, technology is being developed to utilize a variety of methods, including sensors. In general, due to the lower molecular weight of ammonia compared to air, it is considered to install a detection sensor and ventilation system at the top.[5]

However, the actual operating environment of a ship is relatively humid compared to land. Especially in the engine room and fuel storage area of a ship, humidity can be high if ammonia leaks. Ammonia is high water solubility and can react with

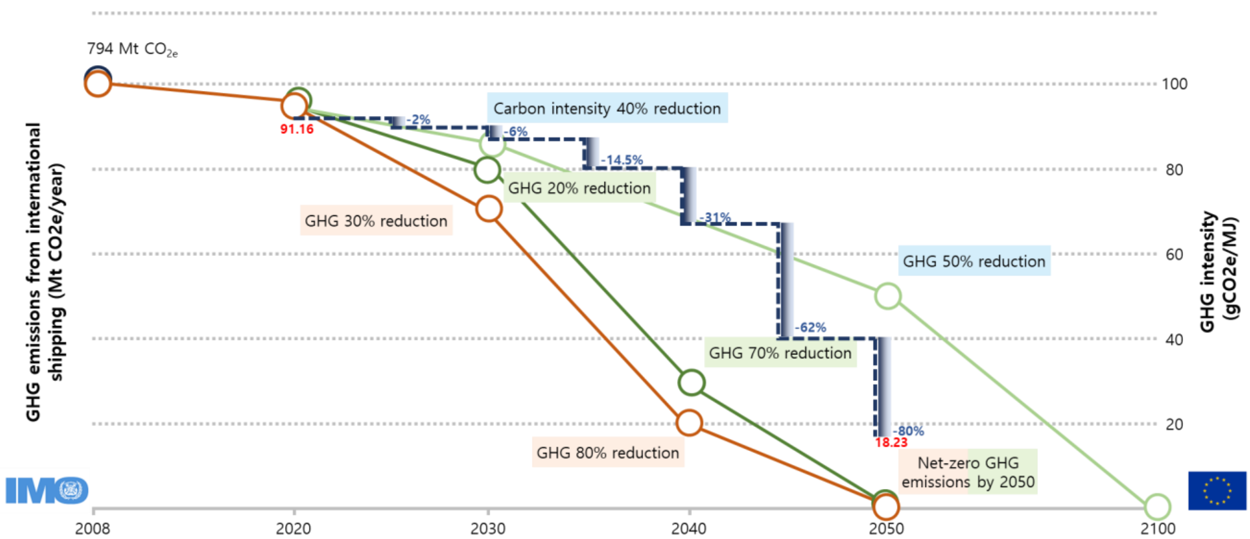

Figure 1. GHG emission regulation trends of International Mariteme Organization and Eupean Comission

moisture in high humidity conditions within the enclosure and potentially stagnate at the bottom of the enclosure.

In this study, we experimentally analyzed the actual dispersion of ammonia when it leaks in an enclosed space with high humidity, simulating the situation of fuel preparation rooms and engine rooms that utilize ammonia at sea.

2 EXPERIMENTAL METHODS

Korean Register has established a Green Ship Equipment Testing and Certification Center to develop technologies that respond to the increasingly stringent air pollution regulations and is currently developing ship engines and exhaust gas aftertreatment technologies.

To meet the International Maritime Organization and the EU decarbonization goals for shipping, the company has built an ammonia-fueled engine test bed to develop engines that use ammonia, a zero-carbon fuel, to develop engines, equipment, and technical rules.

The KR ammonia fuel engine test bed is configured to use high-pressure liquid ammonia and low-pressure gaseous ammonia, and the design, manufacturing, installation, and licensing of major facilities were carried out in accordance with Korean laws and regulations.

2.1 Experimental apparatus

We utilized the KR ammonia fuel engine test bed to analyze the diffusion of ammonia at various humidity conditions during leaks in enclosed areas such as the fuel preparation room and engine room. According to Korean law, the ammonia fuel supply system, including ammonia storage tank, ammonia low-pressure pump, and ammonia high-pressure pump, is installed in an open area on the ground, so this test was conducted in a medium-speed engine laboratory with an ammonia engine, which is the same environment as the enclosed area on a ship.

Figure 2. Ammonia fuel storage and supply system of Korean Register's test center

An ammonia fuel system (Table 1) was utilized to supply ammonia into the ammonia fuel engine test bed to simulate leakage of ammonia within the confined space. Liquid ammonia stored in the ammonia fuel storage tank was supplied to the ammonia fuel gas supply system using a low-pressure pump to vaporize and deliver it to the laboratory. To quantitatively simulate the leakage of ammonia, we used the Mass Flow Controller MD 600 (Line Tech), which is capable of delivering up to 1,000 SLPM and has an accuracy of ± 0.25 % F.S., unaffected by fluctuations in temperature and pressure.

The leaked ammonia was measured using the FT-1000 Tx (SungwhaFT), which is an amperometric electrochemical gas sensor widely used in industrial safety equipment, process control applications, and ships. The sensor can measure up to 150 ppm of ammonia, with a response time of less than 20 seconds and an accuracy of ± 2 % F.S.

To measure the temperature and humidity of the enclosed area, we used a capacitive humidity sensor (ROTRONIC HYGROMER IN-1) and a temperature sensor (Pt100 Class A), Hygroclip2 (Rotronics), which uses the principle that the capacitance changes depending on the molecular weight of the water adsorbed on the hygroscopic membrane. The humidity can be measured from 0 to 100 % RH, and the accuracy is ± 0.8 % RH; the temperature can be measured from -100 to 100 ℃, and the accuracy is ± 0.2 K.

The measurement of the data from each sensor was performed using the Analog Data Acquisition module LAM002 (Horiba) of a dynamometer installed in the laboratory with an analog measuring frequency of up to 100 Hz.

Table 1. Specification of ammonia fuel storage and supply system of Korean Register test center

Item	Liquid ammonia	Gaseous ammonia
Pressure	40 ~ 83 bar	5 ~ 8 bar
Temperature	25 ~ 45 ℃	35 ~ 45 ℃
Flowrate	Max. 3,300 kg/h	Max. 700 kg/h
Supply system	Tank → L.P P/P → LFSS	Tank → L.P P/P → FGSS

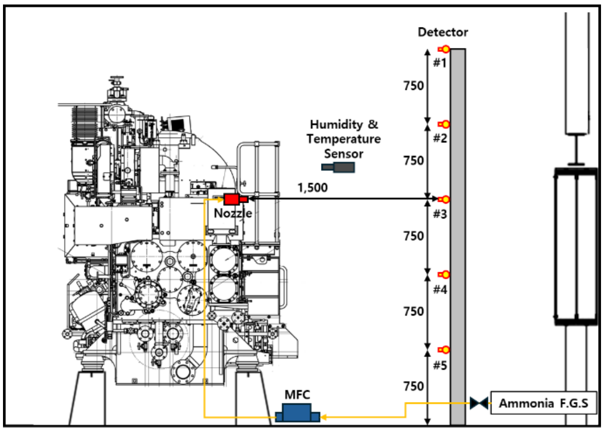

Figure 3. Schematic diagram of experimental set up

2.2 Experimental conditions

In this study, in order to simulate the leakage of ammonia in enclosed areas such as the fuel preparation room and engine room, the leakage of ammonia in the ammonia fuel preparation room of a power generator engine (25 bore 6 cylinder, about 1.7 MW) was assumed and calculated through the modeling program (ALOHA) provided by the US EPA It was set to a small leakage (5 mm) at the fittings of various temperature and pressure sensors installed in the 80 A diameter piping of the gas phase fuel supply for the ammonia supply of the power generator engine in the fuel preparation room. The leakage amount was simulated to be about 100 LPM by calculating the amount of ammonia leaking from the fuel supply pipe (Length : 16 m) in the fuel preparation room after the emergency shut-off valve. In consideration of this, we utilized a mass flow controller to supply ammonia at a constant 100 LPM to the laboratory. Considering the treatment of the leaking ammonia, the ammonia was sprayed for 75 seconds, which is enough time for all sensors to detect the ammonia.

To analyze the diffusion of ammonia at various humidity conditions, we reviewed the humidity conditions of the oceans in which ammonia-fueled ships can operate.[6] The relative humidity was distributed from a minimum of 10 % to a maximum of 90 %. In this study, the temperature in the enclosed area was fixed at 20 ℃, and ammonia was sprayed at 20 %, 50 %, and 80 % relative humidity, considering the various humidity conditions in the real world and the specifications of the research team's experimental equipment.

3 RESULTS

3.1 Dispersion characteristics of various humidity conditions

The results obtained by spraying ammonia at different humidity conditions in the enclosed area are shown in Figure. 4 (a) for the lowest humidity condition of 20 % relative humidity, Figure. 4 (b) for 50 % relative humidity, and finally Figure. 4 (c) for the highest humidity condition of 80 % relative humidity.

The Detector #2, installed at 3,250 mm, was the first to detect ammonia at 7 seconds after the ammonia spray at 20 % relative humidity, followed by Detector #1, installed at 4,000 mm, about 2 seconds later. After that, it was detected by Detector #3(2,500 mm), Detector #4(1,750 mm), and Detector #5(1,000 mm). At 50 % relative

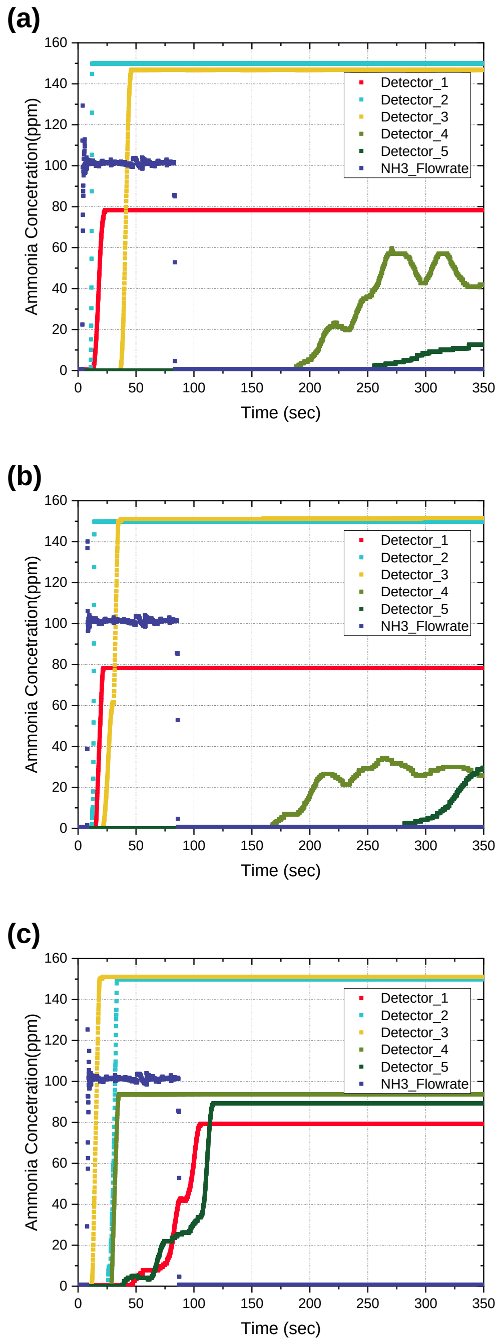

Figure 4. Dispersion characteristics of various humidity conditions. (a) 20 % RH, (b) 50 % RH, (c) 80 % RH

humidity, Detector #2(3,250 mm) was the first to detect ammonia and exhibited a measured maximum 4 seconds after spraying ammonia, followed by Detector #1(4,000 mm) about 3 seconds later. Although there is a slight difference in reaction time, the relative humidity of 20 % showed a similar trend. However, at 80 % relative humidity, Detector #3(2,500 mm) was the first to detect the ammonia at 4 seconds after spraying, followed by Detector #2(3,250 mm) about 14 seconds later. Detector #4(1,750 mm) was the third to start detecting and measured around 80 ppm. After that, Detector #5(1,000 mm) and finally Detector #1(4,000 mm) detected. At 80 % relative humidity, the detection speeds were characterized by different detector height than in other conditions, indicating that high humidity conditions affect the diffusion of ammonia.

3.2 Ammonia detection speed of various humidity conditions

The leak detection speed of ammonia for different humidity conditions in the enclosed area is compared in Figure. 5. The ammonia detection concentrations were compared by humidity condition, taking into account the interim guidelines of the IGF Code: when the ammonia detection started (Figure 5. (a)), when the ammonia concentration reached 25 ppm (Figure 5. (b)), and when the maximum detection value of each detector during the experiment was reached (Figure 5. (c)).

At 20 % relative humidity, Detector #1 (4,000 mm), Detector #2 (3,250 mm), and Detector #3 (2,500 mm), which were installed at the same or higher height as the ammonia spray nozzle (2,500 mm), started detecting within 70 seconds, Detector #4 (1,750 mm), which was installed lower than the spray nozzle, was detected after 210 seconds, and Detector #5 (1,000 mm) was not detected. The 50 % RH condition showed a similar trend, with Detector #5 (1,000 mm) showing a difference in detection, which is likely due to uncontrolled flow in the enclosed space. At 80 % relative humidity, Detector #4 (1,750 mm) and Detector #5 (1,000 mm), which were installed lower than the ammonia spray nozzle, detected faster than in the lower humidity condition, which is likely due to high water solubility of ammonia which has a lower molecular weight than air, causing the ammonia to descend to the bottom of the enclosure instead of rising to the top. It can be seen that the time to reach an ammonia concentration of 25 ppm is also faster for the detector installed lower than the ammonia spray nozzle at 80 % relative humidity compared to other humidity conditions. The time to reach the highest value measured for each detector also showed the same trend.

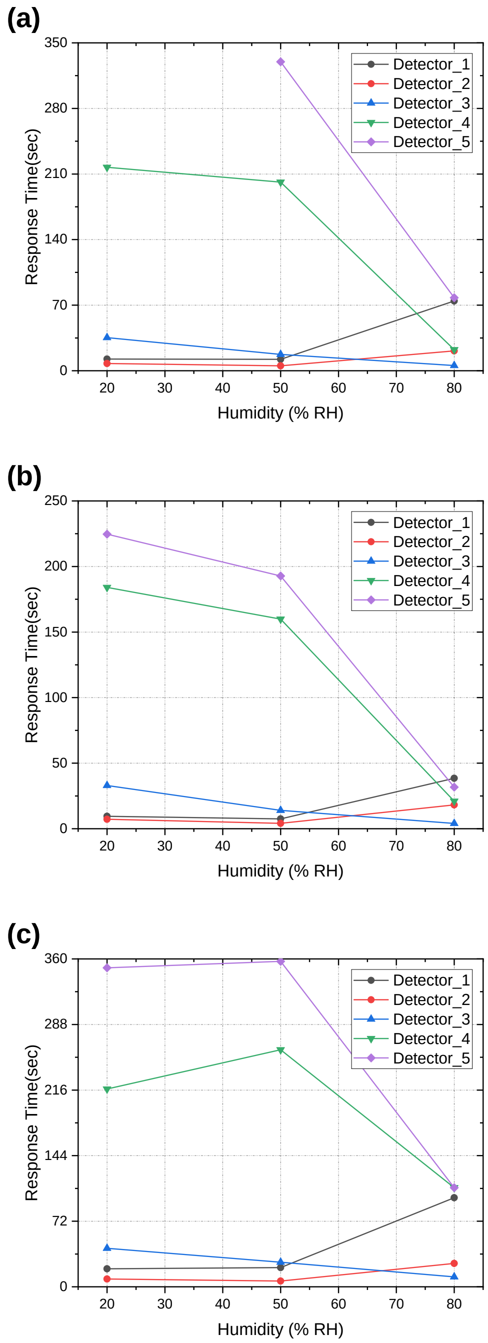

Figure 5. Ammonia detection speed of various humidity conditions. (a) Time to start detection, (b) Time to reach 25 ppm ammonia, (c) Time to reach detection maximum level

3.3 Vertical distribution of the ammonia for various humidity conditions

To analyze the diffusion of ammonia in the enclosed area, the vertical distribution under various humidity conditions is shown in Figure 6. Similar to the previous analysis, we set the ammonia detection concentration to 25 ppm and the maximum detector measurement as the reference value. Considering the downward

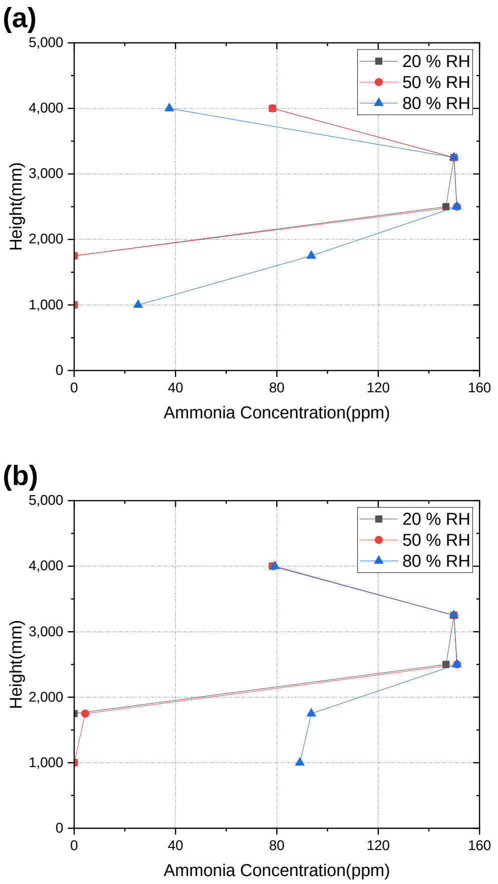

Figure 6. Vertical variation of the ammonia for various humidity conditions of ammonia detection level 25 ppm at 1,000 mm(a) and ammonia detection maximum level at 1,000 mm(b)

accumulation of ammonia in high relative humidity conditions, the ammonia measurements by height under different humidity conditions are shown in Figure 6. (a), based on the time to reach the reference value (25 ppm) of Detector #5 installed at the lowest height (1,000 mm) at 80% relative humidity, which is 144 seconds. In low relative humidity conditions, no ammonia was measured below 1,750 mm, and ammonia was measured at 80% relative humidity. In addition, ammonia measurements by height for different humidity conditions are shown in Figure 6. (b), based on the 177 seconds to reach the baseline value (highest measured value, 80 ppm) at 1,000 mm at 80 % relative humidity. Under low humidity conditions, the detector installed below 1,750 mm was not measured, but at 80 % relative humidity, it was measured.

4 CONCLUSION

In this study, we analyzed the diffusion characteristics of ammonia under various humidity conditions during a leak in an enclosed area.

The temperature in the enclosed area was fixed and the relative humidity was changed to 20 %, 50 %, and 80 %, and ammonia was sprayed into the enclosed area with the same flow rate and duration. The results show that ammonia is generally considered to diffuse upward into the atmosphere upon leakage due to its low molecular weight in air, but under conditions of high relative humidity, ammonia diffuses downward into the atmosphere instead of upward.

In general, when considering the handling of ammonia on land and at sea, ammonia leakage ventilation systems may be installed with an emphasis on the upper part of the structure, considering its upward diffusion into the atmosphere.

Through this study, the situation where ammonia may diffuse downward and stagnate locally under conditions of high relative humidity should be considered. In the case of leakage of ammonia in enclosed areas such as fuel preparation rooms and engine rooms on ships, the ventilation and treatment system should be configured in consideration of the case where ammonia does not diffuse upward to the atmosphere when the relative humidity is high by sea area. In the future, we will study the diffusion characteristics of ammonia by varying the conditions from trace leakage to large leakage of ammonia and setting the flow conditions according to the ventilation system.

5 DEFINITIONS, ACRONYMS, ABBREVIATIONS

CCC: Sub-Committee on Carriage of Cargoes and Containers

FGS: Fuel Gas Supply System

F.S: Full Scale

GHG: Green House Gas

IGC Code: International Code of the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk

LFSS: Low flash-point Fuel Supply System

LPM: Liters Per Minute

MEPC: Marine Environment Protection Committee

MRV: Monitoring, Reporting and Verification

MSC: Maritime Safety Committee

RH: Relative Humidity

SLPM: Standard Liters Per Minute

US EPA: United States Environmental Protection Agency

6 ACKNOWLEDGMENTS

This study was supported by the Ministry of Oceans and Fisheries of KOREA through the project "Development of 2,100 PS LNG-Ammonia dual fuel engine"

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