

DYNAMIC SIMULATION STUDY ON EFFECT OF LNG TEMPERATURE ON JETTY BOIL-OFF GAS GENERATION AT LNG EXPORTING TERMINALS

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ABSTRACT

Liquefied Natural Gas (LNG) is obtained by cooling natural gas below $-161\text{ }^{\circ}\text{C}$. The liquefaction reduces volume of natural gas by about 600-fold. The reduction in the volume makes natural gas transportation economical over longer distances. However, the liquefaction process itself requires significant amount of energy. Furthermore, differences between temperatures of ambient and LNG cause heat leak into LNG. This results in constant boiling of LNG, and vapors are generated. In order to maintain the pressure of LNG container within safe limits, the vapors generated, called boil-off gas (BOG), must be relieved. In this work, Aspen Plus and Aspen Plus Dynamics v8.8 process simulation tools are used to quantify BOG generation at LNG exporting terminals, for various LNG temperatures.

An LNG ship with four moss type spherical tanks is considered in this study. Typical tank design parameters and insulation schemes are used to simulate heat leak calculations. LNG exporting terminal operations are simulated to calculate BOG generation dynamically with respect to LNG loading time. BOG generated during LNG ship-loading is called Jetty BOG or JBOG. This study will provide valuable information about effect of LNG temperature on JBOG that would help in operating LNG plants at optimum conditions and economically minimizing JBOG generation. Minimizing JBOG at LNG exporting terminals will reduce flaring, and thus reduce wastage of material, energy, and potentially environmental impact.

INTRODUCTION

Natural gas production and consumption are growing worldwide. With abundant reserves of natural gas, lower prices, and cleaner burning characteristics, it is preferred over other fossil fuels. In 2015, the global natural gas liquefaction nameplate capacity reached 301.5 MTPA (million tonnes per annum) [1]. The total LNG trade reached 244.8 MT (million tonnes) in 2015, up 4.7 MT from 2014. As of January 2016, an additional 142 MTPA of liquefaction capacity was under construction world-wide, and the total proposed natural gas liquefaction capacity reached 890 MTPA [1].

Natural gas is liquefied to reduce its volume and make it economical for transportation over longer distances. LNG supply chain includes liquefaction plant to liquefy natural gas, LNG loading/exporting terminal, LNG carrier (ex. Ship) to transport LNG, LNG unloading/receiving terminal, and regasification terminal to convert LNG into gas for distribution. This work is focused on LNG exporting terminal. BOG is generated in all segments of LNG supply chain. BOG generated during LNG ship-loading is referred here as Jetty BOG or JBOG. JBOG rate is relatively higher than BOG generated during other segments of LNG supply chain due to the following factors: (1) ship-tanks are hotter than LNG temperature when they arrive at LNG loading terminals; (2) Ship-tanks have relatively higher surface area compared to LNG storage tanks of same volume; (3) Heat leak into the loading facility (pumps, pipelines, etc.) during holding mode (when loading is not in progress) causes additional BOG generation during loading of LNG; and (4) LNG loading rates are usually higher than LNG production rates, which result in higher rates of vapor displacement.

JBOG generation is very dynamic in nature and changes with LNG loading time due to following factors: (1) ship-tank temperature changes with loading time, thus heat added to LNG also changes; (2) LNG loading rate changes with loading time. Initially LNG loading rate is low to avoid thermal shock to LNG pipeline and to the tank-material, then JBOG compressor capacity limit controls the LNG loading rate. LNG flowrate is ramped down once tanks are filled up to 80% in volume.[2] Due to the dynamic behaviour, dynamic process simulation is necessary to study the LNG loading process.

BOG generated during any segment of LNG supply chain should be recovered using some recovery methods. Otherwise, BOG needs to be flared, which adds green-house gases to the environment. With environmental regulations becoming more stringent, flaring is generally not a viable option. Also, it is important to avoid wastage of material and energy by utilising BOG. BOG generation in natural gas liquefaction plant and at LNG exporting/loading terminals has been discussed in the literature. For example, Huang, et. al. provided methods to simulate LNG related systems and suggested use of end-flash-gas as fuel gas to run turbines in LNG plant [3]. Huang, et. al.,

in another publication, provided various BOG recovery strategies at LNG loading terminals, particularly for long jetties which tend to generate more JBOG due to greater heat leaks [2]. Chaker et. al. state that most publications in the past have focused on regasification terminals and have not addressed the area of liquefaction plants; thereby providing discussion on generation and management of BOG in LNG plant, and the associated networks and machinery to manage BOG handling [4]. Wicaksono et. al. studied efficient use of recovered jetty-BOG as fuel gas using mixed-integer-nonlinear-programming for fuel-gas-network [5]. Pillai et. al. studied optimum design of BOG compressor network, and stated need for dynamic simulation of BOG system [6]. Several BOG recovery strategies are proposed by Kurle et. al. for BOG generated at LNG plant and exporting terminals [7]. Meanwhile, overall heat transfer coefficients for LNG storage tanks and ship tanks are calculated [7]. Effects of ship-tank temperature, tank-cooling-rate, JBOG compressor capacity on JBOG generation are studied in the author's previous work [8].

In this work, effect of LNG temperature on JBOG generation is studied and the optimum temperature of LNG is found out through dynamic process simulation. Different cases of LNG temperatures are considered by assuming that LNG is being sub-cooled after LNG storage tanks when LNG loading into ship-tanks is in progress. The optimum LNG temperature reduces JBOG generation as well as keeps the total energy consumption for natural gas liquefaction and JBOG recovery at

the lowest possible value.

PROCESS SIMULATION

A typical LNG loading facility is simulated in Aspen Plus v8.8 and exported to Aspen Plus Dynamics v8.8. The process schematic for LNG loading facility, ship tanks, and BOG handling facility in dynamic simulation is shown in Figure 1. Feed streams 'LNG--ST1' and 'LNG--ST2' are coming from some LNG storage tanks at exporting terminal. LNG composition (by wt%) is methane 93.01, ethane 5.10, propane 0.73, n-butane 0.12, i-butane 0.12, n-pentane 0.06, i-pentane 0.06, and nitrogen 0.8. LNG in the feed streams is saturated liquid at 1.06 bar and $-161.66\text{ }^{\circ}\text{C}$ temperature. The two streams pass through LNG sub-coolers 'SC1' and 'SC2'. Pumps transfer the LNG from shore to LNG ship. For the case of JBOG, the length of jetty affects the BOG generation. In this study, a jetty with 6,000 m equivalent pipe length is considered [2]. Two LNG transfer lines, each with 24 in. inner diameter and 6,000 m equivalent pipe length, are considered to have overall heat transfer coefficient of $0.26\text{ W}/(\text{m}^2\cdot\text{K})$ [9]. Total capacity of two lines is $10,000\text{ m}^3/\text{hr}$. 'LNG-P1' and 'LNG-P2' make one transfer line and 'LNG-P3' and 'LNG-P4' make another transfer line. Four flash tanks ('SHIP-T1' through 'SHIP-T4') with spherical geometry specification are simulated to represent four moss type spherical LNG tanks within a single LNG carrier. For about $140,000\text{ m}^3$ total capacity of ship tanks, and 1 m height of the cylindrical portion at equator, diameter of

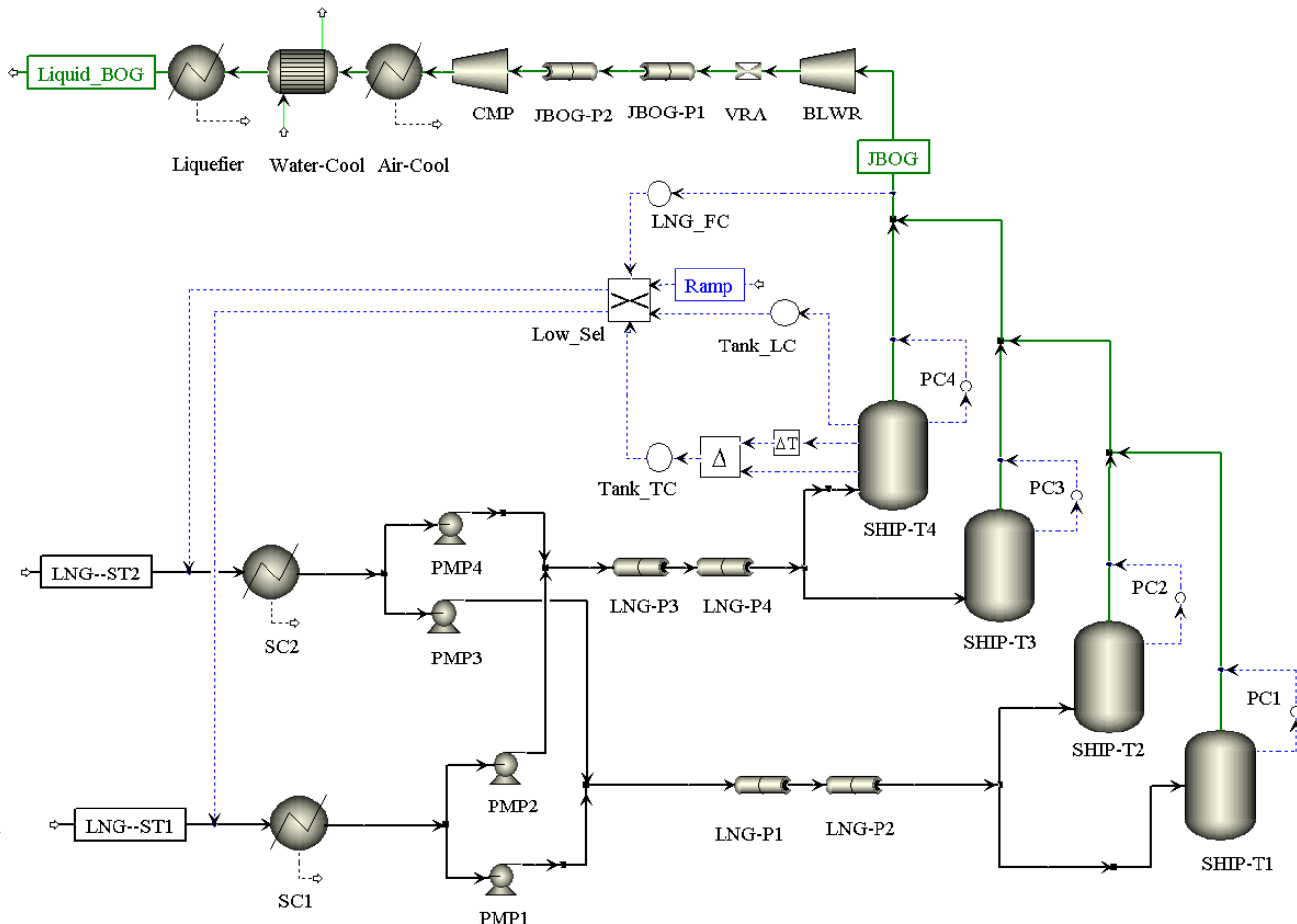


Figure 1 Aspen-Plus-Dynamics process modelling schematic for LNG loading facility, ship tanks, and BOG handling

each ship tank is calculated to be about 40.4 m. The overall heat transfer coefficient of the ship-tanks is calculated to be 0.11 W/(m²·K) [7]. The initial temperature (temperature just before LNG loading starts) of the tanks is assumed to be -125 °C. The flash-tank model used for the ship-tanks, considers vapor-liquid equilibrium and even-temperature-distribution throughout the contents of the tank. Vapors generated from the four tanks are sent from ship to shore by a blower ('BLWR' in Figure 1) or compressor installed on the ship. VRA is vapour return arm where 0.25 bar pressure drop is assumed. 'JBOG-P1' and 'JBOG-P2' transfer JBOG from ship to shore. JBOG is then compressed to 50 bar in compressor ('CMP'). JBOG is cooled to near ambient temperature using air and water, then it is further cooled and liquefied in 'Liquefier'. For a pipe insulation, the heat transfer is maximum when pipe radius equals critical radius. The critical radius of a pipe is given by equation (1) [10]. In equation (1), Rc is critical radius of insulated pipe, ki is thermal conductivity of insulation, and ha is film heat transfer coefficient of surrounding fluid (air). For polyurethane rigid foam, thermal conductivity is 0.022 W/(m·K) [11]. For film heat transfer coefficient of air as 35 W/(m²·K), Critical radius equals 0.63 mm. The pipe radius is 305mm, which is much greater than the critical radius. Therefore, the issue of critical radius will not affect this case.

$$R_c = \left(\frac{k_i}{h_a} \right) \quad (1)$$

The dotted lines in Figure 1 show the process control schematic for LNG loading. LNG loading rate depends on JBOG compressor capacity, maximum allowed cooling-rate for wall of the ship-tanks, and LNG loading line capacity. The three constrains correspond to one manipulated variable which is LNG flow rate in LNG--ST1 and LNG--ST2 streams. In Figure 1, 'LNG_FC' decides LNG flow rate to keep JBOG within compressor capacity. The compressor capacity is assumed to be 80,000 kg/hr. 'Tank_TC' reads the cooling rate of the tanks by comparing current tank temperature with the temperature 20 minutes in the past. Maximum cooling rate is set to 3 degree per 20 minutes (based on reference of 10 °C per hour [12]). 'Tank_TC' manipulates LNG flow rate to keep tank-cooling-rate within the limits. When LNG level reaches 80 volume% of the tanks, LNG loading rate is ramped down by using a program script 'Ramp'. 'Low_Sel' chooses the lowest value out of all the controllers' outputs. This LNG flowrate would satisfy all the constraints specified above.

As shown in Figure 1, a simple heat exchanger model from Aspen simulation is used, instead of a completed refrigeration loop, to calculate cooling duty to sub-cool LNG (in 'SC1' and 'SC2') and to liquefy JBOG (in 'Liquefier' unit). In order to calculate actual energy input required to achieve this cooling duty, typical values of Coefficient of performance (COP) of a refrigeration cycle can be used. This way, the simulation results can be applied to different refrigeration cycles by using the following equation.

$$\text{Compressor Work} = \left(\frac{\text{Cooling Duty}}{\text{COP}} \right) \quad (2)$$

A COP value of 2 is used for the calculations of energy requirements and illustrations in the plots. However, a range of optimum LNG temperatures is also given in the next section for COP rage of 1 to 5. COP of 2.13 and 1.26 are reported in literate, for Cascade refrigeration cycle and C3MR refrigeration cycle respectively, for natural gas liquefaction processes [13]. Dynamic simulations of LNG loading process were run at various LNG temperatures between -161.66 (saturated point) to -166 °C of LNG temperatures. Two strategies for BOG recovery are considered: (1) use of BOG as fuel gas, and (2) liquefaction of BOG. The liquefied BOG can be sent to storage tanks as additional LNG production. Fuel gas pressure is assumed to be 50 bar. BOG is usually compressed before liquefaction. For the case of liquefaction, BOG compression to 50 bar is considered. From dynamic simulation results, the energy required to sub-cool LNG, BOG compression to 50 bar, and BOG liquefaction to -162 °C was noted down. For strategy (1), the total energy required would be energy required to sub-cool LNG and energy required to compress BOG. Similarly, the total energy required for strategy (2) would be the addition of energy required for LNG sub-cooling, BOG compression, and BOG liquefaction.

RESULTS AND DISCUSSION

Saturated liquid boils upon addition of small amount of heat and generates vapors. Conversely, sub-cooled liquid has ability to absorb some heat before it starts boiling. BOG generation is mainly due to heat leak form environment into LNG, which is due to the temperature gradient between LNG temperature and temperature of the surroundings. If LNG is sub-cooled vapor generation due to heat leak should decrease.

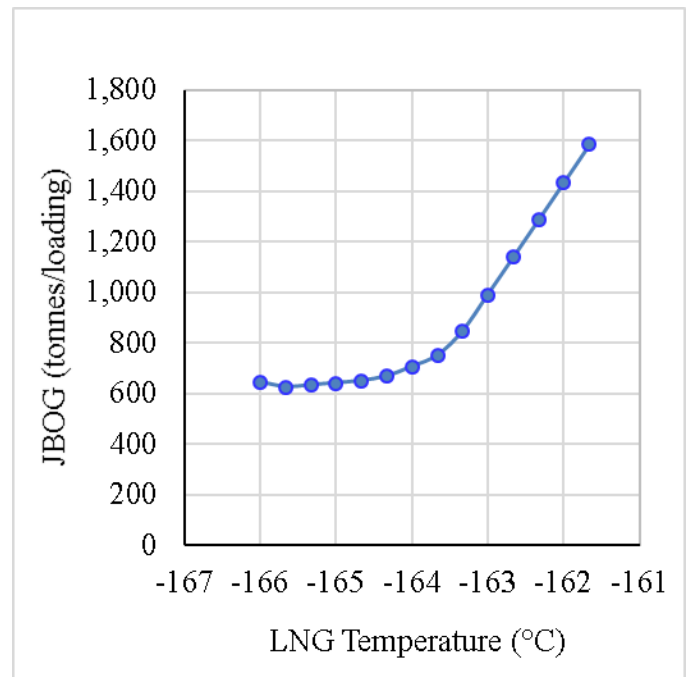


Figure 2 JBOG generation per LNG loading for each temperature case

The reduction in JBOG would result in decrease in energy required to recover it. However, LNG sub-cooling also consumes energy. Higher the degree of sub-cooling, larger will be the amount of energy required. Due to the opposite effect of the two quantities on energy consumption, there should be trade-off/optimum value for energy requirement.

Figure 2 shows JBOG quantity per loading of LNG for each temperature case. For saturated LNG JBOG generation is about 1,584 tonnes, which decreased significantly for sub-cooled LNG up to about -164.5 °C. JBOG generation for LNG sub-cooled below -164.5 °C stays nearly the same. These results are obtained from Aspen Plus Dynamics v8.8 simulation tool. LNG sub-cooling decreases JBOG generation due to LNG flashing and heat leak. Vapor displacement would still contribute JBOG generation, thus total JBOG generation (due to all factors) decreases until LNG temperature is about -164.5 °C, after which it remains practically the same.

Figure 3 shows energy consumption for the case of BOG recovery as fuel gas. As LNG temperature decreases from -161.66 °C (saturated liquid) to -166 °C, the energy input required for sub-cooling saturated LNG increases from 0 to 501 GJ for one LNG loading cycle. As effect of LNG sub-cooling, JBOG quantity decreases from 1,584 tonnes to 625 tonnes over a period of one loading. Thus, energy required to compress JBOG to 50 bar decreases from 1,309 GJ to 556 GJ. The total energy consumption for this case decreases to 895 GJ when LNG temperature is about -163.7 °C. After that, it starts increasing again; because the decrease in JBOG quantity becomes insufficient to compensate energy required for sub-cooling LNG, by decreasing JBOG recovery energy requirements.

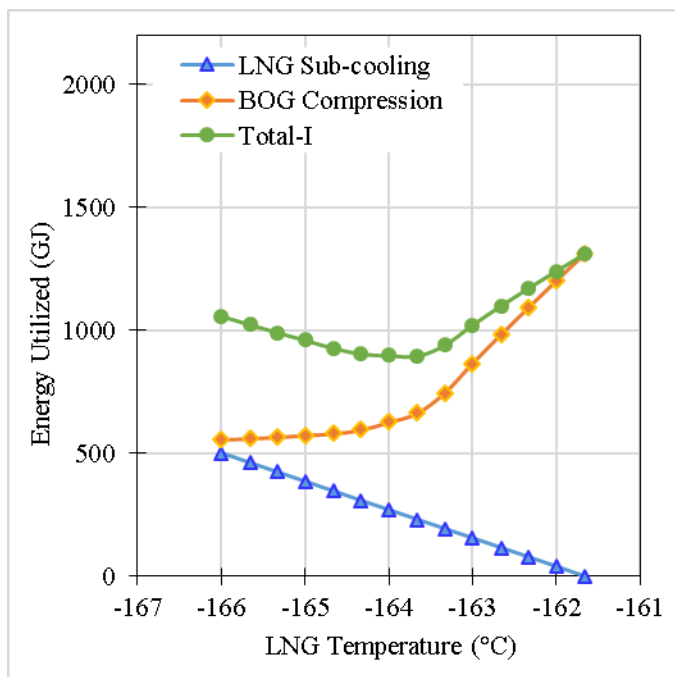


Figure 3 Energy consumption for BOG recovery as fuel gas with respect to LNG temperature

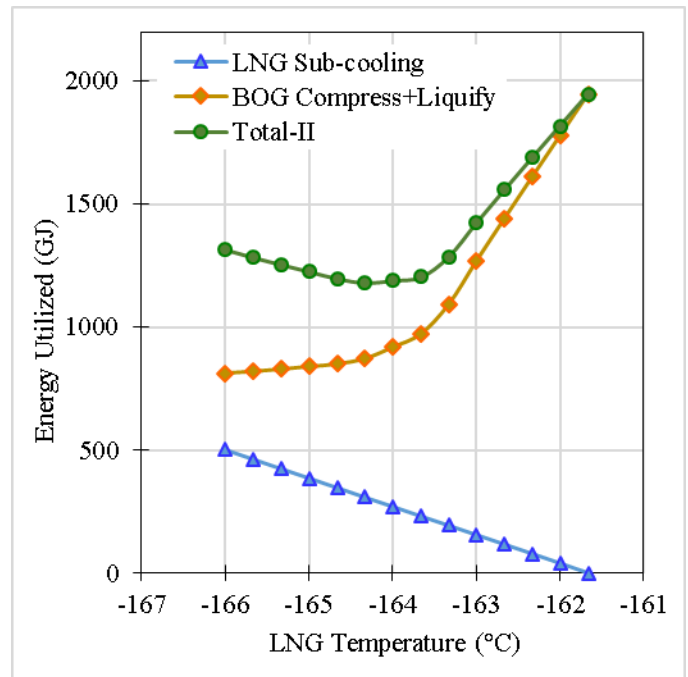


Figure 4 Energy consumption for BOG recovery by liquefaction with respect to LNG temperature

Figure 4 illustrates energy requirements for the case of JBOG recovery by BOG liquefaction. In this case JBOG is compressed as well as liquefied, resulting in more energy consumption per unit quantity of JBOG. Thus, the decrease in JBOG compensates energy required for LNG sub-cooling at temperatures lower than that in previous case. Energy required for JBOG liquefaction is 637 GJ for saturated LNG, and 257 GJ for LNG temperature of -166 °C. The total energy requirement for LNG sub-cooling, BOG compression, and BOG liquefaction is 1,946 GJ for saturated LNG, and 1,314 GJ for LNG temperature of -166 °C. The lowest total energy requirement is observed for LNG temperature of about -164.3 °C. The total energy requirement at this point is 1,180 GJ.

The details explained above are based on COP of 2. The optimum LNG temperature for BOG recovery as fuel gas is between -163.5 and -164.4 °C for COP ranging from 1 to 5. The optimum LNG temperature for BOG recovery by BOG liquefaction is between -163.8 and -164.7 °C for COP ranging from 1 to 5.

CONCLUSION

JBOG generation can be decreased economically by up to 60% (as compared to the case of saturated LNG), by sub-cooling LNG. At the same time, total energy required for natural gas liquefaction and BOG recovery can be minimized. 3 to 4 °C sub-cooling required to reach the optimum temperature may be provided by existing C3MR refrigeration cycles by slightly adjusting mixed refrigerant composition, if necessary. Recovery of BOG is important to avoid flaring and undesired impact on environment. Efficient recovery of BOG is necessary to minimize recovery cost and avoid wastage of energy.

Even though every LNG plant is not the same, the methodology from this work can be applied to calculate optimum LNG temperature to minimize energy consumption and reduce jetty boil-off gas generation. Sub-cooling LNG not only reduces JBOG, but also BOG generated during transportation would be relatively lower due to the sub-cooled LNG being able to absorb heat before vaporization.

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