INTRODUCTION

The international trade and transport volume of liquefied natural gas (LNG) have been increasing year by year. Because LNG has the lowest emissions level per joule of energy released of all fossil fuels, it is advantageous to use.\(^1\) With abundant reserves and relatively low prices, LNG is highly competitive on the world energy market. Therefore, in order to comply with stricter emission rules issued by the International Maritime Organization (IMO), the use of LNG as a substitute for marine fuel onboard is attracting more attention from stakeholders.\(^2,3\)

Compared with traditional marine fuel, LNG can reduce SO\(_x\) emissions by 90%-95%, CO\(_2\) emissions by 20%-25%, and NO\(_x\) emissions by 85%-90%.\(^4,6\) Hence, dual fuel (DF) engines, as a potential candidate for the next generation of marine engines, have been adopted in LNG carriers.\(^7\) However, as regulations become more stringent, additional larger ships, such as container ships and bulk carriers, are expected to adopt two-stroke DF engines.\(^8\)

Despite the X-DF engine has limitations such as the greenhouse gas (GHG) that caused by methane slip, methane number (MN) dependency, it is still valuable in practice.\(^9,10\) Recently, the propulsion systems of the LNG-fueled ships and
LNG carriers are increasingly using the X-DF engine supplied by WinGD as a substitute for high-pressure DF engines because the X-DF engine complies with the NOx emissions standard of the IMO Tier III without any additional exhaust gas treatment, and it also operates at low pressure.11-13 As the trend of the future green ship, the X-DF engine is now specified for LNG-fueled ships and LNG carriers including CMA CGM’s 22,000 twenty-foot equivalent unit (TEU) series LNG-fueled ultralarge container ships and the conventional-type LNG carriers.13 In order to construct each fuel gas supply system (FGSS), a fuel tank for storing LNG with a capacity determined by the operating time and the sailing route of the vessel should be installed on the vessel.

During the voyage, the LNG in the tank is in a harsher environment than when on the land, and the changes in the conditions of the outside atmosphere depend on the ship’s practical operating conditions. In addition, the design conditions of FGSS also change according to the engine power. Therefore, various operating conditions should be considered to maintain optimal conditions in an LNG fuel tank.

When using an X-DF engine, the methane number (MN) of the fuel gas (FG) is determined by the composition of the LNG, and the MN must be maintained at an appropriate level or a higher level for the gas mode operation. At present, the MN given by the engine manufacturers is 80 or higher to prevent a reduction in the normal engine output.9

Each component of LNG has a different boiling point. Therefore, in order to maintain the pressure in the tank, the heat ingress from outside should be compensated by the evaporation heat, and the evaporation heat will generate boil-off gas (BOG) inevitably.14,15

The BOG is mainly formed by the vaporization of low-boiling nitrogen and methane, which causes a change in the composition of the LNG remaining in the tank. This process is called LNG aging.16,17 Due to the special properties of an LNG-fueled ship, the composition of Heavy Hydrocarbon (HHC) that accumulate in a small-capacity LNG fuel tank and are recycled during the handling process of the FGSS accelerates LNG aging, which may have a significant impact on FGSS operation.

As shown in Figure 1, LNG is stored and transported in tanks in a cryogenic state for long periods. Due to heat ingress into the LNG through the tank shell insulation from the ambient atmosphere, vaporization of relatively light components such as nitrogen (N₂) and methane (CH₄) increases the proportion of heavy hydrocarbon components in the residual LNG in the tank, like ethane (C₂H₆), propane (C₃H₈), and butane (C₄H₁₀).18 The predicted composition of the LNG based on the sailing duration of the vessel varies with different conditions; the amount of BOG and recycled HHC is the key factors. If only the heavy hydrocarbon remains in the fuel tank and the composition of the supplied FG from FGSS does not meet the recommended composition, the engine may no longer be able to operate in gas mode.

Several studies have been conducted on the LNG aging that occurs in the LNG storage tanks during marine transport/storage as cargo at sea and overground. Wood and Kulitsa19 presented an overview of LNG cargo aging during the marine transport and handling process of LNG on LNG carriers (LNGC). Floating storage units (FSU) and floating storage and regasification units (FSRUs) are considered in terms of conditions that affect the boil-off gas rate (BOR). Miana et al20 presented two different models involving BOR for calculating the phenomenon of LNG aging during ship transportation. Pellegrini et al21 presented an LNG vapor-liquid equilibrium model, which is compared with experimental data, predict that LNG aging in above-ground tanks recourse to the heat flow into the tank. Migliore et al22 modified their model and predict the temperature evolution of vapor-liquid phase in the process of depressurization by using a nonequilibrium method.

Despite various early studies, there have been no reports yet on LNG aging in large LNG-fueled merchant ships using two-stroke Otto cycle DF engines. In this study, in order to examine the effects of changes in LNG composition over time in an X-DF engine system, dynamic simulation of the handling process of the FGSS, including the fuel tank, is conducted and examined. By analyzing the simulation results, we hope to obtain some guidance on the design of FGSS in the future, which is the purpose of this paper.
SYSTEM DESCRIPTION

2.1 FGSS for X-DF engine

The LNG fuel propulsion system is mainly composed of the LNG fuel tank, the FGSS, and the gas engine. In addition, the components depend on the size of the ship, the sailing route, the sailing distance, and so on.

Based on the pressure and temperature of the FG required by the engine, LNG engines can be classified as high-pressure engines, medium-pressure engines, and low-pressure engines. Here, the specifications of FGSS components depend on the engine type. The engine considered in this paper is a medium-pressure X-DF engine developed by WinGD Company, with an operating pressure and operating temperature of 16 barg and 30°C, respectively.

The LNG FGSS of the X-DF engine should be designed to meet these pressure and temperature requirements. Besides meeting the engine requirements for FG, the pressure
control (or vapor control) in the LNG storage tank should also be taken into account in general. In addition, a pressurized FGSS with an LNG pump should be designed because the total amount of BOG generated in the fuel tank normally does not meet the total amount required by the engine. Based on the FGSS utilizing in the LNG Carriers,23,24 the FGSS with a heavy hydrocarbon separator developed in this research was shown in Figures 2 and 3, the fuel is pumped from the LNG fuel tank by the pump at the constant flow rate and pressure required by the engine. After it is vaporized by the LNG vaporizer and heated by the heater to the temperature required by the engine, the fuel is supplied to the engine. For the purpose of controlling the pressure of the LNG fuel tank, the BOG compressor has become a necessary option. Because BOG is used as a FG, the discharge pressure should meet the engine requirements when selecting a BOG compressor.

### 2.2 Heat and material balance

For FGSS model, the heat and material balance should be checked to ensure the system is in thermodynamic equilibrium. The reason for ensuring the heat and material balance of LNG fuel is to determine the size of each piece of equipment by calculating the capacity of each pump, heat exchanger, and fluid. So as to obtain the optimal design value, two cases were considered, as shown in the Table 1.

According to Seo et al and Ryu et al, the maximum operating pressure of the IMO type C LNG fuel tank are 4 and 5 bara.25,26 The operating pressure in this research is assumed as 3.5 barg. In the rich LNG case, the temperature of the LNG stream through the HHC separator is set at −90°C to separate the heavy hydrocarbons.

As shown in Table 1, all the compositions with an MN above 80 meet the operating conditions of the engine. According to the database of Clarksons research,27 a Neo-Panamax container ship named Cap San Juan was selected as the target model for the FGSS design. Table 2 summarizes the major specifications of the target ship. Table 3 summarizes the operating conditions of the simulated cases. In order to satisfy the FG condition, the system should include a heavy hydrocarbon (HHC) separator as mentioned above to maintain the MN at 80 or higher. Furthermore, assuming that the efficiency of the internal combustion engine is approximately 50%,28 the amount of fuel required is calculated according to the composition of the FG with consideration for the lower heating value (LHV). The heat ingress into LNG fuel tank is assumed as 44 kW. Consequently, the LHVs of LNG fuel at FG heater outlet, based on lean and rich LNG case, were calculated as 49.46 and 49.53 MJ/kg, respectively.29 Therefore, the required FG flow rates in lean and rich LNG cases are determined by Equation (1).30,31

\[
\dot{m} = \frac{P_e}{\eta \times \text{LHV}} \times 3600
\]

where \(\dot{m}\) is the FG flow rate at FG heater outlet; \(P_e\) is the power of main engine and aux. engine; \(\eta\) is the thermal efficiency of the engines.

In the lean and rich LNG case, the FG flow rates required by the engine are approximately 6842 and 6832 kg/h, respectively.
In the lean LNG case, the FG contains more methane than in the rich LNG case, while the heating value is lower than in the rich LNG case, and more fuel is needed as a result.

Although the components in FG differ greatly between the lean LNG case and the rich LNG case, the difference in the FG mass flow rate required for the engine is small.

2.3 | Main equipment for FGSS

There is a significant difference between the cases when determining the specifications of FGSS components. The properties of the LNG depend on the different LNG components. The specifications of equipment conditions for FGSS in each case are listed in Table 4.

For LNG pumps, steady-state analysis indicates that a large capacity pump is required in the lean LNG case. This is because the heat value in the lean LNG case is lower than that in the rich case, and as a result, a larger amount of LNG is needed to obtain the same output power for the engine.

For a BOG compressor, the amount of BOG generated in the lean LNG case is greater than the amount of BOG generated in the rich case. Therefore, it is necessary to choose a larger capacity BOG compressor.

3 | DYNAMIC PROCESS MODELING

3.1 | Dynamic FGSS module

A schematic of dynamic FGSS module for an LNG-fueled ship developed in Aspen HYSYS is shown in Figure 4. The FG flow rate required by the engines is controlled by both the BOG flow generated in the LNG fuel tank and the flow of NG vapor through the HHC separator. The liquid part

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**Table 3** Data on the operating conditions of simulated cases

| Property             | Lean LNG case | Rich LNG case |
|----------------------|---------------|---------------|
| Main engine power (MW)| 40            | 40            |
| Aux. engine power (MW)| 7             | 7             |
| LHV (MJ/kg)          | 49.46         | 49.53         |
| Required FG flow rate (kg/h) | 6,842      | 6,832         |

**Table 4** Main equipment specifications for the FGSS

| Equipment            | Lean case                                           | Rich case                                           |
|----------------------|-----------------------------------------------------|-----------------------------------------------------|
| LNG pump             | 18.0 m³/h × 420 mlc (meter of liquid column)       | 17.3 m³/h × 410 mlc (meter of liquid column)       |
| LNG vaporizer        | Duty: 1140 kW                                       | Duty: 1115 kW                                       |
|                      | UA: 30 100 kJ/C·h                                   | UA: 27 150 kJ/C·h                                   |
| FG heater            | Duty: 465 kW                                        | Duty: 483 kW                                        |
| BOG compressor       | 70 m³/h × 139 kJ/kg                                 | 62 m³/h × 126 kJ/kg                                 |
| GW circulation pump  | 11 m³/h × 40 mlc                                    | 11 m³/h × 40 mlc                                    |

**Figure 4** A schematic of dynamic flow sheet
from the bottom of the HHC separator is recycled into the LNG fuel tank. This dynamic FGSS module will be used to analyze the aging in the LNG fuel tank. Table 5 summarized the parameters used for the LNG fuel tank and HHC separator.

For the LNG fuel tank, the vapor and the liquid in the tank are assumed to be in thermal equilibrium. The heat ingress through the walls of the LNG fuel tank depends on the temperature of ambient. Since the heat transfer from the ambient to the LNG fuel tank is a combination of conduction and convection, the $Q$ can be expressed as:

$$Q = U \cdot A \cdot \Delta T = \left( U_L A_L + U_V A_V \right) \cdot (T_A - T) \quad (2)$$

where $U$ is the overall heat transfer coefficient; $A$ is the contact area; $U_L, U_V$ is the overall heat transfer coefficient of liquid and vapor phase; $A_L, A_V$, respectively, is the contact area of liquid and vapor phase; $T_A$ is the ambient temperature; $T$ is the temperature at thermal equilibrium in tank.

### 3.2 Initial and boundary conditions for dynamic process simulation

A dynamic process simulation can be performed by directly importing the derived corresponding capacity of each piece of equipment in the steady state into the dynamic model. In this study, the thermodynamic properties of each stream are calculated by using the Peng-Robinson equation of state, which is widely used in the oil and gas industry. Also, the standard van der Waals (vdW) mixing rules for $a, b$ that require the knowledge of binary interaction parameters quoted by Danesh were used:

$$P = \frac{R T}{V_m - b} - \frac{a \cdot a}{V_m (V_m + b) + b (V_m - b)} \quad (3)$$

Here, the parameters $a, b, \alpha$ are defined as follows:

$$a = \Sigma \Sigma x_i x_j (a_i a_j)^{1/2} (1 - k_{ij}) \quad (4)$$

$$b = \Sigma x_i b_i \quad (5)$$

$$\alpha = a_{ci} \cdot a_i \quad (6)$$

$$a_{ci} = 0.45724 \frac{P^2 T^2}{R^2 \rho_i} \quad (7)$$

$$\alpha_i = [1 + \kappa_i (1 - T_{ci}^{0.5})]^2 \quad (8)$$

$$\kappa_i = 0.37464 + 1.54226 \omega_i - 0.26992 \omega_i^2 \quad (9)$$

$$b_i = 0.07780 \frac{R \rho_i}{P_{ci}} \quad (10)$$

where $R$ is the gas constant; $V_m$ is mole volume; $a, b$ are the equation of state parameters of pure component; $\alpha$ is the function for reduced temperature and the acentric factor; $\kappa$ is the function for the acentric factor; $\omega$ is the acentric factor; $a_i, b_i$ are traditionally estimated for each mixture from critical temperature and pressure; $k_{ij}$ is the binary interaction parameter.

For the FGSS model, each case was set to the most severe conditions because the performance requirements of each component must be met in all cases when considering a large number of cases and various marine environments.

Dynamic process simulation was used to design an automated process, identify the bottleneck, check the start/stop mode, check the proportional integral derivative (PID) tuning parameters, and identify factors that change over time. In fact, the physical properties of the LNG in the tank are constantly changing. As described above, changes exist everywhere depending on the amount of BOG vaporization and the amount of HHC recirculation over time. Therefore, dynamic process simulation should be performed to confirm these changes.

This study analyzed the LNG aging phenomenon that occurs in an LNG fuel tank to determine the applicability of FG generated during a long-term voyage. Particularly, the changes in the physical properties of the LNG tank for a medium-pressure X-DF engine caused by the differences in the LNG storage tank capacity, as well as the LNG composition were analyzed. In addition, whether specifications of the FG supplied to the engine that would meet the operating requirements during actual navigation was analyzed by dynamic modeling. The initial conditions of the dynamic process simulation in each case are listed in Table 6.

| Parameter               | Value         |
|-------------------------|---------------|
| LNG fuel tank           |               |
| Volume (m$^3$)          | 2000/4000     |
| Diameter (m)            | 10/14         |
| Height (m)              | 25.46/25.98   |
| Thickness of metal (m)  | 0.01          |
| Thickness of insulation (m) | 0.35    |
| HTC of metal (W/m-K)    | 45.0          |
| HTC of insulation (W/m-K) | 0.0215 |
| Ambient temperature (°C) | 25           |
| HHC separator           |               |
| Volume (m$^3$)          | 2.262         |
| Diameter (m)            | 1.2           |
| Height (m)              | 2.0           |
RESULTS AND DISCUSSION

4.1 Different compositions of LNG

4.1.1 Case study 1: lean LNG case in 2000 m³ tank

During long-distance sailing, LNG aging does not occur even if the fuel in LNG tank depletes when the methane composition is 95 mole % or higher, which is an ideal composition that meets the flow characteristics of each rotary machine. However, the composition of the lean LNG is close to the composition of pure LNG. It is almost impossible to obtain pure LNG from an LNG terminal unless it has a refining facility. In this case study, for the lean LNG case, the LNG aging phenomenon that occurs in an LNG fuel tank with a 90 mole % methane composition was analyzed.

The composition of the LNG supplied varies across different terminals and can be predicted based on the sailing route. Furthermore, as mentioned above, it is difficult to obtain 95 mole % or higher methane content from LNG bunkering terminals. Therefore, as shown in Table 6, the composition of lean LNG in this dynamic process simulation is set to simulate the LNG aging phenomenon.

The main dynamic behaviors of Case 1 are shown in Figure 5. Judging from the elapsed time, it can be seen that the FGSS with lean LNG composed of 90 mole % methane is relatively stable. The FG flow rate required by the engine is controlled by the BOG flow generated in the LNG fuel tank and the flow of methane vapor through the HHC separator. Then, Figure 6 shows the set point (SP) pressure of the FG is 17.0 bara which is set by the pressure control valve to meet operating requirements.

According to the control logic of dynamic process simulation in this study, when the pressure of LNG fuel tank is >3.5 barg or the FG through the HHC separator cannot meet the flow required by the engine, the BOG compressor will start. At 75.7 hours, the sudden start of the BOG compressor had a temporary impact on the entire FG supply system shown as Figures 5 and 6.

As shown in Figures 5 and 6, when the FGSS starts up, the heavy hydrocarbon is recycled to the LNG tank through the HHC separator. At the same time, LNG aging occurs. As the LNG components in the tank become heavier, the density of LNG in the tank increases sharply. Due to the increase in density, changes in physical properties of the feed LNG result in limited performance of the LNG feed pump. As shown in Figure 6, although the output value (OP) of the control valve fully opened, the process variable (PV) of the FGSS, or in other words, the actual pressure of the FG supply drops significantly after the fuel limit line is reached. Here, the time limit at which the engine can no longer operating in gas-only mode is known as the “fuel limit.” In summary, as the FGSS operation continues, the LNG in the tank becomes heavier due to LNG aging, and when the LNG tank level reaches 13%, the FG will no longer be able to supply the engine.

Furthermore, it was found that proportion of HHC component stored in the LNG tank increased as the heavy hydrocarbon component was recycled by the HHC separator. Therefore, the increase in LNG mass density affects the

| Property                  | Case 1 Lean LNG | Case 2 Rich LNG | Case 3 Lean LNG | Case 4 Rich LNG |
|---------------------------|----------------|----------------|----------------|----------------|
| Tank volume (m³)          | 2000           | 2000           | 4000           | 4000           |
| Time duration of the      | 119.3          | 71.8           | 217.4          | 129.5          |
|Simulation (h)             |                |                |                |                |
| Initial tank pressure     | 3.5            | 3.5            | 3.5            | 3.5            |
| (barg)                     |                |                |                |                |
| Initial FG pressure       | 17.0           | 17.0           | 17.0           | 17.0           |
| (bara)                    |                |                |                |                |
| Initial tank filling (%)  | 95.9           | 95.1           | 95.9           | 95.1           |
| Component (mole %)        |                |                |                |                |
| Methane                   | 90.86          | 81.82          | 90.86          | 81.82          |
| Ethane                    | 6.76           | 16.16          | 6.76           | 16.16          |
| Propane                   | 1.62           | 1.52           | 1.62           | 1.52           |
| i-Butane                  | 0.48           | 0.20           | 0.48           | 0.20           |
| n-Butane                  | 0.25           | 0.20           | 0.25           | 0.20           |
| i-Pentane                 | 0.01           | 0.00           | 0.01           | 0.00           |
| n-Pentane                 | 0.00           | 0.00           | 0.00           | 0.00           |
| Nitrogen                  | 0.02           | 0.10           | 0.02           | 0.10           |
maximum capacity of the pump, resulting in a relative decrease in discharge pressure to meet the required flow conditions.

4.1.2 | Case study 2: rich LNG case in 2000 m³ tank

We observed the behavior of LNG aging in a rich LNG case containing 80 mole % methane and a large amount of HHC components. The composition of the rich LNG case is shown in Table 6. The compositions of ethane and propane are relatively high compared to those of the lean LNG case. It can be inferred that the LNG aging in the LNG tank is more active in the rich LNG case.

The initial conditions of the tank in Case 2 are almost the same as those Case 1 which could confirm from Table 6. The demand pressure of FG is also set at 17.0 bara. Based on the physical properties of LNG, the specifications of some equipment may change, but the equipment composition of the system will not change.

As shown in Figure 7, the proportion of HHC components recycled from the bottom of the HHC separator increases over time, which is similar with that of Case 1. Figure 8 shows a decrease in fuel gas pressure caused by the internal LNG aging in tank. With the phenomenon of continuous LNG aging, the mole percentage of methane in the fuel tank continued to decrease, while the composition of HHC gradually increased. As a result, the mass density of LNG gradually increases.

4.1.3 | Comparison of case study 1 and 2

As can be seen from Figure 9, the LNG fuel supply terminated when the percentage of methane mole in both Cases 1 and 2 decreased to approximately 67%. In addition, compared with Case 1, the phenomenon of LNG aging is faster in Case 2 due to the higher HHC composition in the rich LNG. Therefore, the operation duration in Case 2 was 57.39% of that in Case 1. Meanwhile, the operation duration for Case 1 and Case 2 were 109.6 and 62.9 hours, respectively.
As seen from the results of the LNG aging study based on the LNG component, it was found that as the process continued, the composition of the LNG in the tank changed as the HHC component was recovered to the LNG tank, thereby affecting the operation. Furthermore, it was found that the higher the HHC content in the initial feed LNG, the faster the aging progressed.
4.2 Different volumes of LNG tank

In this section, we discuss the effect on aging of increasing tank capacity from 2000 to 4000 m$^3$. Generally, the fuel tank capacity used by an LNG-fueled ship is not always the same, and the engine is selected according to the sailing route, ship speed, and cruising range. The required amount of fuel can be calculated according to the technical parameters of the engine, and the tank capacity can be determined by the consumed amount. Tank capacity is an important variable and can affect the determination of the capacity of the FG supply system. It has already been mentioned that the composition of LNG varies at each bunkering terminal. The results obtained above show that the LNG component is an important variable, but the difference in tank capacity studied in this section are also important factors for predicting and analyzing LNG aging.

4.2.1 Case study 3: lean LNG case in 4000 m$^3$ tank

As explained in the previous 2000 m$^3$ lean LNG case (Case 1), if the HHC component is relatively small, the aging of the LNG in the tank will decrease. As shown in Figures 10 and 11, the aging of lean LNG in a 4000 m$^3$ tank is significantly slower than that in the 2000 m$^3$ tank, and the FGSS can be in operation until the level of the tank reaches 13%, that is, most of the LNG in the tank can satisfy the requirement of FG pressure as fuel.

Meanwhile, because the volume of this tank is much bigger than in Case 1, and the composition and density have gradually changed, the maximum capacity of the rotating machine is satisfied for a long time.

The HHC component increases over time, which is similar to the LNG aging process in Case 1. As a result, the pressure
does not meet requirements for the rotary machine due to the changes in physical properties of the feed LNG. However, with the increase in tank volume, the aging speed is significantly reduced, based on which the sailing distance and the duration of gas-only mode in FGSS can be anticipated. In addition, it can be seen that, in the lean LNG case, most of the LNG in the tank is consumed as fuel for continuous sailing, as in Case 1.

### 4.2.2 Case study 4: rich LNG case in 4000 m³ tank

With different components and tank volumes, the LNG in the tank becomes heavier as time goes on. The physical properties of the changing LNG bring effects on the FG supply system, in other words, the occurrence of LNG aging in the tank is a problem for the operation of an LNG-fueled ship. In this section, we study the behaviors of the LNG aging phenomenon in the 4000 m³ level tank of rich LNG containing a large amount of heavy hydrocarbon components. It can be predicted that the LNG aging will appear even if the tank volume increases. It is only a matter of time.

It can be seen from Figures 12 and 13 that over time, the FG supply pressure did not meet the required pressure due to LNG aging. Unlike the lean LNG case (Case 3), because the initial feed LNG contains lots of HHC, the LNG accelerated aging and the FGSS could not operate when the LNG tank level was below 49%. As a comparison, in the lean LNG case (Case 3), the residual LNG quantity was approximately 13%, which means that most of the LNG could be used as fuel. It was also verified that the speed of LNG aging was lower than that in Case 2, because the tank volume was larger.

### 4.2.3 Comparison of case study 3 and 4

As shown Figure 14, coincidentally, when the mole percentage of methane in both Cases 3 and 4 dropped to approximately 67%, the LNG fuel could not sustain the system. Moreover, compared with Case 3, Case 4 has a higher composition of HHC in rich LNG, resulting in faster aging of the LNG. Then, the operation duration in Case 4 was 55.05% of Case 3. The operation duration time in Case 3 and Case 4 were approximately 215.5 and 118.6 hours, respectively.

According to the results of LNG aging based on the different capacities of LNG fuel tanks, when the initial LNG composition was the same, the larger the fuel tank volume, the slower the phenomenon of LNG aging will be. However, in the end, as the HHC component is recovered into the LNG tank, the composition of LNG in the tank changes, thus affecting the operation of the engine.

In summary, Case studies 1-4 indicated that LNG aging was affected by the initial LNG composition and the size of the LNG fuel tank. The degree of LNG aging can be visually expressed by the duration of the operating time of the engine. The duration operating time for the rich LNG cases (Cases 2 and 4) are approximately 55%-57% of that for the lean LNG cases (Cases 1 and 3). Meanwhile, when the volume of LNG fuel tank doubled, the duration of operational time is also twice as much, approximately. In addition, with the deepening of LNG aging, the increase in the mass density of LNG affects the maximum capacity of the pump, resulting in a relative reduction in the discharge pressure that did not meet the required flow conditions for the engine. Thus, the gas-only mode of the X-DF engine terminated its operation.

### 5 CONCLUSION

The purpose of this study was to predict the phenomenon of LNG aging over time in the ship apparatus of medium-pressure X-DF Otto engines, and to conduct a dynamic simulation of the FGSS, including the LNG fuel tank. Case studies

![Figure 10: Flow rate trends and LNG tank level for Case 3](image-url)
of different LNG components and different volumes of LNG fuel tanks were carried out. The analysis of the simulation results provides a certain significance for the future design of the FGSS in LNG-fueled ship. Furthermore, according to the results of this study, several solutions focused on the problem of LNG aging for the FGSS of X-DF engines were
The main research conclusions of this study are as follows:

When designing the MN control system in the steady state, due to the LNG aging phenomenon, the design margin of the LNG supply pump cannot meet the pressure required by the X-DF engine no matter how high the design margin is. As a result, the remaining LNG level in the LNG fuel tank in the rich LNG cases 2 and 4 was approximately 47% and 49%, respectively, compared with approximately 13% in the lean LNG case (Cases 1 and 3). Consequently, the rich LNG in the fuel tank could never be completely used up as a fuel. When the ratio of moles for methane fell to approximately 67% in all cases, coincidentally, the LNG fuel failed to sustain the system and reached the so-called fuel limit. Consequently, because the LNG fuel used by an LNG-fueled ship is substantially determined by the receiving terminal, the composition of LNG supplied is very important. If possible, the MN of the bunker fuel should be higher than the minimum value specified by the engine manufacturers.

Moreover, the fuel limit of an LNG-fueled ship equipped with an X-DF engine depends on the composition of the LNG and the volume of the LNG fuel tank. Due to the lower HHC content, the fuel limits in lean LNG cases, Cases 1 and 3, are 109.6 and 215.5 hours, respectively, while that in the rich LNG cases, Cases 2 and 4, are 62.9 and 118.6 hours, respectively. When the volume of LNG fuel tanks increased from 2000 to 4000 m³, the fuel limit in each case also increased by approximately twofold. In Cases 3 and 4, the limit increased by 196.6% and 188.6%, respectively, compared with Cases 1 and 2.

For ships equipped with LNG engines, there are significant differences in the voyage conditions depending on the type of ship. For example, for liners, the engine of a container ship is used more frequently than that of a bulk carrier because the container ship needs to enter and depart ports regularly, and the variance in LNG components is also larger. If rich LNG is used, significant changes in composition will have a great impact on operations, so special attention should be paid to the composition of LNG when bunkering.

For the reasons stated above, there are three solutions to the aging problem of LNG fuel for X-DF engines. Firstly, the most important thing is the management of LNG components for the bunkering. Secondly, it is also possible to solve this problem by using HHC as a fuel for the dual fuel boiler. Finally, the LNG aging problem can also be solved by setting up a separate storage tank instead of recycling the classified HHC to the LNG fuel tank. However, some additional costs will be incurred at the beginning. Therefore, a system model with a separate storage tank for the recycled HHC will be constructed in the future study. Furthermore, the dynamic simulation and economic analysis will provide excellent guidance for the design and operation of apparatus in the X-DF engine of LNG-fueled ships.

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NOMENCLATURE

BOG  Boil-off Gas
DF  Dual Fuel
FG  Fuel Gas
FGSS  Fuel Gas Supply System
FSU  Floating Storage Units
FSRU  Floating Storage and Regasification Unit
GHG  Greenhouse Gas
GW  Glycol Water
HFO  Heavy Fuel Oil
HHC  Heavy Hydrocarbon
HTC  Heat Transfer Coefficient
IMO  International Maritime Organization
LHV  Lower Heating Value
LNG  Liquefied Natural Gas
LNGC  LNG Carriers
MN  Methane Number
MW  Mega Watt
NG  Natural Gas
NOx  Nitrogen Oxide
OP  Output Value
PV  Process Variable
SOx  Sulfur Oxide
SP  Set Point
TEU  Twenty-foot Equivalent Unit Container
X-DF  Extra-long Stroke Dual Fuel

SYMBOLS

\( a \)  Energy parameter
\( \alpha \)  Alpha function
\( b \)  Size parameter
\( \kappa_i \)  Function of \( \omega_i \)
\( k_{ij} \)  Binary interaction parameter
\( \dot{m} \)  FG flow rate at FG heater outlet
\( \eta \)  Thermal efficiency of the engines
\( P \)  Pressure
\( P_{ci} \)  Pressure at critical point
\( P_e \)  Power of engine
\( R \)  Gas constant
\( T \)  Temperature
\( T_{ci} \)  Critical temperature
\( V_m \)  Molar volume
\( \omega_i \)  Acentric factor

CONFLICT OF INTEREST

None declared.

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