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Tracking boil off gas generation into liquefied natural gas supply chain using HYSYS simulator.

S Z Naji¹, A A Abd² and A S Hashim²

¹Petroleum Engineering Department, University of Kerbala, Iraq.

²Water Recourses engineering college, Al-Qassim Green University, Iraq.

Corresponding author's e-mail address: samah.alrashid@uokerbala.edu.iq

Abstract. Liquefied natural gas (LNG) is becoming one of the prominent clean energy sources with its abundance, high potential energy, and low emission and price. Unavoidable reality is that boil off gas (BOG) generates, because of low temperature of LNG, about -162.5 °C at 101.3 kPa for storage and transportation of liquefied natural gas. As natural gas productions increasing globally, BOG and handling problems become serious critical subject in both economic and environment regulations. In this work, liquefied natural gas storage facilities and loading facilities are simulated to investigate the generated BOG by calculating the heat leaks through cargo tank, pipelines, storage tank, and the generated heat by equipment's. Later, boil off gas rates are estimated for each sector into LNG supply chain with different operational conditions, parameters and voyage time. Factors that affect BOG such as operation temperatures and pressures, methane content, and nitrogen content are presented. Current study would help to properly store and transport LNG to minimize the venting of BOG into supply chain, and thus reducing greenhouse emissions, save energy, and reducing waste of natural gas.

1.Introduction

Liquefied natural gas (LNG) is the fastest growing energy sector due to increasing the demands of clean energy. Worldwide, the natural gas trade increased by 50 % between 2006 and 2014 which is almost double the last 10 years ago. Natural gas exporting countries increased from 6 to 26 countries in the period from 2000 to 2014 [1]. United States Energy Information Administration states that the world natural gas trade, by both pipeline and shipment in the form of LNG, will be poised to increase tremendously in the future [2]. 297 million tons per year is the operating capacity of natural gas recorded in 2014 [3]. New liquefied natural gas plants are under construction will promote LNG trade with up to 125 million tons per year [4].

Economically, natural gas transport in liquefied phase for long distance reduces cost because Liquid phase can reduce volume up to 600 times less than that for gas phase for same mass. However, to liquefy natural gas huge energy is required due to its bubble point below -161 °C. Large difference in temperature of liquefied natural gas and its surrounding can result heat leaks into in spite of careful and efficient insulation. This seep heat leads to evaporate part of LNG into different sectors of the LNG supply chain to generate boil off gas. Boil off gas (BOG) is considered real problem in natural gas trade



which reduces the quality of LNG, changes the compositions percent, and increases the pressure of storage tank. Methane and nitrogen are the lighter components of LNG, while ethane, propane, and others represent heavy components. Therefore, methane and nitrogen evaporate first due to their lower boiling point. Generally, boil off gas releases to environment to keep pressure in tank at acceptable range. However, releasing methane to environment is more dangerous than carbon dioxide CO₂ because it has radiative efficiency 26 times higher than (CO₂) [5]. CO₂ emission from unused natural gas from oil production industry was 250 million of tons in 2011 [6], while methane was the second contributor in the greenhouse gas emission between 1990 to 2011 [7]. Therefore, it is important to reduce the flaring and venting of natural gas.

Liquefied natural gas supply chain includes loading and unloading, shipping, and LNG storage. Liquefied natural gas evaporates continuously due to its low temperature and lost as boil off gas through the sectors of supply chain. The rate of BOG depends on the operation and construction conditions which are around 0.12% per day [8]. This rate is considered as losses and due to more intensive global competitions and stricter environmental regulations, venting BOG is unacceptable. Recently, part of boil off gas burns to power the steam turbines in order to reduce the pressure in tank and reducing the flaring, efficiency of this process is estimated around 30% [9].

In addition, BOG applications are fuel in loading stage, re-liquefied in case of large rate, burn or sent to the re-gasification unit, and/or sent back to the ship's tank. Several factors have direct effects on the generation of BOG which are depressurization of LNG, heat ingress through the pipelines and storage tanks, and heat generated by some equipment like pumps [8] [10] [11].

The BOG rate is affected by design and construction of storage tanks, operating conditions, the compositions of LNG itself [2]. Boil off gas rate strongly depends on the mass heat of vaporization and density of LNG [12]. In what follows, we first simulate cargo tank to estimate total leaking heat for a variety of operation. The BOG rate is affected by design and constructional conditions, and voyages time. In addition, the leaking heat through the pipelines and storage tank has been estimated with different scenarios. Later, we use these quantitative of heats to determine the total amount of boil off gas generation at each stage. Analysis study has been conducted to test the effect of varying temperatures and pressures of storage tank on boil off gas rate. Due to their low boiling point, the effect of methane and nitrogen content on the boil off gas has been summarized. The study would help proper handling of BOG problems and prediction of the positions that BOG can consist and at what rate. As well as, the study can help designers to plan a suitable method to deal with the generated BOG rate based on the operation conditions.

2. Process description

After liquefaction process, natural gas sends to the storage tank at export country until ships arrive to transport the product. Fig. 1 illustrates the process of transport liquefied natural gas from export region to the import region. The ships are usually powered with steam engines, while the speed of ship depends on its capacity typically to travel with 19 knots. The loading plant almost needs 12 to 14 hours to load ship with vessel capacity up to 130000 m³. Then, ship sails to transport LNG which takes around 12 days in total to travel 5000 miles. Almost, unloading process needs between 10 to 12 hours to unload LNG at receiving terminal. LNG sends to offshore storage tank with storing capacity up to 250000 m³ using cargo pumps. Liquefied natural gas continuously evaporates because of heat leakage during storing, shipping, and loading/unloading process. These vapor rates called boil off gas are considered a problem. The process of transport LNG simulated using HYSYS program V8.8. Aspen HYSYS (or simply HYSYS) is a chemical process simulator used to mathematically model chemical processes, from unit operations to full chemical plants and refineries. HYSYS is able to perform many of the core calculations of chemical engineering, including those concerned with mass balance, energy balance, vapor-liquid equilibrium, heat transfer, mass transfer, chemical kinetics, fractionation,

and pressure drop. The thermodynamic property fluid package used for this simulation was Peng-Robinson. The calculations of heat losses in the pipelines follow Begges and Brill correlations which is available by HYSYS and storage tank calculations use equations of heat modes. Some assumptions have been made to simplify the complexity of simulation. The cargo tank is assumed to be normal storage tank, the unloading and loading pipelines are assumed to have same diameter. Methane percent in this simulation in range 80 % to 99%, 0.1% to 2% nitrogen content and the rest are ethane, propane, i-butane and n-butane [1].

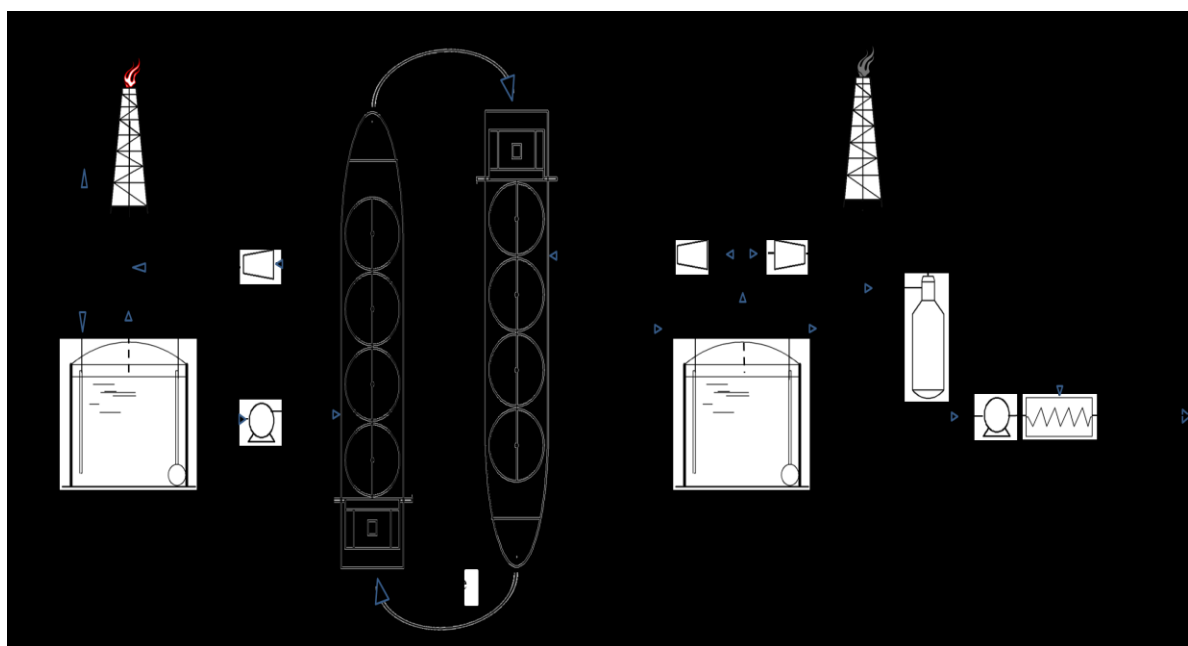


Figure 1. LNG supply chain.

3. Results and Discussion

3.1 Heat leaking calculations

Heat leak calculations through storage tank and transport facilities are necessary to study boil off gas generation. Heat transfers from environment to liquefied natural gas by three modes conduction, convection, and radiation.

3.1.1 Heat leaks to cargo tank

Cargo tank is moss type spherical tank with capacity up to 143000 m³. During the voyage, cargo tank gains some heat from ambient, this heat warms up LNG temperature and generates amount of vapor depending on the operational conditions and voyage time. BOG generation in cargo tank depends on the operational conditions and the sea conditions, which is around 0.1 to 0.15 % [13]. The process of transporting LNG from export to import terminal called laden voyage, whereas the return voyage of the tanker after the unloading process called ballast voyage. During ballast voyage small amount of LNG stays in the tanker to keep the temperature of inside around -162°C which can be considered as losses as well. Possible reasons behind evaporation into cargo tank are the sloshing of cargo in partially filled tanks due to the action of waves, friction on the inner wall of cargo tank creating an additional thermal effect and temperature difference between ambient and cargo tank. The ships usually travel with speed up to 9.7 m/s and by assuming that the distance of journey 4000 km which needs 5 days of traveling. Ship's tank translates up to 3600 kg per one hour, **fig. 2** shows the varying of BOG rate with voyage time. The boil-off gas can be sent as fuel to the propulsion system or re-liquified to change it into liquid phase again.

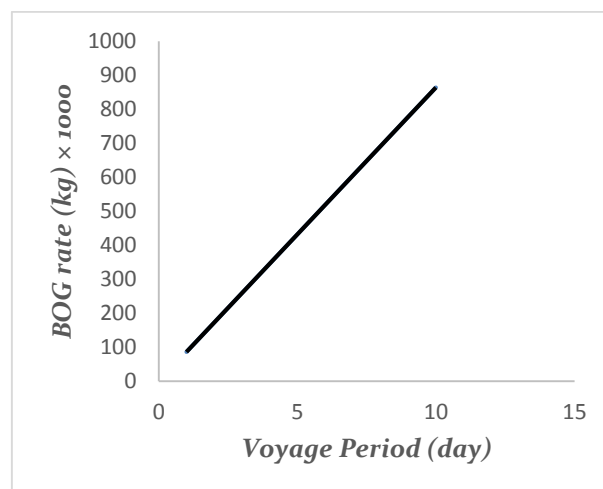


Figure 2. Voyage time against BOG rate

3.1.2 Heat leaks to pipelines

Loading pipes are two parallel lines come with diameters 0.6096 and 0.6604 meter or one line with diameter up to 0.762 meter. Tank pipelines are input and output of liquefied natural gas, condensed liquefied natural gas input, perlite input and BOG output pipelines. All pipelines paths are through the top of storage tank, which can be easily checked from platform. Due to direct contact with cryogenic liquid, the pipes distribution and location should be designed in reasonable way. Otherwise, the following situations might be happened (1) shock chilling of line contraction can produce stress concentration or bending deformation; (2) because of heat gasification, LNG can flow into the adiabatic section structure, and then press the vapor back inside the container, it is also known as the penetration phenomenon. Therefore, pipelines usually are designed as S type in the interlayer in storage tank. Pipelines are settled in the same side of the tank at the top of the outer tank, which is easy for installation and maintenance. Whereas, inside tank pipelines should be arranged vertically. Pipelines material of construction is stainless steel 304, thickness and design diameter depend on the capacity rate of liquefied natural gas. LNG pipelines precooling is important as action before loading or unloading to reduce boil off gas rate [13]. Analysis study has been conducted to predict the total amount of heat leaks through pipes with different lengths. **Fig. 3** shows that total heat leaking through pipes increases, as the length of pipes increases with different ambient temperatures. Whereas, the heat leaks increase at constant rate when temperature of surrounding increases.

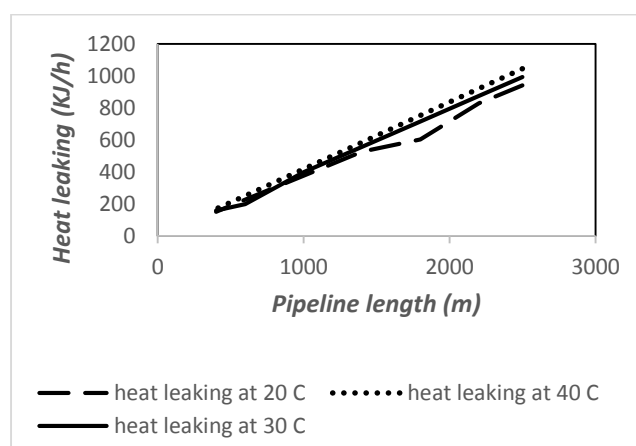


Figure 3. Pipelines length with heat leaking for different ambient temperature.

3.1.3 Heat by pumps energy

Pumps are considered as main element in the unloading/loading process, where LNG transfers from cargo to storage tank by pumps located on the ships. The required energy for each pump depends on the required capacity which is usually in the range of 1200 m³/h to 1400 m³/h for the large one. Where the small pump, which is called spray pump, comes with a capacity between 40 to 50 m³/h [14]. Typically, the spray pump is used to provide LNG to the spray ring to keep the entire of tank in cold state. The simulation shows that the required energy for the pump system is at least 4630 kW for 200000 m³ storage tank. Where most of this energy converts into heat which raise the temperature of LNG by almost 0.5 °C. The evaporation process can be reduced by increasing the operating pressure of the tank [15].

3.1.4 Heat leaks to storage tank

Storage tanks at both production plant and receiving terminal are stored LNG in atmospheric pressure and temperature around -162.5 °C with rate of boil off gas called tankage boil off gas (TBOG). This gas at LNG plant usually is compressed and exported to the plant fuel system. While, it is either flared or sent to the regasification plant using BOG compressors at receiving terminal. Generally, the designers try to reduce the number of tanks and increase the capacity of storage to minimize the cost. Type of tanks choice of single, double, and/or full containment depends on the cost, land availability, and safety purposes.

3.1.4.1 The limitation of heat leakage for storage tank

Although, large insulation thickness around the offshore storage tank stills, heat transfers to the liquefied natural gas. Usually, heat leaks in two forms: continuous and transient, where continuous leaking time shorter than that for transient type [16]. **Fig. 4** shows the main parts of liquefied natural gas storage tank. Analysis study has been conducted to estimate amount of leaking heat by three main parts top roof, insulation wall and bottom slab. Generally, total heat leakage limitation is 0.25 volume % per day and can be calculated based on eq. 1;

$$Q_{\text{total}} = \Delta G \times q = n \times G_o \times q \quad (1)$$

where n is boil off gas rate (vol%/day), G_o , is mass of LNG in tank (kg), and q is LNG heat of evaporation about 509 kJ/kg. Value of accepted limit of leaking heat for this simulation estimated to be 1250 kw.

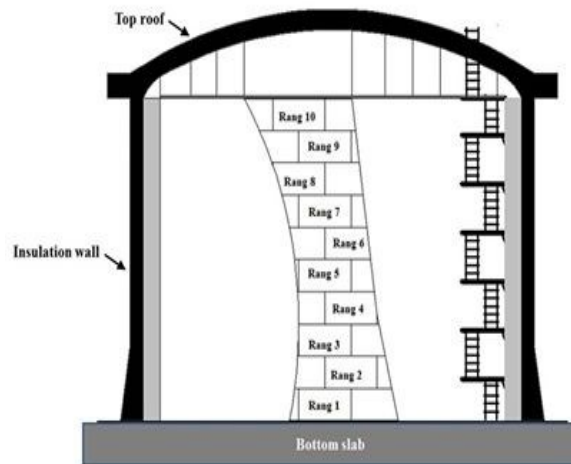


Figure 4. LNG storage tank.

3.1.4.2 Heat leakage- from isolation part

Leaking heat through the insulation part depends on thermal conductivity of construction material and thickness of insulation as shown in **fig. 5**, which can be estimated using eq. 2.

$$Q_a = \lambda_c \times A_m \times \frac{\Delta T}{\delta} \quad (2)$$

Where λ_c is the effective thermal conductivity which is $0.09 \frac{w}{m.k}$ for this simulation, A_m is surface area of inner tank which is 9917 m^2 , δ is thickness of insulation part, and ΔT is temperature difference between outer and inner wall. Value of leaking heat is estimated to be 152 kw.

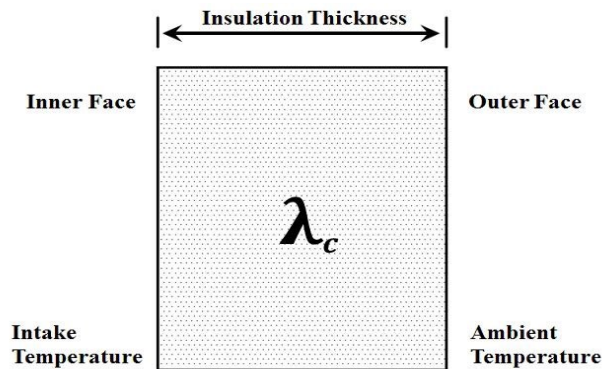


Figure 5. The insulation offshore tank

3.1.4.3 Heat leakage- from bottom part

Bottom slab consists of more than one layer with different thicknesses and materials of construction. The bottom slab layers are foundation layer comes with thickness up to 2000 mm, concrete slab layer with thickness 900 mm and thermal conductivity 0.79 w/m.k , cellular glass with thickness 450 mm and thermal conductivity 0.056 w/m.k , and perlite concrete with thickness 70 mm and thermal conductivity in range 0.09 to 0.22 w/m.k as shown in **fig. 6**. The thickness and material of construction can be manipulated to keep leaking heat through at lower possible value. Total leaking heat through bottom slab can be estimated using eq. 3, where ϕ is average heat intensity and V is total volume of bottom slab.

$$P = \phi V \quad (3)$$

While, total heat intensity is 5.97 w/m^3 calculated by eq. 4, using 273 k of top concrete slab temperature and the bottom temperature of inner tank is 110 k .

$$t = -\frac{\phi}{2\lambda}x^2 + \left(\frac{t_{w2} - t_{w3}}{\delta_{\text{tot}}} + \frac{\phi\delta_{\text{tot}}}{2\lambda}\right)x + t_{w3} \quad (4)$$

where λ is average thermal conductivity, x is thickness without foundation and concrete slab, and δ_{tot} is total thickness with foundation. Finally, total heat leaking inside the offshore storage tank from bottom slab is 132.7 kw .

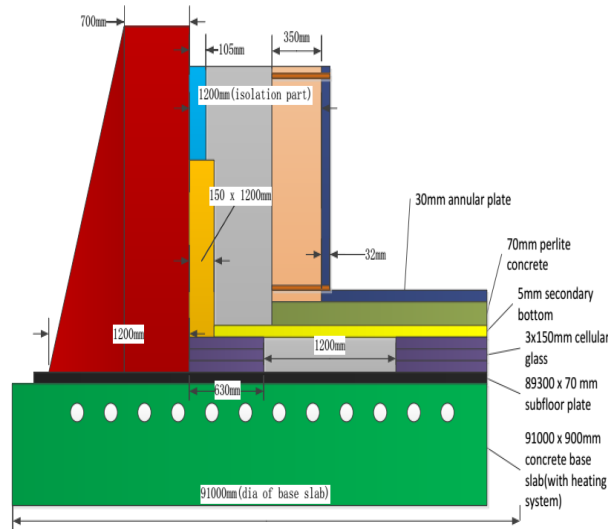


Figure 6. Bottom of tank and corner protection.

3.1.4.4 Heat leakage from roof

Top roof is another possible section to ingress heat, where heat transfers with environment by conduction, convection, and radiation. Conduction heat flux can be calculated using eq. 5:

$$Q_{\text{conduction}} = K_{\text{concret}} * \frac{\Delta T}{t_c} \quad (5)$$

Where, K_{concret} , is thermal conductivity of concrete which is about $2.324 \frac{\text{w}}{\text{m.k}}$, t_c is the thickness of the concrete [17]. While, convection heat transfer per unit area can be calculated using eq. 6:

$$Q_{\text{convection}} = h \cdot \Delta T \quad (6)$$

here, h is the convection heat coefficient of concrete which is $12.78 \text{ w/m}^2 \cdot \text{k}$. The heat transfer at the roof comes in two phases conduction for the upper and bottom part of the roof, and radiation in-between as shown in **fig. 7**. Therefore, the heat transfer equations will be as below:

$$\begin{aligned} Q_{\text{conduction.1}} &= K_{\text{concret}} * \frac{(T_a - T_b)}{t_c} * A_{\text{roof}} \\ Q_{\text{radiation.2}} &= F * \epsilon * \sigma * (T_b^4 - T_c^4) * A_{\text{roof}} \\ Q_{\text{conduction.3}} &= K_{\text{deck insulation}} * \frac{(T_c - T_d)}{t_d} * A_{\text{Deck}} \end{aligned} \quad (7)$$

Where k_{deck} is the thermal conductivity of the deck insulation which is $0.038 \frac{\text{w}}{\text{m.k}}$, t_d is deck insulation with value 0.05 m , and t_c is thickness of concrete, A_{roof} and A_{deck} are the areas of the roof and suspended deck with 7467.4 m^2 and 6647.6 m^2 respectively, F is the form factor assumed to be 1, ϵ is emissivity, and σ is Stefan Boltzmann constant with value $\sigma = 5.67 \cdot 10^{-8} \text{ W/m}^2 \cdot \text{K}^4$. Temperatures of environment is assumed to be 288.13 k , and temperature inside the tank assumed to be 110.15 k . The emissivity should

be calculated as a resultant for both carbon steel liner emissivity which is 0.66 and deck insulation emissivity which is 0.96 as shown in eq. 8 [17].

$$\varepsilon = \frac{1}{\frac{1}{\varepsilon_{\text{Carbon steel}}} + \frac{1}{\varepsilon_{\text{Deck insulation}}} - 1} = 0.64 \quad (8)$$

At equilibrium conditions, amount of heat transfer modes through the roof can be assumed to be equals:

$$\begin{aligned} Q_{\text{conduction.1}} &= Q_{\text{radiation.2}} = Q_{\text{conduction.3}} \quad (9) \\ K_{\text{concret}} * \frac{(T_a - T_b)}{t_c} * A_{\text{roof}} &= F * \varepsilon * \sigma * (T_b^4 - T_c^4) * A_{\text{roof}} \\ &= K_{\text{deck insulation}} * \frac{(T_c - T_d)}{t_d} * A_{\text{Deck}} \end{aligned}$$

By solving these equations, the temperatures distribution can be evaluated to be $T_b = 284.27$ k and $T_c = 280.78$ k. Now the heat transfer through the roof into the storage tank can be calculated to be 368.5 kw. The assumption comes with only 5% of this heat will consider, therefore the total heat that will seep through the top roof is 18.425 kw.

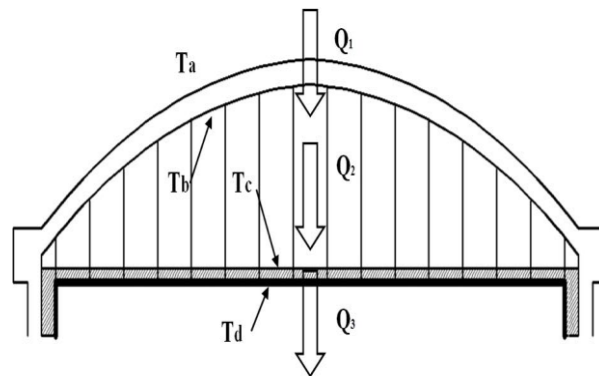


Figure 7. Heat distribution on top roof

3.1.4.5 Total Heat leakage through offshore tank

The total leaking heat through top roof, insulation wall, and bottom slab storage tank can be calculated by using eq. 10:

$$Q = Q_a + Q_b + Q_c = 303.125 \text{ Kw} < 1250 \text{ Kw} = Q_{\text{total}} \quad (10)$$

Which means the overall heat seeps inside the offshore tank is unacceptable range. Based on this heat, boil off gas rate per day produces in offshore tank based on the calculated amount of heat leaking can be estimated by eq. 11.

$$\text{Boil off Gas rate} \left(\frac{\text{kg}}{\text{h}} \right) = \frac{\text{Rate of heat leakage}}{\text{Heat of vaporization}} \quad (11)$$

3.2 Boil off gas quantities

Boil off gas generation depends on liquefied natural gas compositions, liquid level in the tank, surface area of the tank, and operation conditions like pressure and temperature. In addition, the construction materials of the supply chain units are another factor that can affect the BOG generation because of their thermal conductivity property. The pressure drop between cargo tank and storage tank increases the BOG generation where there is almost 0.1 °C change in temperature for 1 kPa.

According to this design and based on estimated leaking heats, the amount of generated BOG at the cargo tank depends on voyage time which is almost 3600 kg/hr. boil off gas rate that produces by pumps energy is 20000 kg/hr. Whereas, boil off gas generation in pipelines is varying with length of pipelines and material of construction which is almost 1.6 kg/hr for 2500 m with steel 304. While, BOG generation at both storage tanks is almost 3287.9 kg/hr, where one tank produces 1643.95 kg/hr which is equal to 3.56 m³/hr (85.44 m³/day) with 461.2 kg/m³ LNG density. For tank with capacity 200000 m³, this is equivalent to 0.043 vol.% which is in range of normal storage tank design specifications. Whereas, the total boil off gas generation for this simulation is 26889.5 kg/hr.

3.3 Storage tank pressure

Usually, the pressure of LNG storage tank is about 101.3 kPa, however pipelines that handle the LNG to storage tank may cause a pressure drop. Therefore, analysis study has been conducted to check the effect of varying storage tank pressure on boil off gas rate. While. The temperature of storage tank is assumed to be constant at -162.5 °C. The compositions of LNG for this study are 90% methane, 1% nitrogen, 5.9% ethane, 2.7 % propane, and small amount of n-i butane. Fig. 8 shows that as the pressure of storage tank increases, the boil off gas rate decreases to reach zero at 114.3 kPa.

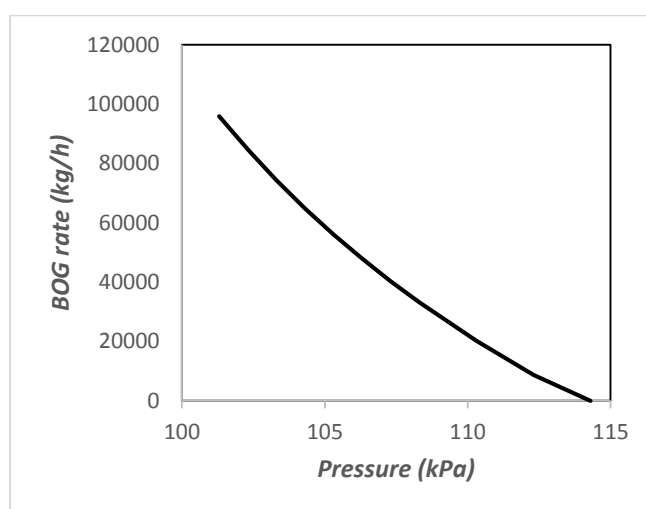


Figure 8. Pressure of storage tank against BOG rate

3.4 Storage tank temperature

During the holding mode which is the period between unloading and loading liquefied natural gas tankers, Heat ingresses from ambient to the tank where the driving force for heat transfer is the temperature difference between environment and inside tank. Well, to keep the temperature of LNG constant and in balance with pressure, LNG cools itself with process known as auto-refrigeration by evaporating part of LNG and it consists of boil off gas. Therefore, temperature can play key role in management the generated rate of BOG. Analysis study has been conducted to test the effect of varying tank temperature on the generated amount of BOG. The compositions of liquefied natural gas in this simulation are 90% methane, 1% nitrogen, 5.9% ethane, 2.7 % propane, and small amount of n-i butane. **Fig. 9** shows that BOG rate starts increases as temperature increases at different rates with constant pressure at 101.3 kPa.

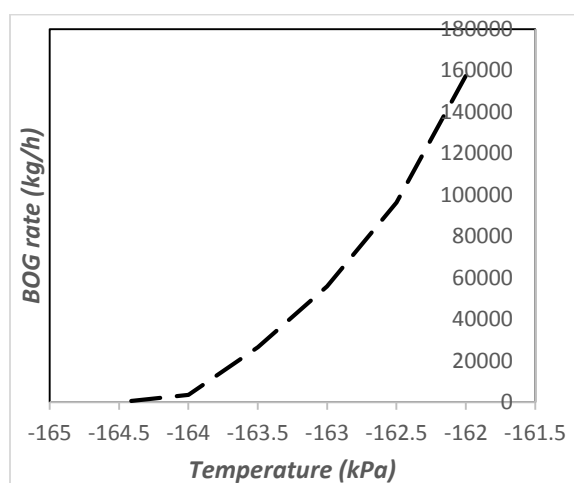


Figure 9. Temperature of storage tank with BOG rate

3.5 Methane and nitrogen content

Nitrogen and Methane considered as volatile components come with evaporation rate higher than less volatile components such as ethane, propane and other higher hydrocarbons. Analysis study has been conducted to examine the effects of varying methane percent in range 88% to 99% on the boil off gas rate at pressure 101.3 kPa and temperature -162.5 °C with 1% nitrogen. **Fig. 10** shows that increasing methane percent in liquefied natural gas causes increasing boil off gas rate. Whereas, **fig. 11** shows the effect of varying nitrogen content in storage tank on the boil off gas rate at pressure 101.3 kPa and temperature –

162.5 °C with 90% methane. The results are supported by fact that the high volatile components produce high evaporation rate.

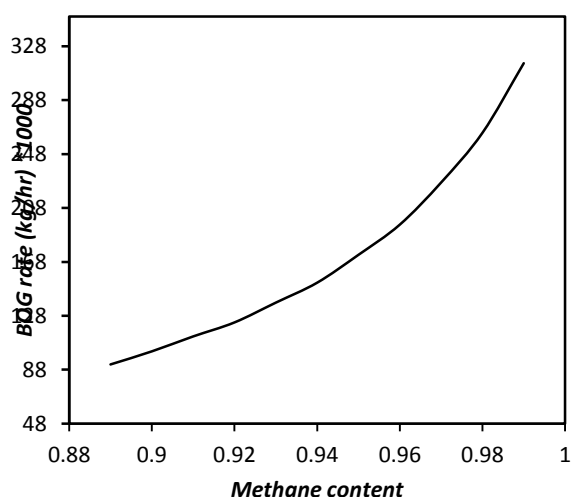


Figure 10. Methane content against BOG rate in storage tank

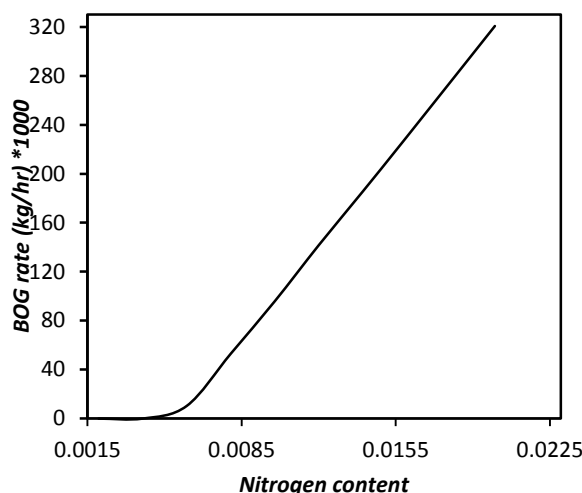


Figure 11. Nitrogen content against BOG rate in storage tank

4. Conclusions

This paper provides comprehensive analysis study to estimate the heat leaks for each part of LNG supply chain and discusses boil-off gas in regarding to this heat. Elements causing boil off gas are presented and the produced amount of BOG at each sector through the supply chain has been estimated. Effects of temperature, pressure, nitrogen content, methane content are tested to conclude best range of conditions that can reduce BOG to low rate. The assumptions for this steady simulation were cargo tank assumed to be normal storage tank, the unloading and loading pipelines assumed that have same diameter. Methane percent in this simulation in range 80 % to 99%, 0.1% to 2% nitrogen content and the rest are ethane, propane, i-butane and n-butane. Fig. 2 displays the generated BOG variation with voyage time, the results show BOG rate increases over time. Fig. 3 explains the effects of pipelines length on the generated BOG for different ambient temperature, the results show that BOG rate increases as pipelines length increases for all range of temperature. Fig. 8 and fig. 9 explain the effects of temperature and pressure on BOG rate, the results show that the best storage tank temperature to stop BOG is -164.5 °C with 101.3 kPa pressure, whereas 112.3 kPa is best pressure to stop BOG. In regards of methane and nitrogen contents, the results show that BOG rate increases as nitrogen and methane increase this is supported by fact that as more volatile components rates increase, the evaporation rate increases. To conclude, boil off gas generation represents a problem facing LNG trade and attention should be paid to reduce the BOG rate. Many factors can be manipulated to reduce the BOG generation into LNG supply chain such as reducing the voyage time, precooling will reduce the heat ingress to pipelines, and the insulation thickness and material of construction. The study would to help properly handling of BOG problems and prediction of the positions that BOG can take and at which rate. As well as, the study can help designers to plan a suitable method to deal with the generated BOG rate based on the operation conditions. It is also a solid foundation for future dynamic modelling to minimize BOG generation.

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