Journal of the Korean Society of Marine Environment & Safety
Research Paper
Vol. 24, No. 3, pp. 352-359, May 31, 2018, ISSN 1229-3431(Print) / ISSN 2287-3341(Online)
https://doi.org/10.7837/kosomes.2018.24.3.352

Parametric Investigation of BOG Generation for Ship-to-Ship LNG Bunkering

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Abstract : *As a fuel for ship propulsion, liquefied natural gas (LNG) is currently considered a proven and reasonable solution for meeting the IMO emission regulations, with gas engines for the LNG-fueled ship covering a broad range of power outputs. For an LNG-fueled ship, the LNG bunkering process is different from the HFO bunkering process, in the sense that the cryogenic liquid transfer generates a considerable amount of boil-off gas (BOG). This study investigated the effect of the temperature difference on boil-off gas (BOG) production during ship-to-ship (STS) LNG bunkering to the receiving tank of the LNG-fueled ship. A concept design was resumed for the cargo/fuel tanks in the LNG bunkering vessel and the receiving vessel, as well as for LNG handling systems. Subsequently, the storage tank capacities of the LNG were 4,500 m^3 for the bunkering vessel and 700 m^3 for the receiving vessel. Process dynamic simulations by Aspen HYSYS were performed under several bunkering scenarios, which demonstrated that the boil-off gas and resulting pressure buildup in the receiving vessel were mainly determined by the temperature difference between bunkering and the receiving tank, pressure of the receiving tank, and amount of remaining LNG.*

Key Words : *Liquefied natural gas (LNG), Ship-to-ship (STS), LNG bunkering, Boil-off gas (BOG), Gas-fueled ship*

1. Introduction

As an alternative source of energy, the demand for liquefied natural gas (LNG) has increased rapidly. Fig. 1 shows that the global market for natural gas was nearly $1 trillion in 2008. Global total natural gas consumption is expected to rise to 169 trillion cubic feet in 2035, from 111 trillion cubic feet in 2008. Natural gas consumption in emerging economies such as China and India, where consumption is forecasted to grow three times as fast from 2008 to 2035 in comparison to industrialized countries, will account for the largest part of this growth. China provides one of the largest and fastest growing opportunities, as its demand for LNG rapidly increases (IEO, 2011).

In order to comply with the increasingly stringent IMO emission requirements, the use of natural gas as a ship fuel is considered as a realistic and feasible solution (Xu et al., 2015). LNG operation, in comparison to HFO operation for ship fuel, provides a considerably cleaner exhaust, in compliance with the IMO emission regulations for gas engines operating over a broad range of power outputs. Engine models include gas-only engines and dual fuel (DF) four-stroke and two-stroke engines. Dual fuel and single fuel engines have been successfully installed and operated in a number of offshore support vessels and ferry applications (Lee et al., 2017). The “Econuri”, which was the first LNG-powered vessel in Asia, was built in Korea in the 2013 and is currently operated by the Incheon Port Authority (Chun et al., 2016).

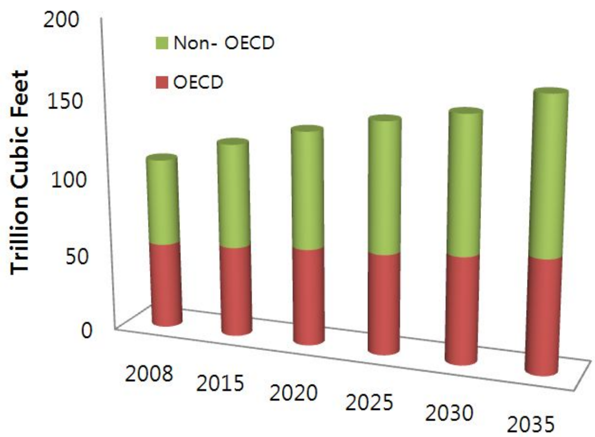

Fig. 1. World natural gas consumption.

To promote the development of LNG as a ship fuel, it is necessary to set up a complete set of infrastructural facilities and to drastically improve the legal system. There are primarily three

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※ This paper is based on proceedings presented by the authors at the 2016 KOSOMES Autumn Annual Conference held in YoeSu, South Korea (Shao et al., 2016).

kinds of waterborne LNG bunkering methods (DNV GL, 2015): terminal-to-ship (PTS), truck-to-ship (TTS), and ship-to-ship (STS) transfers. In terms of legal provisions, the ISO/TS 18683 "Guidelines for systems and installation for supply of LNG as fuel to ships" were published in 2015. The technical specification provided guidelines for the minimum requirements pertaining to the design and operation of an LNG bunkering facility, including the interface between LNG supply facilities, and the receipt of the ship as shown in Fig. 2 (ISO, 2015). Moreover, one of the key steps in safe LNG bunkering is to verify that the supplying and receiving vessels are compatible. Compatibility covers a wide range of topics, and due to complexity, confirming compatibility for LNG bunkering is more important than confirming it for oil fuel bunkering.

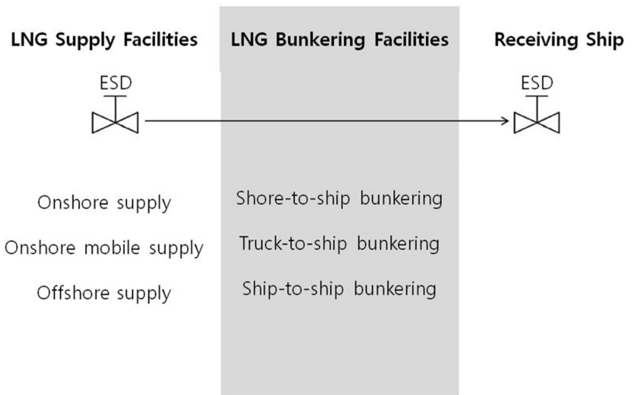

Fig. 2. Interfaces between bunker facility and supply/receiving facilities.

The procedure of STS LNG bunkering is different from that of HFO bunkering, with respect to the cryogenic-liquid transfer generating boil-off-gas (BOG). Although bunkering equipment such as storage tanks, pipes, and valves are insulated in order to reduce heat transfer, its contact with the cryogenic liquid generates a considerable amount of undesirable BOG (Ryu, 2012). The BOG is caused by the heat ingress into the LNG during the storage, transportation, and loading/unloading operations (Dobrata, 2013), and especially during the transfer of LNG fuel between the LNG supply vessel and the LNG-fueled ship while bunkering, due to temperature and pressure difference, which always results in the generation of vapor mass.

Based on the above situation, this study utilized the commercial software Aspen HYSYS in order to process dynamic simulations under several bunkering scenarios. It was found that the BOG and the consequent pressure buildup in the receiving vessel were mainly determined by the temperature difference between the receiver and bunker tank, pressure of the receiver tank, and amount of remaining LNG.

2. Modeling of Bunkering System

2.1 Bunkering Timeline

The timeline used in this simulation according to 2015 ISO/TS 18683 is shown in Fig. 3.

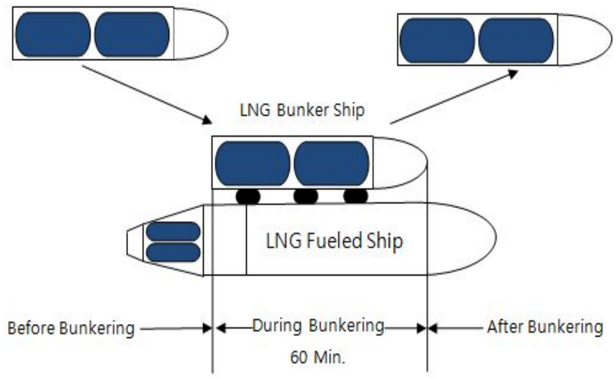

Fig. 3. Bunkering timeline according to 2015 ISO/TS 18683 for small vessels.

The LNG bunkering into fuel tanks (receiving tank of LNG -fueled ship) is a different process to HFO bunkering, due to some unique differences in fuel characteristics. The main difference is that the vapor from a typical petroleum bunker is not considered to create a hazardous zone, due to the flash point being above 60 ℃ (140 F), and due to it being vented into the atmosphere. However, the LNG vapor can form explosive clouds in confined spaces and is considered hazardous. This requires the special handling of the vapor while bunkering. The time limit for the bunker scenario was set to approximately 60 min. to complete the STS bunkering procedure. In order to distinguish different actions more easily during the bunkering operation, the procedural description was divided into three stages:; namely, the stages before, during, and after bunkering (SMTF, 2010).

In general, the bunkering limit is the maximum allowable liquid volume to which the fuel tank may be loaded, and expressed as a percentage of the total fuel tank volume (ABS, 2014). This limit depends on the LNG densities at the bunkering and reference temperatures, and is determined by the following equation:

$$BL = FL(\frac{\rho_R}{\rho_L}) \tag{1}$$

Here, BL is the bunkering limit, FL is the filing limit, while subscripts R and L are the LNG density at the reference temperature and the LNG density at the bunkering temperature, respectively. The typical bunkering limits for the LNG-fueled ships are expected to range from 85 % to 95 % depending on fuel tank type, pressure relief valve setting, and other ship specific considerations.

2.2 Tank geometry

As shown in Table 1, the IMO Type C pressure tanks are installed on both the vessels, and the double shell vacuum is used as the tanks' insulation. The LNG tank volume of the bunkering vessel is 4500 m^3, the diameter is 12.0 m and the length is 40.12 m. Accordingly, for the receiving vessel, the LNG tank volume is 700 m^3, the diameter is 8.0 m and the length is 13.93 m.

Table 1. Geometry for the LNG tanks of bunkering and receiving vessels

Parameter		Value	Tank type
Bunkering Vessel	Tank volume [m^3]	4500	IMO Type C / Double shell vacuum insulation
	Diameter [m]	12.0	
	Length [m]	40.12	
Receiving Vessel	Tank volume [m^3]	700	
	Diameter [m]	8.0	
	Length [m]	13.93	

2.3 Determination of LNG flow rate

Natural gas is a colorless mixture of several gases, but is mainly composed of methane (CH_4) with a typical concentration of 70 % to 99 % by mass, depending on the origin of the gas. Other constituents commonly found in natural gas are ethane (C_2H_6), propane (C_3H_8), and butane (C_4H_{10}).

The bunker piping system consists of an LNG transfer pipe (bunker pipe) and a vapor return pipe (BOG pipe) between the bunkering vessel and the fuel tank of the receiving vessel. The bunker pipe and return pipe are sized according to the design flow rates through the system. The design flow rate is based on the LNG fuel tank capacity, pressure, temperature and other factors, such as vapor return capacity, flow velocity limits, and bunkering time (ABS, 2014). In addition, the flow rate depends on the achievable bunkering rate from the bunker vessel.

First the transfer rate was assumed to be 320 m^3/h, when flow velocity was 5 m/s in Eq. (2). Then, the diameter of the pipeline and mass flow rate calculation method were expressed by Eqs. (3) and (4). Here, the mass density of LNG in the bunkering ship was 406 kg/m^3 when the methane composition was at 96 %.

According to verification by transient simulation, if the flow velocity in the pipeline was set to 4.8 m/s, the bunker scenario time was 1 h 38 min. However, for the bunker scenario, the time should be controlled at ~1 h; therefore, the diameter of the bunkering pipeline was set to 8 in (200 mm), while the BOG return pipeline was set to 4 in (100 mm) in order to satisfy the pressure of the receiver tank and BOG return velocity.

· Transfer rate:

$$Q = 320m^3/h \text{ at } V = 5m/s \tag{2}$$

· Pipeline diameter:

$$D = \sqrt{\frac{4Q}{\pi V}} = \sqrt{\frac{4 \times 320}{\pi \times 5 \times 3600}} = 0.1505m \cong 150mm \tag{3}$$

· Mass Flow Rate:

$$\dot{m} = Q \times \rho = 320m^3/h \times 406kg/m^3 = 130{,}000kg/h \tag{4}$$

2.4 Bunkering Process

LNG bunkering can begin only after the LNG fuel tank has been properly inserted, purged, and cooled down. As the startup simulation, we only considered a cool down process that was accomplished by using cold natural gas and/or LNG.

During transfer, the ship’s fuel tanks will normally contain some quantity of LNG. The volume of the LNG that is normally left in the fuel tank before bunkering is called the tank heel. This small volume of LNG keeps the LNG tank cold before it is refilled during bunkering. The required tank heel is generally calculated with several variables such as tank size and shape, ship motion, heat inflow from external sources, engine gas consumption, and bunkering and voyage schedule. As a general rule of thumb with regard to the initial design considerations, a

Table 2. Modeling of system startup

Conditions for initial bunkering start-up	1) Conditions (pressure/quality) in receiver tank and bunker tank should be in stable state.
	2) BOG return line/LNG bunker line should be closed.
Process Change	1) Open BOG valve (bunker tank side and receiver tank side) for 10 s.
	2) Start the heat ingress in the bunker and receiver tank.
	3) Open LNG bunkering valve (receiver tank side) for 10 s.
	4) Start LNG bunkering pump (8.9 s after startup), and operate flow controller 9 s after the starting point.
	5) Open LNG bunkering valve (bunker tank side) for 10 s.

Table 3. Modeling of system shutdown

Process Change	1) When the filling ratio of the receiver tank reaches 85 %, the mass flow rate changes to 70,000 kg/h.
	2) When the filling ratio of the receiver tank reaches 89.99 %, controller cutoff occurs.
	3) When the filling ratio of the receiver tank reaches 90 %, the pump power cutoff and all valves close for 20 s in order to prevent surge phenomena.
Simulation Control	1) The size of the time step (Adaptive time stepping) is adjusted to 100 ms - 1,000 ms.
	2) Setting of simulation stop: finish filling and close all valves, then stop the system after 30 s.

tank heel of 5 % can be assumed. In our case, however, we assumed that the tank heel was 20 % according to expert consultation. Tank pressure during bunkering can be maintained within acceptable limits by consuming LNG or by using vapor control methods.

The bunkering process by STS was divided into two parts, namely, the startup and shutdown of the system, as shown in Table 2 and Table 3.

For the modeling of the system startup, several conditions need to fit to the initial bunkering startup. Additionally, not only the pressure and quality are required to be in a stable state, but a closed LNG bunker line is also required. For startup modeling, five steps were followed during the process.

For system shutdown, the mass flow rate changed to 70,000 kg/h, when the receiver tank filling ratio was at 85 %. Then, the controller and pump were required to be cutoff, when the conditions were satisfied. What calls for special attention is that the simulation control was also being processed during the cutoff.

3. Transient Simulation

A case study of STS LNG bunkering was performed by Aspen HYSYS. Fig. 4 and 5 show the dynamic simulations at the start and finish period of the bunkering scenario. Fig. 4 shows the startup of the simulation, when the receiving tank filling rate was at 20 %, while Fig. 5 shows the time of the receiving tank filling rate reaching 90 %, when the bunkering procedure should have been completed. The conditions of the bunkering and receiving vessels are shown in Table 4. The table shows that the storage tank capacities of LNG were 4,500 m^3 for the bunkering vessel and 700 m^3 for the receiving vessel. The simulation condition for the case was selected as the temperature difference (△t) between the bunkering tank and receiving tank being 12.5 ℃, with the pressure difference (△p) being approximately 3.0 bar at startup in the bunkering scenario, according to expert consultation.

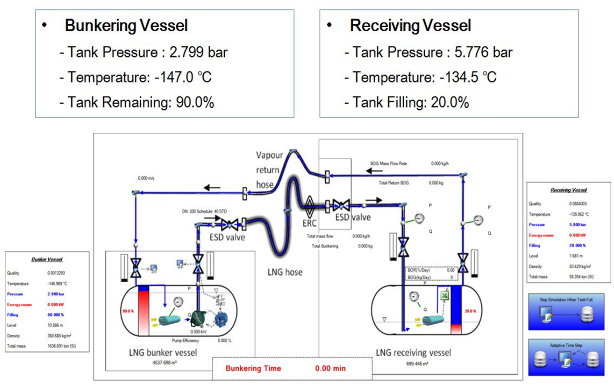

Fig. 4. Transient simulation at commencement of bunkering.

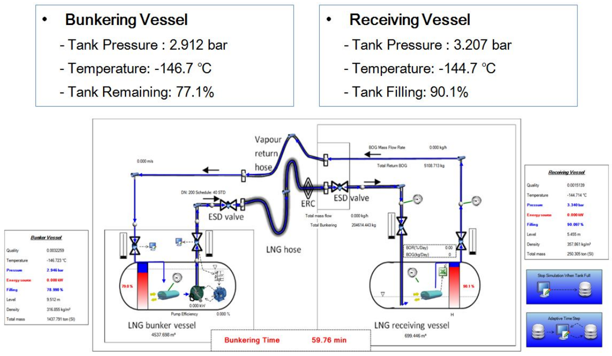

Fig. 5. Transient simulation at completion of bunkering.

When the bunkering procedure was completed, the physical properties of both the bunkering and receiving vessels were significantly different. The temperature difference (△t) between the bunkering tank and the receiving tank was changed from 12.5 ℃ to 2 ℃, which was considered as the heat ingress. The pressure difference (△p) has also decreased from 2.9 bar to 0.3 bar. The tank level of the bunkering vessel decreased from 90 % to 77.1 %.

Table 4. Conditions of bunkering and receiving vessels

		Bunkering Vessel (4,500 m^3)	Receiving Vessel (700 m^3)
Start Bunkering	Tank pressure (barg)	2.799	5.776
	Temperature (℃)	-147.0	-134.5
	Tank level (%)	90.00	20.05
Finish Bunkering	Tank pressure (barg)	2.912	3.207
	Temperature (℃)	-146.7	-144.7
	Tank Level (%)	77.1	90.1

4. Results

To understand the parametric effects of temperature and pressure on the bunkering limit, it is helpful to consider an example where the LNG and vapor are not consumed from the tank. In this case, the LNG fuel tank was a closed system and remained at a saturated condition, which means that the liquid and vapor were in equilibrium. Even though the tank was insulated, some heat leaked into the tank and caused an increase in the liquid and vapor temperatures, while remaining in a saturated condition.

4.1 Transient BOG variation

The differences between the properties of the bunkered LNG and the LNG in the receiving tank can cause issues that require careful control of the BOG. In most cases, the bunkering operation will consist of filling a colder LNG (bunkering vessel) into a tank containing a relatively warmer LNG (LNG-fueled ship). The temperature difference between the two liquids can be significant; thus, the saturated vapor pressures will also be different. If the vapor spaces of the bunker's colder tanks and the receiver's warmer tanks are interconnected directly prior to the commencement of the LNG transfer, the receiving tank is likely to depressurize rapidly due to the condensation of vapor. Similarly, if the LNG of the bunker vessel is cold, it will be pumped into a warm tank of the receiving vessel, and a considerable amount of flash gas might be generated as the cold LNG is warmed by the contents of the tank. Vapor control during bunkering is critical and can be handled in several different ways, depending on the supplying and receiving capabilities of the system and the LNG conditions in the tanks (ABS, 2014).

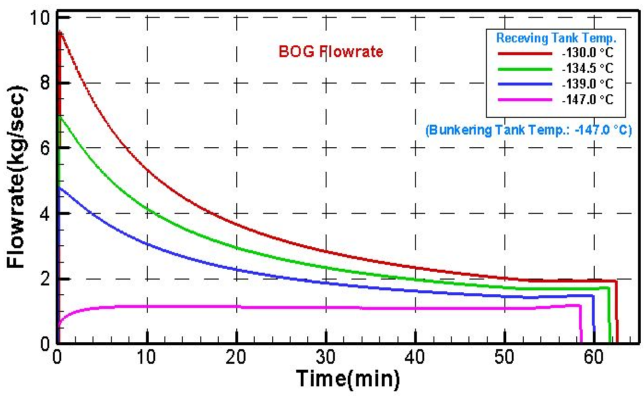

Fig. 6. BOG flowrate of receiving tank.

Fig. 6 shows the relationship between the variation of the BOG flowrate in the receiving tank, and the temperature difference between the two tanks. At the beginning of the bunkering procedure, when the pump starts, a great mass of heat ingress to the LNG transfers from the bunkering tank into the receiving tank. The amount of generated BOG is proportional to the temperature difference (△t) between the bunkering and receiving tanks. As shown in the figure, the amount of filling in the receiving tank increased, while the temperature difference decreased. Then, the generated BOG gradually decreased. At the end of the bunkering procedure, the BOG flow rate decreased rapidly when the pump stopped due to LNG no longer being transferred into the receiving tank.

The LNG density decreased as the temperature increased. If the receiving tank was nearly full, the storage space available for BOG was relatively small. Therefore, the increase in liquid volume due to lower density could significantly reduce the available volume of vapor space. This decrease in available BOG volume as a result of temperature changes resulted in higher vapor pressure.

4.2 BOG return

Heating is counteracted by the cooling effect of evaporation as the LNG boils off. The gas boils off in order to fill the lost volume of the LNG or vapor in the tank, while maintaining the LNG liquid and vapor in equilibrium at the cooler saturated temperature and pressure. Therefore, slow or no removal of LNG and BOG from a tank can cause the tank temperature and vapor pressure to increase from the heat flux into the tank, while fast removal without forced generation of boil-off gas can cause the LNG tank temperature to decrease (ABS, 2014). It is important to know the temperature in the LNG fuel tanks, in comparison to the bunkered temperature of the LNG, because the temperature difference can have a significant effect on the vapor control process.

In this study, the receiving LNG storage tank was stored and transported under the LNG conditions as a cryogenic liquid (-162 ℃). The capacity of the receiving tank was 700 m^3. The LNG evaporated at temperatures above its boiling point, while the boil-off-gas generated was similar to any other liquid. BOG emerged from the heat ingress into the LNG during shipping, storage, and on/off loading operations (Dobrata et al., 2013). In this simulation, BOG was caused by the temperature difference (△t) between the bunkering and receiving tanks. As the quantity of the BOG increased, the pressure in the LNG receiving fuel tank also increased. At this point, it was required to control the BOG increase in order to retain the LNG storage tank pressure within the range of safety.

Fig. 7 shows the relationship between the variation of the BOG return mass from the receiving tank for the temperature difference (△t) between the bunkering and receiving tanks. It can be seen from the plot that the amount of BOG return mass from the receiving tank was proportional to the temperature difference (△t) between the bunkering and receiving tanks. From the plot, the temperature difference (△t) between the bunkering tank and the receiving tanks could be observed at 0.0 ℃, 8.0 ℃, 12.5 ℃, and 17.0 ℃, while the mass of the BOG that returned from the receiving tank was 3,873.38 kg, 7,893.55 kg, 10,408.63 kg and 13,038.30 kg, respectively.

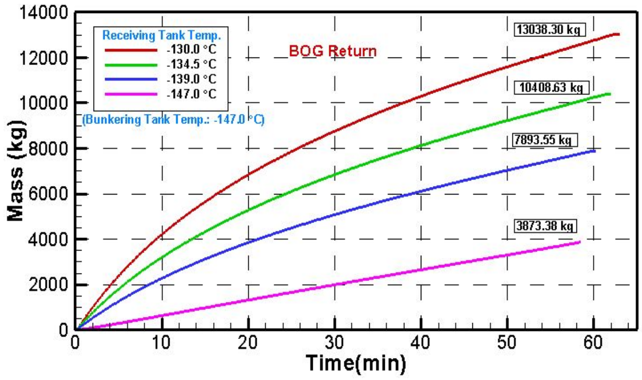

Fig. 7. Mass of BOG return from receiving tank.

4.3 Variations of supply and receiver tank pressure

For the safety system, if the tank temperature was allowed to increase unchecked, the pressure in the tank would increase to the point where the pressure relief valves opened. The temperature of the LNG at this point was the reference temperature. Here, the reference temperature was the temperature corresponding to the saturated vapor pressure of the LNG at the set pressure of the pressure relief valves (ABS, 2014). Since the density of the LNG at the reference temperature was lower than the density at the bunkering temperature, it was clear that the bunkering limit would always be lower than the filling limit.

Fig. 8 shows that at the initial bunkering, the pressure of the receiving tank increased due to the excessive BOG resulting from heat ingress. However, the rate of BOG generation decreased with the increase of LNG bunkering. When the filling rate of the receiving tank reached 85 %, the pressure rate in the bunkering tank increased due to the decreasing LNG flow rate, which is shown in Fig. 9. If the LNG in both tanks had a similar temperature, and as the receiving ship’s fuel tank was filled with LNG, the LNG displaced an equal volume of BOG that was already in the tank. Then, the vapor had to be condensed to liquid or transferred from the receiving fuel tanks in order to eliminate the excessive pressure buildup. Therefore, the vapor control in the two tanks could be accomplished by a BOG return line, which allowed the displaced vapor from the receiving tank to be returned to the bunkering vessel’s tank. Moreover, the variation of transient pressure for both tanks was proportional to the temperature difference (△t) between the bunkering and receiving tanks.

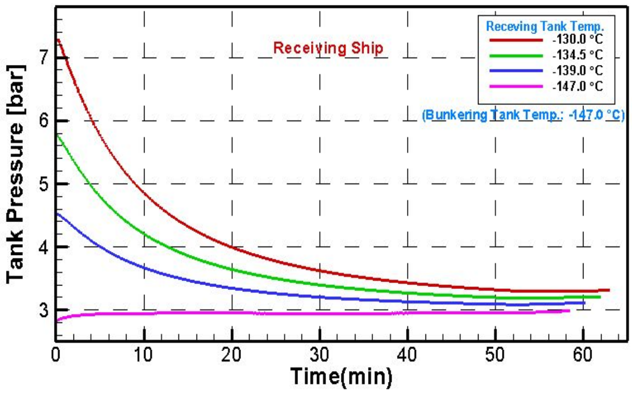

Fig. 8. Variation of receiving tank pressure.

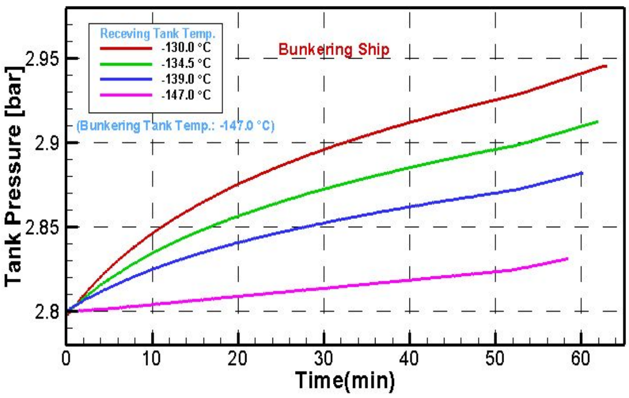

Fig. 9. Variation of bunkering tank pressure.

4.4 Total LNG bunkering amount

Some vessels may require a shorter bunker time than others, depending on their operating profile. Depending on the size of the fuel tanks and frequency of bunkering, the owners may wish to maximize the bunker rate.

Fig. 10 presents the total amount of LNG bunkering with respect to bunkering time and temperature difference (△t). For the typical case with a duration of 60 min., the total amount of LNG bunkering was 230,511.9 kgs, when the filling rate of the receiving tank reached 90 %. Then, the amount was inversely proportional to the temperature difference (△t) between the bunkering tank and receiving tank due to the generation of BOG during the LNG bunkering scenario.

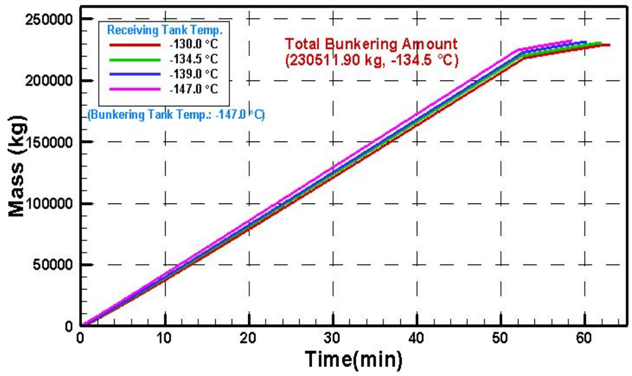

Fig. 10. Total LNG bunkering amount.

5. Conclusion

In Europe, LNG bunkering is an established technology conducted by a tank lorry or directly from an onshore terminal. However, this is not an alternative for ocean-going ships, where the LNG volumes are significantly large, and the supply is excessively time-consuming. Therefore, STS LNG bunkering becomes the alternative for larger ships. Moreover, LNG bunkering requires careful attention to safe operations, as it entails potential risks pertaining directly to cryogenic liquid transfer and BOG controls, considerably more so than those for HFO/MDO bunkering.

In STS LNG bunkering, the storage tank capacities of LNG are 4,500 m^3 for the bunkering vessel and 700 m^3 for the receiving vessel. The BOG generated during bunkering operations returns to the cargo tank of the bunker shuttle. This study only focused on the effects of STS bunkering under temperature differences. Therefore, we proposed that the modeling of the bunkering system needs to be calculated by a limit timeline and proceed by following a process dictated by guidelines. The results were obtained after 1 h of STS bunkering simulation as follows:

(1) The boil-off rate and consequent pressure buildup in the receiving vessel were mainly determined by the temperature difference between the bunkering and receiving tanks, the pressure of the receiver tank, and the amount of remaining LNG.

(2) The amount of BOG generation and BOG returns were proportional to the temperature difference between the bunkering and receiving tanks.

(3) As the quantity of the BOG increased the pressure in the receiving fuel tank increased as well, and the variation of transient pressure for both tanks was proportional to the temperature difference.

The results analyzed in this paper can be helpful as a feasibility study for STS LNG bunkering in any other port and provide specific guidelines for developing any type of bunkering procedure.

Acknowledgments

This work was part of "Test evaluation for LNG bunkering equipments and development of test technology (Grant No. 20180048)" supported by the Ministry of Oceans and Fisheries of Korea government.

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Received : 2017. 12. 07.
Revised : 2018. 02. 19. (1st)
: 2018. 02. 27. (2nd)
Accepted : 2018. 05. 29.