



Analysis of Bunkering Procedures for Establishing Safety Regulations for Ammonia-Fueled Ships

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ABSTRACT: As environmental concerns increase globally, the International Maritime Organization has been strengthening regulations to limit pollution from ships, attracting increasing interest in ammonia as a zero-carbon marine fuel. This study aimed to establish safe bunkering procedures for ammonia-fueled ships through thermodynamic analysis. The research analyzed two bunkering scenarios, ship-to-ship and truck-to-ship, calculating the boil-off rate and return boil-off gas for each scenario. A thermal analysis showed that the ship-to-ship scenario generated 271.9 kg/h of return boil-off gas with a total heat ingress of 92.84 kW. The truck-to-ship scenario produced 243.95 kg/h of return boil-off gas with a total heat ingress of 84.4 kW. Based on these findings, comprehensive bunkering procedures were developed for both scenarios, consisting of 14 steps for ship-to-ship and 13 for truck-to-ship, addressing the unique challenges of ammonia handling. These procedures include evaporated gas recovery systems, ammonia catch systems, and nitrogen purging to minimize leakage and explosion risks. The results of this study contribute to the development of safety regulations for ammonia-fueled ships by establishing systematic operational procedures that consider the toxicity and corrosiveness of ammonia.

1. Introduction

As environmental concerns have become prominent worldwide, the International Maritime Organization (IMO) has been continuously strengthening regulations to limit environmental pollution caused by ships. Recently, at the IMO's MEPC 80th session in July 2023, the “2023 Greenhouse Gas Strategy” was adopted. The existing goal of reducing total emissions by 50% compared with 2008 levels by 2050 has been raised, with an agreement to achieve at least 20% reduction by 2030, at least 70% by 2040, and net-zero emissions by 2050. The ambition level includes using at least 5% zero-carbon fuels by 2030 (with efforts to reach 10%). The main environmental pollutants generated by fuel use in ships include nitrogen oxide (NOx), sulfur oxide (SOx), carbon dioxide (CO₂), and particulate matter (PM), and regulations have been applied to control these environmental pollutants in the marine environment. Additionally, ship emission regulations according to IMO's International Convention for the Prevention of Marine Pollution from Ships (MARPOL) Annex VI

have been progressively strengthened. Regarding SOx regulations, as of January 1, 2020, the maximum sulfur content limit for ship fuel oil operating in all global waters has been restricted from 3.5% to 0.5% (Kim et al., 2020).

To satisfy the regulation, the demand for environmentally friendly energy is increasing, and zero-carbon energy sources such as ammonia (NH₃) and hydrogen (H₂) are attracting attention. However, in terms of storage and transportation, liquid hydrogen presents technical challenges, including a low storage temperature of -253°C at atmospheric pressure, hydrogen embrittlement in tanks, and high infrastructure construction costs. In contrast, while NH₃ has handling problems related to its toxicity and corrosiveness, it has a relatively higher liquefaction temperature of -33°C at atmospheric pressure. Additionally, it benefits from already developed port infrastructure as 180 million tons of NH₃ are produced and transported annually as a global chemical commodity (Korean Register, 2023). Therefore, owing to the current technical challenges with using hydrogen, NH₃ is the most feasible solution for achieving net-zero emissions (NZE).

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Research on using NH₃ as fuel in ships is continuously being conducted. For example, major ship engine manufacturer MAN Energy Solutions has completed testing on a single cylinder of an NH₃ fuel engine. They are also continuously conducting full-scale tests on two-stroke engines, with delivery targeted for 2026 (Man Energy Solutions, 2024). Wärtsilä plans to supply a solution including NH₃ fuel engines, fuel supply and NH₃ emission mitigation systems, and an SCR after-treatment system, targeting commissioning in the second quarter of 2026 (Wärtsilä, 2024). Additionally, Win GD plans to supply the NH₃ engine X-DF-A for NH₃ carriers by the third quarter of 2026, having secured nearly 30 orders including gas carriers, container ships, and tankers (WinGD, 2024). HD Hyundai Heavy Industries plans to commercialize the high-pressure direct injection NH₃ dual-fuel engine H22CDF-LA after completing type approval tests and suitability reviews with seven classification societies: American Bureau of Shipping (ABS), Det Norske Veritas (DNV), Lloyd's Register (LR), Bureau Veritas (BV), Registro Italiano Navale (RINA), Nippon Kaiji Kyokai (NK), and Korean Register (KR) (Hyundai Heavy Industries, 2024). Therefore, as the commercialization of NH₃ combustion engine-powered ships accelerates, the demand for bunkering operations for NH₃ fuel supply will increase.

Consequently, safety issues must be considered for safe NH₃ bunkering operations. Table 1 shows the hazards of NH₃, an environmentally friendly ship fuel, according to the National Fire Protection Association (NFPA) 704 Code (Kojima, 2024; Machaj et al., 2022). In the Health section, it is rated as Value 3, indicating high risk due to the toxic hazards of NH₃, whereas the flammability risk is shown as relatively low owing to its high autoignition temperature of approximately 650 °C (Mounaïm-Rousselle et al., 2021).

NH₃ must be handled with care during the fueling process owing to its toxicity and corrosiveness, and research on bunkering safety technology is also continuously being conducted. Yang and Lam (2024) evaluated operational risks through three scenarios from the perspective of release scale based on NH₃ toxicity and corrosion hazards. They also analyzed diffusion for leakages through a simulation and presented quantitative risk assessment, mitigation strategies, and guidelines through sensitivity analysis for dangers according to environmental conditions.

Duong et al. (2023) conducted an analysis of research papers and regulatory guidelines, investigating experiments and research on terminal/pipeline-to-ship (PTS), ship-to-ship (STS), and truck-to-ship (TTS) scenarios for vessels. They assessed risks and reviewed the dangers related to leakage. They identified potential risk factors in

Table 1 Hazard of NH₃ fuel (NFPA 704)

Hazard	Value	Description
Health	3	Can cause severe or permanent injury.
Flammability	1	Must be preheated before ignition can occur.
Instability	0	Normally stable, even under fire conditions.

bunkering and presented challenges and recommendations for improving safety against leaks.

Jo et al. (2024) derived leak analysis equations that should be considered when conducting bunkering demonstration research. Among scenarios according to leakage points in the bunkering process, they analyzed the phenomenon of gas inside a storage container expanding through damaged areas by considering thermodynamic variables for changes in the NH₃ density, temperature, and pressure, and they analyzed errors in leakage rates.

Liu et al. (2024) selected NH₃ leakage scenarios according to wind speed and direction in the STS bunkering procedure and analyzed leakage diffusion through a simulation. They built a model through computational fluid dynamics (CFD) and analyzed the effects on NH₃ dispersion, proposing the necessity of safety zones according to concentration. However, only gas leakage scenarios were considered, and vaporization and gas diffusion due to seawater contact and leak prevention systems for safety were not included.

Based on the aforementioned content, the use of NH₃ fuel in ships is expected to increase, as will the demand for bunkering. Therefore, research on safety, which is essential in the bunkering procedure, has been conducted. Although all the mentioned studies presented important research results for developing regulations and guidelines for bunkering, the changes in NH₃ according to conditions such as temperature and pressure occurring during STS NH₃ transfer and problems in the bunkering operation procedure have not been sufficiently analyzed. Therefore, this paper proposes procedures to control the boil-off gas (BOG) generated in the fuel tank during the bunkering process and develop safety technology necessary for the commercialization of NH₃-propelled ships and fuel transfer. The remainder of this paper is structured as follows. Section 2 establishes the concept of the bunkering system and the scope of the research, and Section 3 thermodynamically analyzes the BOG generated in the NH₃ fuel tank and the gas generated during the transfer procedure. This analysis can ensure safe operation within the tank design pressure range and prevent potential gas leakage risks. Section 4 presents the results and the necessary procedures for safe transfer by applying to the bunkering procedure. Finally, Section 5 presents the conclusion.

2. Design for NH₃ Bunkering System

2.1 NH₃ Storage Methods

Fuel tanks applied to NH₃-propelled ships should be selected to establish bunkering procedures. Systems and methods differ according to the storage method of NH₃ fuel, and storage conditions can be classified into three types (KR, 2021). Table 2 shows the storage methods applicable to NH₃-propelled ships. NH₃ can be stored in liquid state at approximately -33 °C at atmospheric pressure using the fully refrigerated (FR) method. It can be stored through the application of IMO Type-A, which is primarily used for mass transportation in existing cargo carriers with storage conditions similar to liquefied petroleum gas (LPG). Non-refrigerated (NR) storage is

Table 2 Comparison of NH₃ storage methods

Storage application	Operating temperature (°C)	Operating pressure (kPa)
FR	-33.2	101.3
SR	-10 to 4	280–360
NR	19–37	820–1,420

possible at room temperature (25 °C) in a saturated liquid state at 1,000 kPa or higher. The semi-refrigerated (SR) method is not preferred owing to efficiency and economic problems caused by having to satisfy both FR and SR design conditions. Primarily, FR and NR methods are applied for storage and transportation at sea (Sagel et al., 2022). In this study, FR and NR storage methods were considered for efficient large and small volume storage for ammonia propulsion vessels.

2.2 NH₃ Bunkering Method

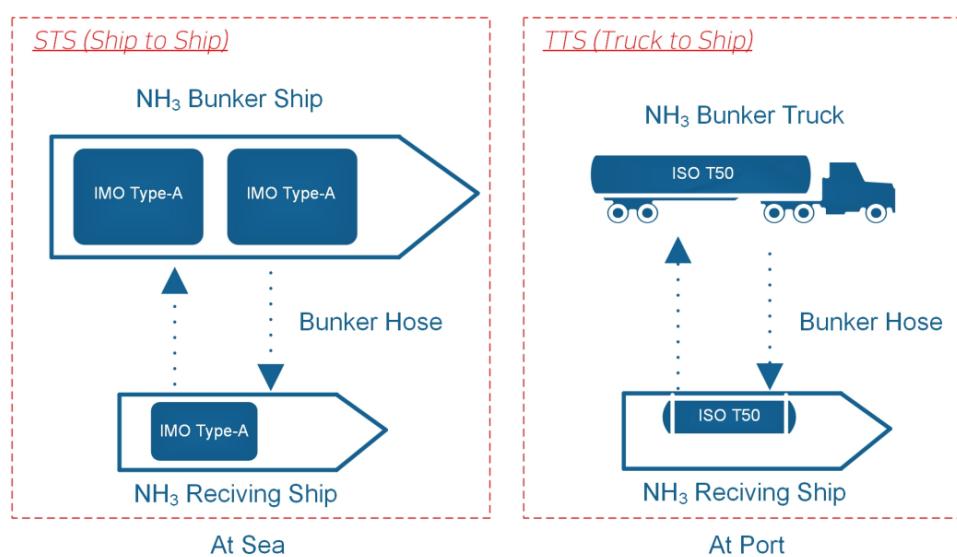
For fuel supply through bunkering, the methods are shown in Fig. 1. In this study, the STS and TTS methods were applied as bunkering methods for supplying fuel from the port or the bunkering ship (BS) to receiving ship (RS) for NH₃ transfer. For STS, both BS and RS were selected with the FR method for ocean-going vessels. For TTS, using the NR-to-NR method, we assumed that NH₃ is stored through ISO T50 tanks, which are container tanks designed according to the International Organization for Standardization (ISO) standards for transporting ammonia at sea (Kim, 2019).

The equipment required for the loading/unloading system necessary for bunkering operations according to different scenarios is shown in Table 3. The STS equipment configuration requires a fuel pump for NH₃ transfer, a nitrogen generator to replace inert gas in the piping, and an NH₃ catch system to prevent leakage. Additionally, for STS, which uses atmospheric pressure storage, a compressor is required for BOG return and to purge NH₃ gas from pipes and equipment. For TTS, the natural flow of gas is induced through pressure accumulation in the pressurized storage tank. Therefore, compressor installation was not considered.

2.3 NH₃ Fuel Tank Operations

The operation of tanks in bunkering is shown in Fig. 2. Before transferring fuel to the propulsion vessel, worker safety is secured through stripping, warming, gas freeing, and aerating for dry docking. After the repair and maintenance processes, the vessel goes through drying, inerting, and gassing to prepare for NH₃ transfer again. Here, for IMO Type-A with insulation applied, the initial cooling process prevents thermal shock to the tank before transferring NH₃ at -33.2 °C from a tank at room temperature.

Pre-bunkering operations represent operations when transferring fuel without conducting dry-docking. In the bunkering system, after the fuel tank and connection lines are checked, hoses are connected, and the gas in the tank is replaced with inert gas through N₂ purging of the piping. Depending on the tank type, transfer preparations are performed through the cooling process of lines and tanks using liquid

**Fig. 1** Description of the bunkering concept**Table 3** Configuration of RS and BS

Item	STS	TTS	Purpose
NH ₃ fuel pump	Installed	Installed	NH ₃ fuel supply
N ₂ generator	Installed	Installed	Pipe & equipment purging
NH ₃ catch system	Installed	Installed	Prevent NH ₃ leak
Compressor	Installed	Non-installed	Gas return, Gassing

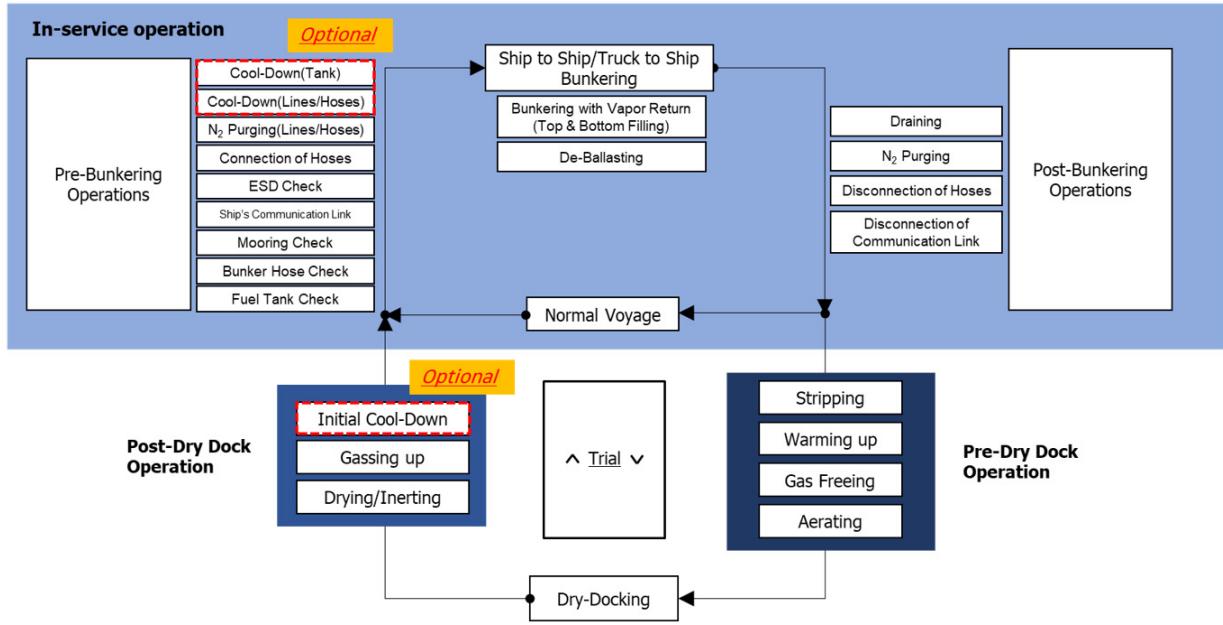


Fig. 2 Description of the tank operating procedure

NH_3 . Subsequently, bunkering is performed by transferring fuel to the ship, returning NH_3 gas generated during bunkering, and de-ballasting. After the transfer is completed, in post-bunkering operations, residual NH_3 in the piping is discharged through draining, and after an N_2 purging to prevent external leakage, the connection between ships is safely disconnected, completing the transfer of NH_3 .

2.4 Design Conditions

Table 4 shows the specifications of the target ships and trucks applied in the previously mentioned bunkering scenarios. In the STS scenario, the target ship for the study was selected as an IMO Type-A atmospheric pressure tank for ocean-going vessels. Because no reference ships using NH_3 fuel currently exist, the tank sizes for BS

and RS were assumed to be 1,000 and 500 m^3 , respectively. The overall heat transfer coefficient was set based on the specifications of ammonia carriers storing at atmospheric pressure and -33.4°C (Song et al., 2022). Additionally, the tank shape for the IMO Type-A tank was assumed to be a cube with minimal heat ingress, and the filling limit was set at 98% according to the IGC code. The bunkering time was assumed to be 5 h.

In the TTS scenario, based on the ship currently in progress at the Busan NH_3 Eco-friendly Energy Regulation-Free Special Zone to establish standards for NH_3 bunkering, the tank sizes of bunkering tank (BT) and BS were set to the volumes of ISO standard 30 ft (9.144 m) and 20 ft (6.096 m) containers, which are 32.6 and 20 m^3 , respectively. The overall heat transfer coefficient was assumed based

Table 4 Basis of the design

Item	Unit	STS		TTS	
		BS	RS	BT	RS
Type of fuel tank	-	IMO Type-A	IMO Type-A	ISO T50	ISO T50
Design pressure of tank	kPa	170	170	2,200	2,200
Operating pressure of tank	kPa	101.3	101.3	1,000	1,400
Tank size	m^3	1,000	500	32.6	20
Tank area	m^2	600	378	56.08	79.07
NH_3 temp.	$^\circ\text{C}$	-33.4	-33.4	25.2	36.5
Latent heat of NH_3	kJ/kg	1,370	1,370	1,166	1,117
Liquid NH_3 density	kg/m^3	681.6	681.6	603.09	585.58
Vapor NH_3 density	kg/m^3	0.89	0.89	7.78	10.83
Overall heat transfer coefficient	$\text{W}/\text{m}^2 \cdot \text{K}$	0.22			0.93
Filling limit	%	98			85
BOG compressor	-	Installed			Non-installed
Bunkering time	h	5			0.83

on ISO tank specifications (Admor Composites Ltd., n.d.). The shape of the ISO T50 was assumed to be a horizontal cylinder, and according to the Ministry of Trade, Industry and Energy's charging standards, a value of 85% was selected. The bunkering time was set at 50 min based on the supply flow rate being applied in the "Mobile-based Ship Ammonia Fuel Bunkering Construction and Safety Demonstration" project being conducted in the Busan Special Zone.

In both scenarios, the external temperature was conservatively set at 45 °C to calculate the BOG and return BOG (RBOG) generated during the bunkering process. The NH₃ temperature in the tank was assumed to be a fixed value in the saturated liquid state under normal conditions. Additionally, we assumed no temperature gradient according to the liquid level in the storage tank.

3. Thermal Analysis of the Bunkering Procedure

3.1 BOR

Heat input into storage tanks promotes the vaporization of liquefied NH₃, generating BOG. This is a major cause of pressure increase inside the tank, which can threaten the structural safety of the tank and related equipment (ABS, 2024). The amount of BOG is generated through calculating the BOR of the liquid evaporating from the tank to ensure safe bunkering operations. BOR refers to the amount of liquid that evaporates from the fuel tank due to heat input and can be expressed as a percentage of the total liquid volume per unit time. This is shown in Eq. (1) (Kim et al., 2024).

$$BOR = \frac{Q_{Heat\ Ingress}}{\rho_{Liquid\ NH_3} \times V_{Tank}} \times 3600 \times 24 \times 100 \quad (1)$$

Here, BOR can be calculated using the heat input to the tank $Q_{Heat\ Ingress}$ (kW), density of NH₃ stored in the tank $\rho_{Liquid\ NH_3}$ (kg/m³), volume of the storage tank V_{Tank} (m³), and latent heat of vaporization of NH₃ λ (kJ/kg).

$$Q_{Heat\ Ingress} = \frac{A_T \times U}{1,000} \times (T_1 - T_2) \quad (2)$$

Therefore, the equation used to calculate the heat input $Q_{Heat\ Ingress}$ to the tank for determining the BOG generated from the NH₃ storage tank is shown in Eq. (2). This is derived through the tank area A_T (m²), overall heat transfer coefficient U (W/m²·K), and difference between the external temperature T_1 (°C) and NH₃ temperature T_2 (°C) inside the storage tank.

3.2 Return BOG Calculation

For the safe transfer of NH₃, the tank design pressure should not be exceeded during bunkering operations. Therefore, a system is required to return NH₃ gas from the RS to prevent the tank design pressure from being exceeded during NH₃ transfer processes (Duong et al., 2024). Eq. (3) for calculating RBOG determines the NH₃ gas generated due to

Table 5 Heat sources for the RBOG

BOG sources	Description
Displaced volume of vapor	Initial vapor inventory in RS
Insulation cool-down	Insulation cooling during loading
NBOG of RV during operation	Normal heat ingress into RS
BOG from facilities	Heat ingress into facilities in BS

incoming heat in thermodynamic equilibrium, and the flow rate calculation is performed through enthalpy changes.

$$RBOG = \frac{Q_{Total} \times 3600}{\lambda} \quad (3)$$

Here, Q_{Total} (kW) is the heat input during the bunkering process, and λ (kJ/kg) is the latent heat of vaporization of NH₃. The components that make up the RBOG that must be returned are shown in Table 5. The elements comprising Q_{Total} include the decreasing gas space due to increasing fluid level in the RS storage tank from continuous fuel transfer, cooling of insulation, BOG generated during bunkering, and the increased energy of NH₃ due to pumping.

Equation (4) represents the total sum of heat input elements occurring during bunkering, and the equations for calculating the BOG generation factors are shown in Eqs. (5)–(8).

$$Q_{Total} = Q_{Displaced\ Vapor} + Q_{Insulation\ Cool\ Down} + Q_{NBOG\ During\ Operation} + Q_{Pump} \quad (4)$$

$$Q_{Displaced\ Vapor} = \frac{V_{Tank} \times \rho_{Vapor\ NH_3} \times \lambda}{t_{Operation}} \quad (5)$$

$$Q_{Insulation\ cool-down} = Q_{Displaced\ Vapor} \times 0.5 \quad (6)$$

$$Q_{NBOG\ during\ operation} = Q_{Heat\ Ingress\ of\ RS} \times 0.5 \quad (7)$$

$$Q_{Pump} = \frac{\dot{V}_{NH_3} \times \rho_{Liquid\ NH_3} \times g \times h}{3600 \times \eta_{Pump} \times 1000} \quad (8)$$

Here, $Q_{Displaced\ Vapor}$ (kW) in Eq. (5) is calculated through the tank volume V_{Tank} (m³), density of gaseous NH₃ $\rho_{Vapor\ NH_3}$ (kg/m³), latent heat of vaporization of NH₃ λ (kJ/kg), and bunkering time $t_{Operation}$ (h). $Q_{Insulation\ Cool-down}$ (kW) in Eq. (6) represents the heat generated by cooling the storage tank insulation. $Q_{NBOG\ During\ Operation}$ (kW) in Eq. (7) is the amount of heat input occurring in the tank during bunkering. Q_{Pump} in Eq. (8) represents the BOG returned through the increased energy by the transfer pump. This is calculated using the volumetric flow rate of the transferred NH₃ \dot{V}_{NH_3} (m³/h), density of liquid NH₃

$\rho_{Liquid\ NH_3}$ (kg/m^3), gravitational acceleration g (m/s^2), pump pressure head h (m), and pump efficiency η_{Pump} (%). The assumptions for these calculations are as follows.

- (1) Heat input due to insulation cooling is 50% of heat input from $Q_{Displaced\ vapor}$
- (2) Heat input to the tank during bunkering is 50% of the RS tank heat input
- (3) Pump efficiency is 75%
- (4) Heat input generated in the piping through NH_3 transfer is ignored
- (5) Pump pressure head is STS: 165 m (1,000 kPa increase), TTS: 68.2 m (500 kPa increase)

For LNG carriers, about half of the returned BOG during loading occurs owing to cooling of the insulation (Widodo and Muharam, 2023). Therefore, in this study, heat input due to insulation cooling was conservatively assumed to be 50% of $Q_{Displaced\ Vapor}$. Therefore, the heat input to the tank during bunkering was assumed to be 50% of the RS tank heat input.

4. Results

4.1 Thermal Analysis of Bunkering

The BOR calculation results from thermodynamic analysis for the two bunkering scenarios in this study are shown in Table 6. In the STS case, the BS had a total heat ingress of 10.3 kW with 27.12 kg/h of BOG generated, and the BOR was measured at 0.098 %/day. The RS had a heat ingress of 6.5 kW with 17.09 kg/h of NBOG generated, and the BOR was calculated as 0.123 %/day. In the TTS scenario, the BT had a heat ingress of 1.458 kW with 4.50 kg/h of NBOG generated, resulting in a BOR of 0.646 %/day. For the RS, the heat ingress was 0.443 kW with 1.427 kg/h of NBOG, and the BOR was calculated at 0.344 %/day. In the STS using cubic atmospheric pressure storage tanks, the RS BOR was analyzed to be higher because smaller tanks have relatively larger surface areas compared with their volumes. In

TTS, the BOR also decreased because of the decrease in surface area corresponding to the decrease in volume of the horizontal cylindrical tanks.

Additionally, the RBOG calculation results for the bunkering system are shown in Table 7. In the STS scenario, the decreasing gas space in the RS during fuel transfer accounted for 32.30 kW, representing 35% of the total heat ingress. The heat ingress from insulation cooling was calculated to be 16.60 kW, accounting for 18%. The NBOG generated during operation was 3.25 kW or 4%, and the BOG due to increased energy of NH_3 through the pump accounted for the largest portion at 41.10 kW or 44%. Therefore, the total heat was calculated to be 92.84 kW, and the returning BOG was 271.9 kg/h.

In contrast, in the TTS scenario, the decreasing gas space in the RS during fuel transfer was calculated to be 80.06 kW, accounting for 95% of the total heat ingress, which was relatively higher than in the STS scenario. Because pressurized tanks do not have insulation, the heat ingress due to insulation cooling was calculated as 0 kW. The NBOG during operation was 0.22 kW, accounting for 0.2% of the total, and the energy increased by the pump was 3.4 kW, accounting for 4% of the total heat ingress. The calculation result was relatively lower compared to the STS scenario, with a total heat of 84.4 kW and 243.95 kg/h of NH_3 in gaseous state requiring return.

In the STS scenario, the energy increased by the pump was analyzed to be the most significant, which was attributed to the effect of thermal energy, where mechanical energy from the pump was converted to internal thermal energy of the fluid during transfer. In contrast, in the TTS scenario, although the RBOG generation was calculated to be relatively small, the decreasing gas space when transferring fuel to the relatively small 20 m³ tank was analyzed to have the most significant impact, accounting for about 95% of the total heat ingress.

4.2 Bunkering Procedure

This study established operating procedures for two scenarios, STS and TTS, for the safe and efficient operation of NH_3 bunkering

Table 6 BOR of the fuel tank

Item	Unit	STS		TTS	
		BS	RS	BT	RS
Total heat ingress	kW	10.3	6.5	1.458	0.443
NBOG	kg/h	27.12	17.09	4.50	1.427
BOR	%/d	0.098	0.123	0.646	0.344

Table 7 RBOG in the bunkering process

Item	STS	TTS
Displaced volume of vapor	32.30 kW	80.06 kW
Insulation cooling	16.60 kW	0 kW
NBOG of RV during operation	3.25 kW	0.22 kW
BOG from facilities	41.10 kW	3.48 kW
Total heat	92.84 kW	84.4 kW
Equivalent flow rate	271.9 kg/h	243.95 kg/h

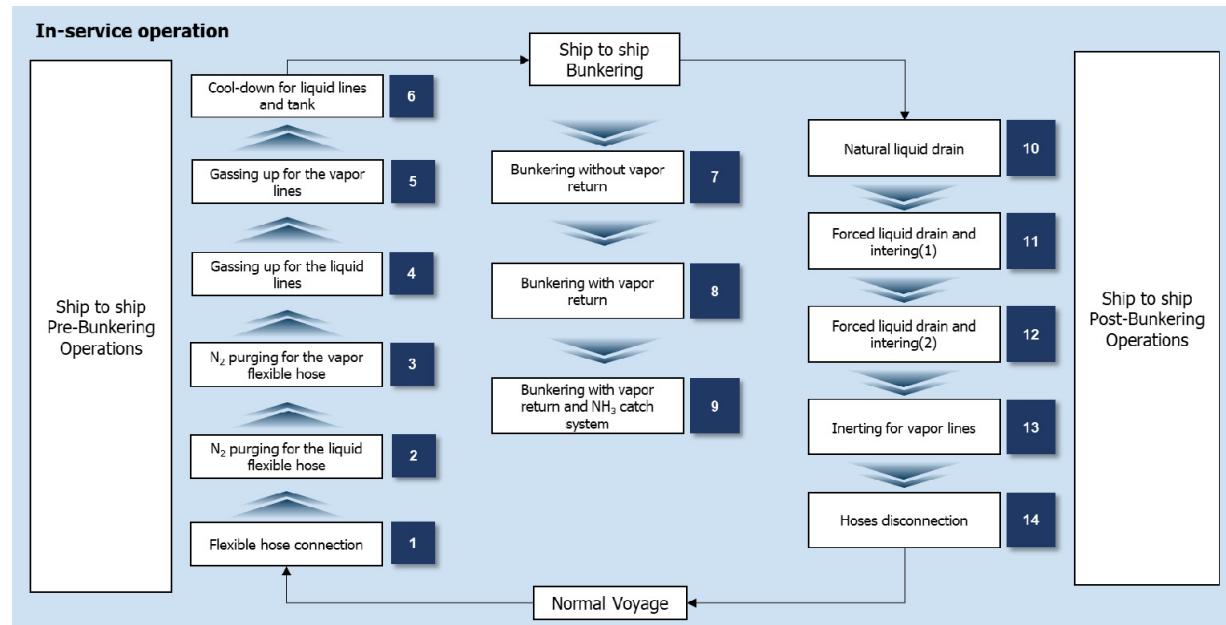


Fig. 3 STS bunkering procedure

systems. Both scenarios comprise three stages: pre-bunkering operations, bunkering operations, and post-bunkering operations, followed by a return to Normal voyage state in a repeating procedure.

As shown in Fig. 3, the STS bunkering system was established with a total of 14 operational steps for the safe transfer of large volumes of NH₃ fuel. Pre-bunkering operations consist of six steps, starting with securing physical connection between ships through a flexible hose connection, followed by sequential N₂ purging operations for liquid and vapor lines to remove impurities and oxygen from the system. Subsequently, gassing operations are performed to replace with NH₃ gas in the liquid and vapor lines. In the initial stage, cooling operations for the liquid line and tank are added to prevent rapid temperature

changes in equipment that may occur during large-volume cryogenic NH₃ transfer. Bunkering operations are conducted in three methods (steps 7–9), consisting of bunkering without BOG return in the initial fuel transfer, bunkering including BOG return due to pressure rise, and BOG return bunkering utilizing the NH₃ catch system according to leakage risk. Post-bunkering operations established operating procedures starting with natural liquid drain (step 10), followed by Forced liquid drain and inerting (steps 11–12) for the liquid line, inerting of the vapor line (step 13), and hose disconnection (step 14).

Fig. 4 shows the procedure for the TTS bunkering system, which consists of a total of 13 steps. While it has a structure similar to STS, it differs in insulation cooling owing to the pressurized storage method

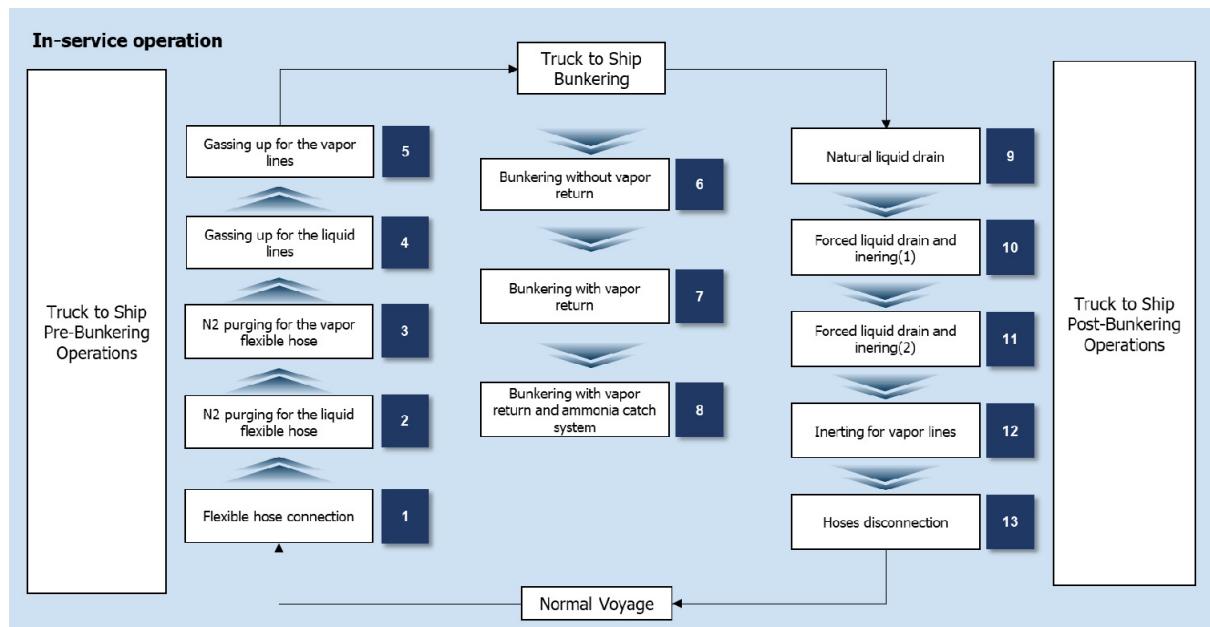


Fig. 4 TTS bunkering procedure

of the storage tank. Pre-bunkering operations consist of five steps, starting with flexible hose connection, followed by sequential N₂ purging and gassing operations for liquid and vapor lines. Bunkering operations are conducted in three stages (steps 6–8), as in the STS scenario, progressing through the transfer procedure with bunkering without BOG return, bunkering including BOG return due to pressure rise, and similarly, BOG return bunkering utilizing the NH₃ catch system for leak prevention. Post-bunkering operations start with natural liquid drain (step 9), followed by two steps of Forced liquid drain and inerting (steps 10–11), replacing with N₂ through inerting of the vapor line (step 12), and establishing a safe NH₃ fuel transfer procedure through hose disconnection (step 13).

NH₃ bunkering procedures require ammonia's toxicity and corrosiveness to be considered compared with existing LNG bunkering. LNG bunkering primarily operates by managing storage tank pressure through BOG recovery, but ammonia requires a BOG recovery system owing to its toxicity and corrosiveness. BOG and RBOG generated during bunkering cause pressure increase in storage tanks owing to heat ingress, necessitating safety assurance by quantitatively calculating and reflecting this in procedures.

This study calculated RBOG generation amounts of 271.9 and 243.95 kg/h in STS and TTS scenarios, respectively, through thermodynamic analysis. Based on this, 14-step and 13-step bunkering procedures were established to prevent leakage risks due to an increase in tank pressure. These procedures differ in the presence or absence of cooling operations depending on NH₃ storage temperature and pressure conditions. Each step is designed to minimize leakage and explosion risks through pressure rise prevention via evaporated gas recovery systems, NH₃ catch systems, and residual NH₃ removal through N₂ purging. In particular, the NH₃ catch system is a device considering the hazards of ammonia, requiring additional safety systems not present in existing LNG bunkering. In post-bunkering operations, residual evaporated gas is completely removed through N₂ purging and NH₃ catch systems, with safety assurance needed even during hose disconnection.

5. Conclusion

In this study, thermodynamic analysis was performed for two scenarios, STS and TTS, for the safe and efficient operation of the NH₃ bunkering system. Based on this, operating procedures for the safe transfer of NH₃ were established. The thermodynamic analysis results showed that in the STS scenario, the BS had a total heat ingress of 10.3 kW with 27.12 kg/h of NBOG, and the BOR was calculated as 0.098 %/d. For the RS, a heat ingress of 6.5 kW, 17.09 kg/h of NBOG, and a BOR of 0.123 %/d were observed. In the TTS scenario, the BT had a total heat ingress of 1.458 kW, 4.50 kg/h of NBOG, and a BOR of 0.646 %/day, whereas the RS had a heat ingress of 0.443 kW, 1.427 kg/h of NBOG, and a BOR of 0.344 %/day. Based on this thermodynamic analysis, the analysis of RBOG generated during the bunkering process calculated the total heat ingress for the STS and

TTS scenarios as 92.84 and 84.4 kW, respectively, with BOG flow rates derived as 271.9 and 243.95 kg/h, respectively. These quantitative results confirmed that RBOG is essential to preventing leakage risks during bunkering operations. Based on these analysis results, systematic operating procedures divided into three stages (pre-bunkering, bunkering, and post-bunkering) were established for both scenarios. Specifically, the FR-to-FR method STS bunkering consists of 14 steps, whereas the NR-to-NR method TTS bunkering consists of 13 steps, with the main difference being the presence or absence of cooling operations depending on the tank type. In ammonia bunkering procedure research, BOG and RBOG analysis is essential for establishing regulations for safe transfer owing to toxicity and corrosiveness. Additional safety devices and procedures considering ammonia's toxicity and corrosiveness differ from existing LNG bunkering, and safety regulations for ammonia bunkering system requirements can be established based on these procedures.

This study established operating procedures based on thermodynamic analysis for safe bunkering operations from leakage risks considering the toxicity and corrosiveness of NH₃. However, further research based on detailed design information and actual operational data is required for accuracy and practical applicability for real NH₃-propelled ships. As the commercialization of NH₃ as an environmentally friendly ship fuel expands in the future, the results of this study are expected to aid in developing safety regulations for NH₃-propelled ships through bunkering procedures that consider RBOG.

Conflict of Interest

Dongho Jung serves as a journal publication committee member of the Journal of Ocean Engineering and Technology, but he had no role in the decision to publish this article. The authors have no potential conflict of interest relevant to this article.

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