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Original Paper

Prediction of boil-off gas and boil-off rate in cargo tank of NGH carrier

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Abstract: Natural gas hydrates are newly emerging as an environment-friendly source of energy to substitute for fossil fuels in the 21stcentury.NGHs are reported to holds much amounts of natural gas (up to 182 standard volumes of gas per volume of hydrate); they are easy to store and safe to carry at about minus 20 degree Celsius under atmospheric pressure because of the self-preservation phenomenon of gas hydrates. The transporting method by gas-ice-hydrate ship carriers has been introduced and developed by a variety of industry and research institutions. Our team has been conducted to develop NGH total systems, including a breakthrough NGH carrier for sea transportation, since 2011. The NGH pellet carrier does not require a separate cooling system for cargo, and the initial temperature is maintained through insulation of the cargo tanks throughout the transport to the final destination. The heat conducted from the exterior and passing through the insulation material of the hull should be cut off as much as possible, but heat inflow inside the cargo tank from an external source is inevitable during transport. In this study, the heat transfer in a cargo tank of a 115K NGH carrier was analyzed through simulation with a commercial CFD code to estimate the boil-off gas/boil-off rate on the developed carrier and understand major hazards that could significantly impact the safety of the vessel.

Keywords: Natural gas hydrate, Gas carrier, Boil-off gas, Boil-off rate, Risk analysis, Computational fluid dynamic, System design, IMO

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1. Introduction

Natural gas hydrates (NGHs) are being magnified as an environment-friendly energy source to substitute for fossil fuels. NGHs are a solid phase of natural gas and water that forms a crystalline lattice, and contain natural gas up to 182 standard volumes of gas per volume of hydrate at about minus 20 degree Celsius under atmospheric pressure because of the self-preservation phenomenon. For these reasons, NGH has the advantage of being applicable to small- and medium-sized gas fields that are considered economically infeasible **[1]-[4]**. Natural gas can be shipped in the liquefied state (LNG), compressed state (CNG), and in the form of hydrates (NGH); the technology is still in the design phase **[4]**.

The technologies of gas hydrate pellet carriers for sea transport has been developed by many industry and research groups. Mitsui Engineering & Shipbuilding Co., Ltd. (MES) has been developed the overall NGH technology such as manufacture of natural gas hydrates from natural gas and water, transportation of the hydrate by ship, and re-gasification of the hydrate to natural gas and water, since 2001. Especially the NGH pellet-type transporting system is known to have the superiority in many aspects, including a high filling ratio in ship cargo tanks, superior fluidity, and improved self-preservation effect. It is one of the best solutions to realizing NGH sea transportation more practical **[5]-[8]**. The NGH pellet carrier is a major connection in the potential gas hydrate process chain starting with the extraction of natural gas from sources and followed by the production of hydrated pellets and their transportation to onshore storage facilities for further processing or marketing. In 2008, the SUGAR project **[9]** was carried out in Germany to develop new technologies for the exploration and exploitation of submarine gas hydrate resources and new concepts for the transportation of natural gas from hydrate storage facilities.

Recently, Korean ship building and plant industries have put large amounts of effort in the development of LNG cargo tank

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technology. Based on the technologies for a LNG carrier, our team has been working on the development of NGH total systems, including a novel NGH carrier, since 2011 **[10][11]**. In our project to establish thermal analysis technology for NGH cargo tanks, related technologies such as BOG estimation, internal structural material and thickness estimation on insulation have been developed to determine the design and safety level of other ship types with similar scopes, e.g., LNG carriers and crude oil tankers **[12]-[15]**.

In this study, the heat transfer for the cargo tank on 115K NGH carrier was analyzed with a commercial CFD code to estimate the boil-off gas (BOG)/boil-off rate (BOR) on the developed carrier and to understand major hazards that can significantly impact the safety of the vessel. The best knowledge available on alternative technologies for the design and assessment of a cargo tank on an LNG carrier was used; the same analysis and assessment techniques were applied to estimating the BOG/BOR of a cargo tank on an NGH carrier using a commercial CFD code. The reliability of the heat transfer was determined by comparing the results with the data from GTT's analysis report.

2. Thermal analysis of LNG carrier

2.1 Verification of thermal analysis and reliability using GTT's data

Table 1 reviews a report on the heat ingress of LNG cargo tanks for preliminary calculations based on GTT's thermal data for membrane-type LNG carriers. First, we reviewed the data to determine the type and volume of cargo tank to be analyzed and derived the values by calculating the total heat flow rate flowing into the cargo tank. Because shipyards normally select a reliability of less than 3% tolerance for estimating the BOG of an LNG carrier, the same level of reliability was applied.

(1) Environmental conditions and properties of LNG carrier

- Environmental conditions:
  - Air temperature: 45 °C
  - Seawater temperature: 32 °C
- LNG properties:
  - Tank filling ratio: 98%
  - Composition: Pure methane CH_4
  - Temperature: -161.5 °C
  - Specific density: 425 kg/m^3
  - Latent heat of vaporization: 511 kJ/kg

(2) BOG calculation

$$BOR=\frac{\phi}{\rho_m \cdot V \cdot L} \cdot 3600 \cdot 24$$

Here,

ϕ : sum of all local heat transfers

ρ_m : density of methane

L : vaporization latent heat of methane

V : cargo capacity (corresponding to 98.0% of total tank capacity)

2.2 Analysis model and boundary conditions

The analysis model for the LNG cargo tank was based on real ship data from the GTT. Because the heat transfer characteristics in the width and longitudinal directions are equal, only one-fourth of the cargo tank volume was modeled in order to reduce the calculation time for grid nodes. The membrane tank was adopted as the thermal analysis model, and the primary/secondary invar and wood for wall insulation were not considered at the wall of the membrane tank. This was so thin because the primary and secondary insulations were made of 0.7 mm invar. The inner wall as modeled using only two-layer insulation because standards organizations have interpreted in rule that it does not have a significant effect on heat ingress from outside the hull. The hull reinforcement of the outer cargo tank was simplified; all external heat effects of the various reinforcements attached to the hull plate were ignored except for some hull structures that can pass well into the cargo tank.

Table 1: Review of heat ingress to LNG cargo tanks for preliminary calculations based on GTT's data

	Cargo tank insulation area (Primary barrier level)				Length of corners		Cargo tank volume (at 100 % tank capacity)	Heat transfer rate (with LNG at -161.5℃)	Tank individual boil-off rate (at 98 % tank capacity)
	Standard Insulation	Reinforced Insulation	Ultra Reinforced Insulation	Total Tank Area	Transverse	Longitudinal (Inclined Oblique)			
Tank No.1	3,355m^2	490m^2	1,041m^2	4,866m^3	202m	274m	24,599m^3	97,986W	0.162%
Tank No.2	5,269m^2	1,041m^2	1,518m^2	7,828m^3	240m	388m	48,641m^3	151,190W	0.126%
Tank No.3	5,269m^2	1,041m^2	1,518m^2	7,828m^3	240m	388m	48,641m^3	151,190W	0.126%

Figure 1 shows the concept for thermal analysis of the hull of an LNG carrier. The process of heat ingress from the air and seawater flows into the inner cargo tank through conduction and convection. The conduction coefficients at each hull part should be determined from the material properties, so the coefficients for conduction in the hull parts and the coefficients of insulation in the insulating materials were formulated according to the properties.

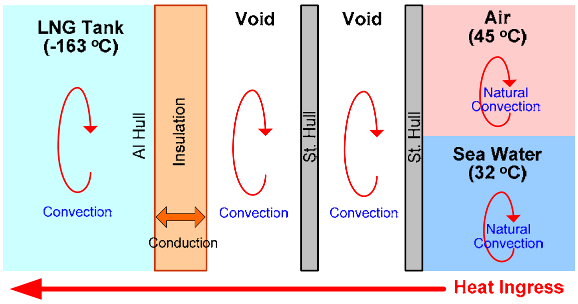

Figure 1: Concept model for thermal analysis of LNG carrier

The commercial software ANSYS Fluent ver.14.0 **[16]** was used for the numerical analysis. The initial temperature conditions were set according to the IGC code (IGC 83/ 90 Amend/ Annex/ Chapter 7/ 7.1.2, Design Temperature) **[17]** to estimate the BOG of the cargo tank in the LNG carrier. Boundary conditions for all edge parts except the cofferdam were set up under the symmetry condition. **Table 2** and **Figure 2** present the boundary conditions for thermal analysis of the LNG tank, side/inner void, ballast tank, and insulation according to IGC 83/90.

Table 2: Boundary conditions for thermal analysis

▪ 3D-1/1 Scale LNG Tank + Side/Inner Void + Water Ballast Tank + Insulation
- Air temperature: 45 °C
- Seawater temperature: 32 °C

▪ Temperature Boundary Conditions (IGC 83/90 Amend/Annex/Chapter 7/7.1.2, Design Temperature
- Air heat: 45 °C
- Water heat: 32 °C
- Cargo hold tank heat: -161.5 °C
- Cofferdam: 5 °C

▪ Convection Boundary Conditions

	Loading (0 knots)	Sea going
Air heat (W/m^2 °C)	25	No wind effect
Air heat (W/m^2 °C)	100	No wind effect
	Natural convection	Forced convection

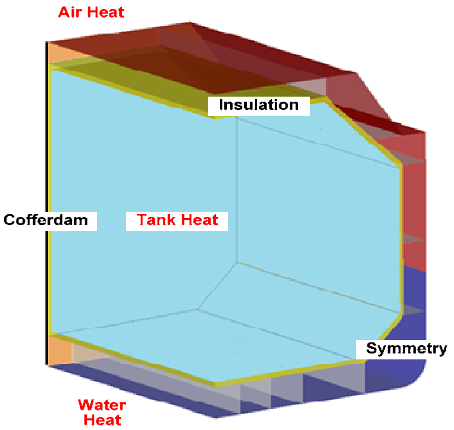

Figure 2: Boundary conditions for cargo hold in LNG carrier

2.3 Definition of insulation

Because the physical properties of a heat-insulating material used to suppress thermal effects are generally private information, it is difficult to know the characteristics of the insulation installed in the cargo tank on each vessel. In general, insulating materials such as polyurethane foam, perlite, and superlite are applied to the cargo tanks of LNG carriers. In this analysis, the heat-insulating material was given the heat transfer characteristics of perlite of S-shipbuilding.

Each insulation has different heat transfer characteristics depending on the temperature variation, like the coefficient of conduction. Therefore, the coefficient of conductivity for this temperature change was considered in the CFD code, and the thermal conductivity was defined as shown in **Figure 3**.

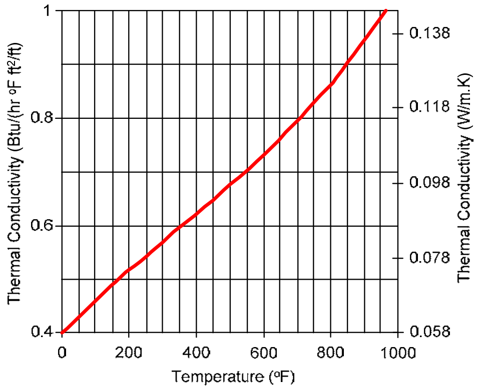

Figure 3: Conductivity of insulation with changing temperature

2.4 Analysis method and results

Figure 4 shows the heat transfer rate over time based on transient analysis of the LNG cargo tank. The quantity of the heat flow changed over time. In GTT's thermal analysis conditions, the BOR was not considered for the loading of LNG or cooling of the cargo tank. Thus, the BOR in our estimation was calculated under thermal equilibrium considering only the operating conditions of the ship. In this study, the thermal equilibrium state was considered to be the average heat flux (25 - 48h) after 24 hours and was used as a factor needed to calculate the BOR (see section A in **Figure 4**).

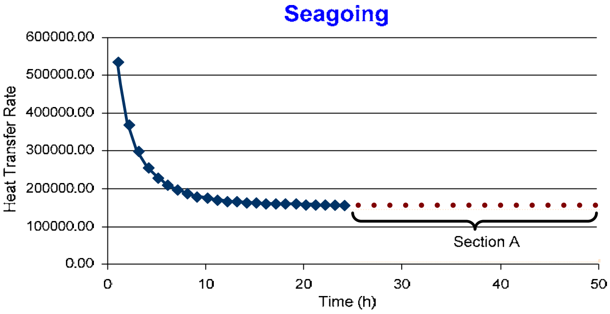

Figure 4: Heat transfer rate by time evolution in LNG cargo tank

Through a comparison with GTT's BOR method (see **Table 3**), the accuracy of the derived prediction model was verified; the maximum relative difference was less than 2% compared with our estimation. **Figures 5 (a)** and **5 (b)** show the temperature distribution of the inner hull structure and the section temperature contours over time. The loading/unloading volumes of the third tank for the LNG ship were calculated as 48,641 (m^3) × 0.98. Then, the total ingress calories (ϕ) for a day was estimated as 152,906(W) × 3,600 (s) × 24 (h).

Table 3: BOG validation between CFD estimation and GTT's data

Boil Off Gas	Heat Transfer Rate	Difference (%)
BOR (Cal.)	0.128	1.14
BOR (GTT)	0.126	

3. Estimation of BOG/GOR in NGH carrier

The ship type and design for the transport of the raw material and the equipment of a gas loading terminal depend on the state in which the raw material will be shipped. **Figure 6** illustrates an example of the regasification concept for a cargo tank transporting an NGH pellet carrier. Ota *et al* **[5]** experimentally confirmed that methane hydrate pellets(MHPs), which are supposed to have similar properties to those of NGH pellet carriers, can be efficiently stowed and transported at around -20 °C under atmospheric pressure because of their self-preservation property.

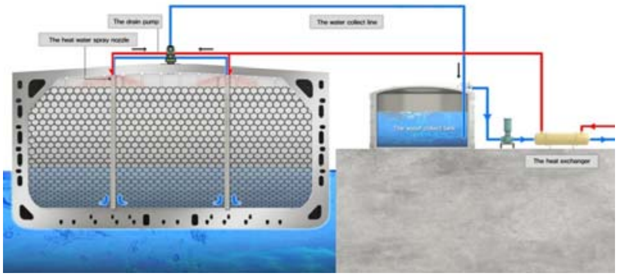

Figure 6: Concept design of cargo hold for regasification in NGH pellet carrier

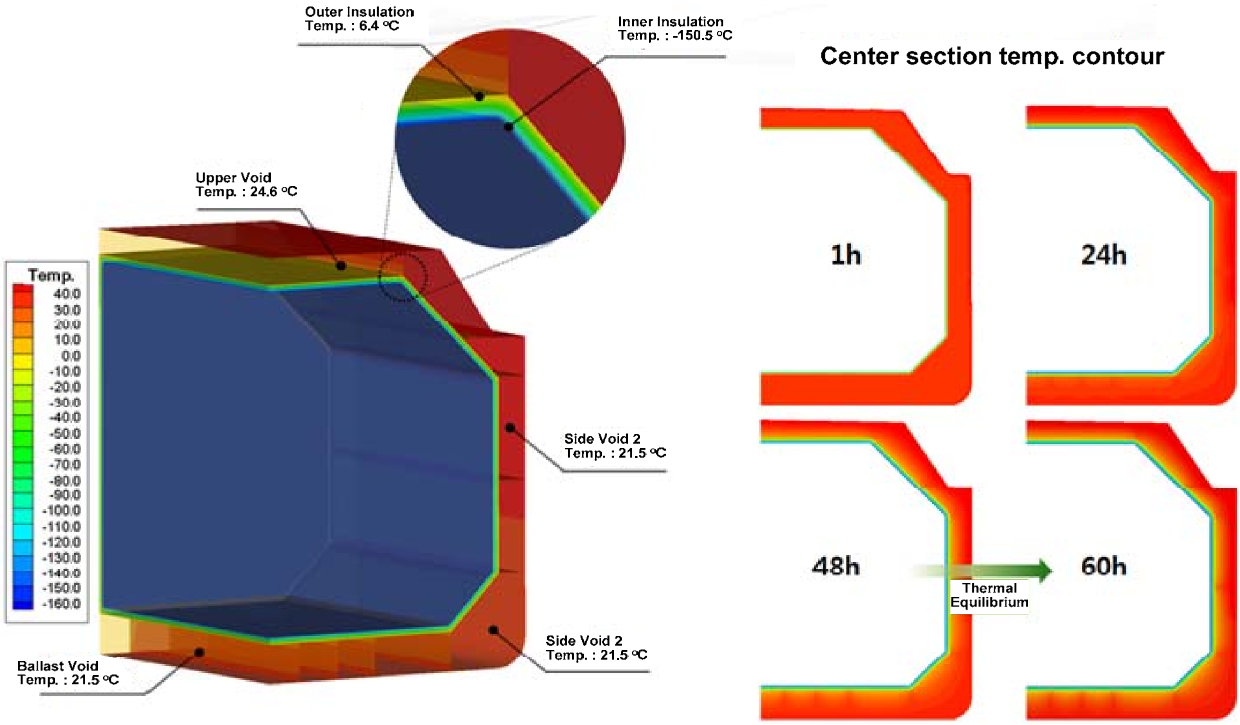

Figure 5: Temperature profile of cargo tank and section over time

Based on thermal analysis techniques for the LNG cargo tanks discussed in the previous section, the BOR in the cargo tank of NGH carrier was calculated using the same conditions and methods. Although there is a large difference in temperature for cargo tanks in an LNG carrier (-163 °C) and NGH carrier (-20 °C), the same analysis method for heat transfer with understanding of the model and grid system of an LNG carrier will provided reasonable information and results for an NGH carrier.

3.1 Analysis of heat transfer

NGHs are known to contain large amounts of natural gas (about 160-180 times their volume) and they are easy to store and safe to transport at about -20 °C under atmospheric pressure because of the "self-preservation effect" with the help of insulation. Heat ingress from the outside through the heat-insulating material should be blocked as much as possible, but heat flowing inside the cargo tank from an external heat source is inevitable. We estimated the heat ingress to a cargo tank through heat transfer analysis using the commercial code CFD program Fluent. By calculating the BOG volume based on the CFD analysis, we determined the presence/absence of insulation and its thickness and selected equipment specifications for BOG treatment.

Figure 7 describes the heat transfer mechanism between an external heat source (sea and atmosphere) and the cargo tank of an NGH carrier. The BOG/BOR due to dissociation generated in the cargo tank can be estimated by calculating (a) the heat of the atmosphere and sea flowing into the cargo tank by conduction and convection; (b) the heat ingress inside the cargo tank by the convection of the external heat source, the heat flux of the hull, and the thermal insulating capacity of the insulation; (c) and the amount of heat ingress.

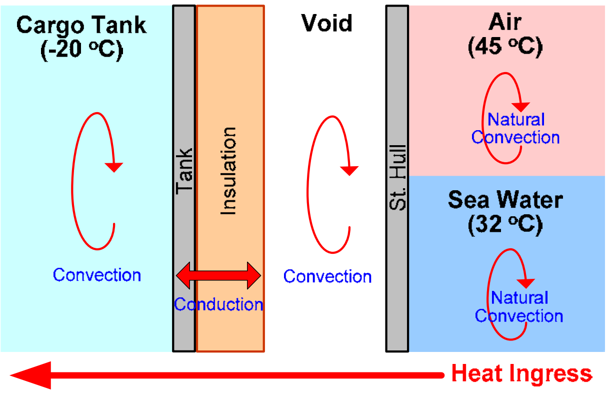

Figure 7: Concept model for thermal analysis of NGH carrier

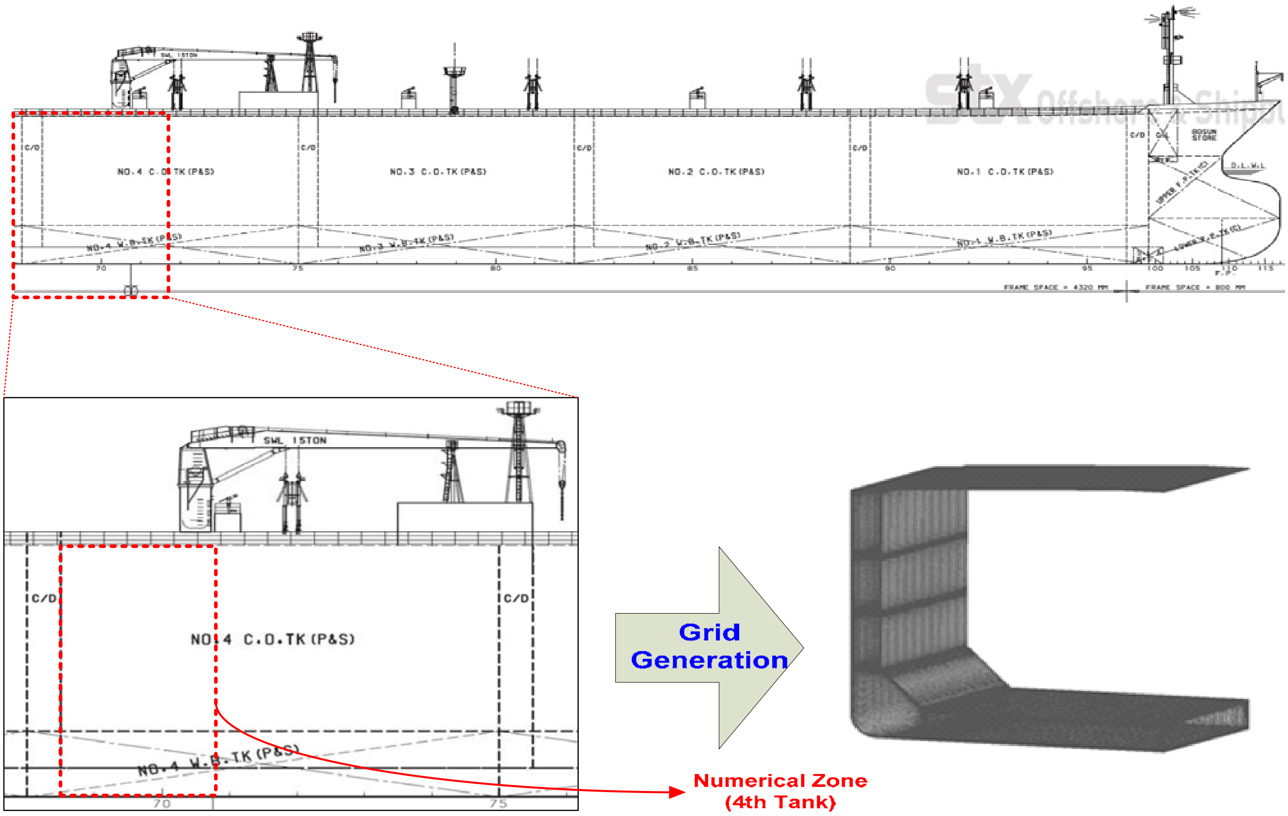

Figure 8: General arrangement and definitions of model

3.2 Definition of analysis model and grid generation

Figure 8 shows the general arrangement and definitions of the model for a 115K NGH carrier. Because the thermal boundary conditions of the longitudinal and transverse direction in the cargo hold are symmetrical, only a quarter of the cargo hold was modeled in this analysis to reduce the computational load. The effects of various reinforcements attached to the hull plate were not considered. Also, the insulating layer, which has complicated geometry in the cargo tank, was ignored because the flow characteristics within the cargo tank were not analyzed.

Although the hull and cargo tank vary slightly in thickness by location, the modeling was carried out using the mean values of the inner and outer hulls for convenience. The thickness of the insulation was set to 100 mm.

3.3 Boundary conditions

The heat sources affecting the BOG in an NGH carrier can be classified as internal heat sources in the cargo tank and external heat sources from the air/sea. Heat transfer takes place by convection in the cargo hold and at the atmosphere/seawater interface and by conduction through the hull and insulating materials. The internal void tank is transferred by convection through the air. **Figure 9** and **Table 4** present the boundary conditions for each part.

Table 5 presents the thermal conductivity, specific heat, and density for the insulating materials in the cargo tank of NGH carrier based on the temperature variation. Polyurethane foam was used for its material properties; its heat transfer characteristics vary according to the temperature. Thus, in order to consider the coefficient of heat transfer depending on the temperature of the heat-insulating material, the insulation characteristics were considered in the analysis model.

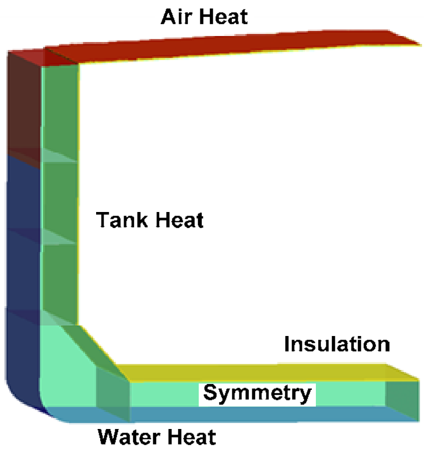

Figure 9: Boundary conditions for cargo hold in NGH carrier

Table 4: Boundary conditions for thermal analysis of 115K NGH carrier

- ■ Analysis model
  - 3D-1/1 Scale NGH tank + Void + Insulation
  - Air temperature: 45 °C
  - Seawater temperature: 32 °C
- ■ Temperature Boundary Conditions (IGC 83/90 Amend/ Annex/Chapter 7/7.1.2, Design Temperature
  - Air heat: 45 °C
  - Water heat: 32 °C
  - Cargo hold tank heat: -20 °C
  - Void: 26 °C
- ■ Convection Boundary Conditions
  - Air heat: 25 W/m^2 °C
  - Water heat: 100 W/m^2 °C

Table 5: Properties of material by temperature change in NGH carrier

	Thermal conductivity		Specific Heat		Density
Item	℃	W/m℃	℃	J/kg℃	kg/m^3
Air	-73.15	0.0181	-73.15	1003	1.225
	-23.15	0.0223	-23.15	1003	
	6.85	0.0246	6.85	1004	
	16.85	0.0253	16.85	1005	
	24.85	0.0259	24.85	1005	
	26.85	0.0261	26.85	1005	
	36.85	0.0268	36.85	1006	
	46.85	0.0275	46.85	1006	
	56.85	0.0283	56.85	1007	
	66.85	0.029	66.85	1007	
	76.85	0.0297	76.85	1008	
	126.85	0.0331	126.85	1013	
	176.85	0.0363	176.85	1020	
	226.85	0.0395	226.85	1029	
	276.85	0.0426	276.85	1039	
Hull	-	16.27	-	502.48	8030
Insulation	-160	0.01106	-	1045	40
	-130	0.01229			
	-100	0.01382			
	-70	0.01637			
	-40	0.0194			
	-10	0.021			
	20	0.02118			

3.4 Results and discussion

As shown in **Figure 10**, the heat transfer rate confirmed that the amount of heat flow inside the cargo tank of an NGH carrier varies with time. In order to estimate the total heat flow in the cargo tank, the evaluation method for heat transfer in an LNG carrier was also applied to the NGH cargo tank. We assumed thermal equilibrium conditions and calculated the total heat flow for 24 ~ 48 h (period A) based on the heat flow rate for 24 h. As indicated in **Table 6**, the BOG and BOR values were estimated using the necessary calories to convert ice in the hydrates and the total amount of gas shipped.

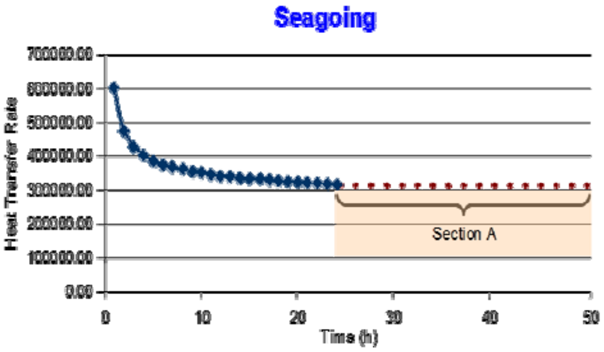

Figure 10: Variation in heat transfer rate with time

Table 6: BOG and BOR with necessary calories and total shipped gases for conversion from hydrate to ice

Classification	Value
Total heat flow for 24 – 48 h	• 7,940.94 W x 24 h = 190,582.56 W = 2,744,389 KJ
Calories for Converting from hydrate to ice	• 17.4662 KJ/mole of gas
Total shipped gases	• 92,896,707 mol
BOG	• 1.57 x 10^5mol/day
BOR	• 0.17 %/day

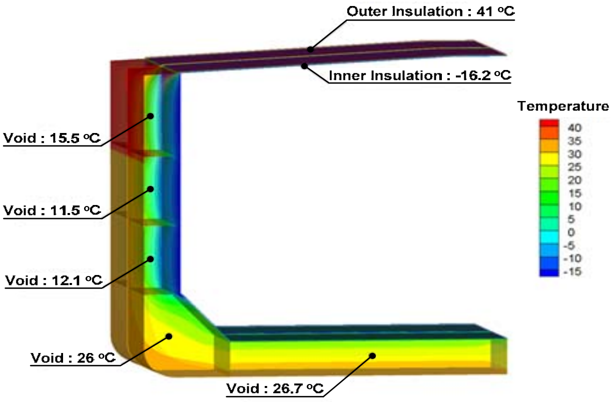

Figure 11: Temperature distribution in out hull

The total heat ingress into the NGH cargo tank over 24 – 48 h was about 2,744,389kJ, and the BOG and BOR based on the amount of heat inflow to the cargo hold were about 1.57 × 10^5 mol/day and 0.17%/day, respectively. If the BOR is calculated according to the heat flow entering into the cargo tanks under the conditions of atmospheric pressure and ocean temperature using the IGC code of IMO, approximately 0.17% of the total cargo volume would dissociate.

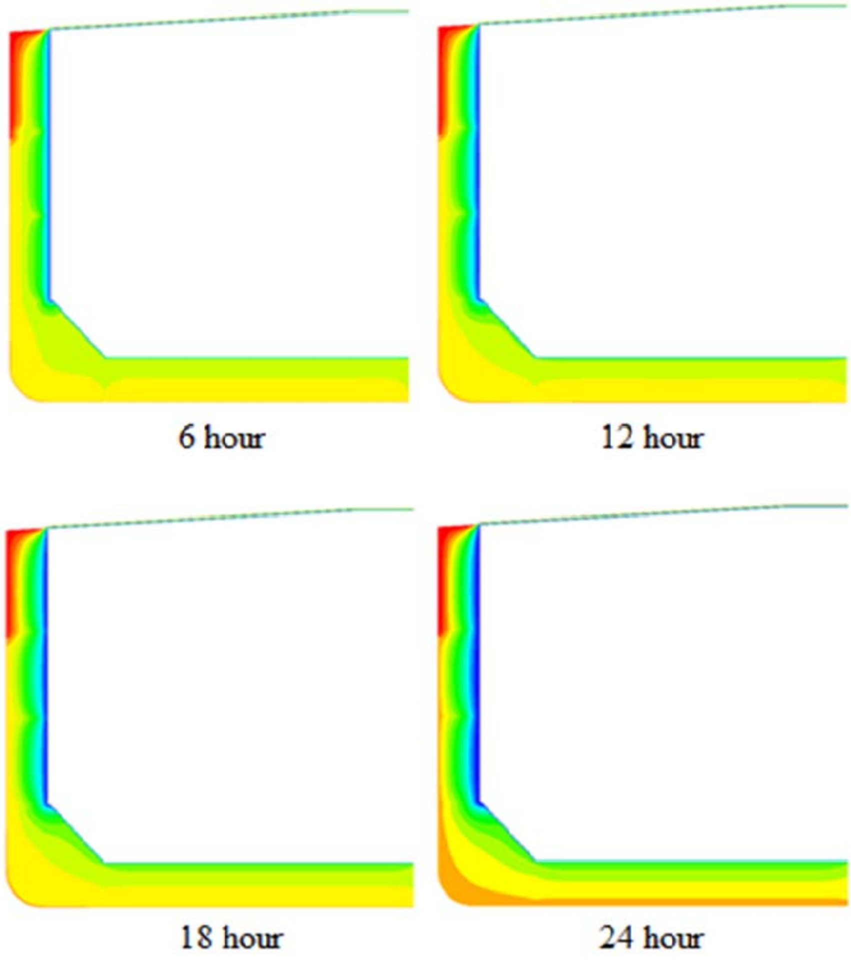
6 hour
12 hour
18 hour
24 hour

Figure 12: Temperature profile at section with time in fourth cargo hold

In general, 1.6% of the BOR in hydrates is generated by the self-preservation effect under the environmental conditions at 1 barg and ‑20 °C. Then the BOR that may occur during ship operation under actual sea conditions was estimated to be 1.77% by summing the dissociation that occurs naturally and caused by an external heat source. **Figures 11** and **12** present the temperature distribution in the outer hull and the temperature profile by section in the fourth cargo tank. Heat flowed into the cargo tank over time.

4. Conclusion

The existing thermal analysis method used for LNG carriers and recommendations from the IMO IGC code were used with the atmosphere conditions and ocean temperature to estimate the heat flow entering into the cargo hold of a 115K NGH carrier. In order to verify the reliability of the analysis, we compared the results of our approach with the thermal analysis data in GTT’s assessment report on LNG carriers.

In summary, our results revealed that the total heat ingress into the NGH cargo tank over 24 - 48 h was estimated to be about 2,744,389 kJ, and the BOG and BOR based on this heat flow were about 1.57×10^5 mol/day and 0.17%/day, respectively. Moreover, the BOR including the self-preservation effect was assessed to be about 1.77% during transportation.

Even if this analysis was carried out based on BOG/BOR estimation methods applied to existing LNG cargo tanks, more understanding is required, and processes for a site-specific project based on operating data need to be developed to verify the results of the presented analysis.

Acknowledgements

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