Minimizing Boil-Off Losses in Liquefied Natural Gas Transportation

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Natural gas (NG) is the cleanest fossil fuel, which is most popular and economical after crude oil. Liquefied natural gas (LNG) is the most economical way of transporting NG over long distances. Because of LNG transportation and storage at −163 °C, boil-off losses are an unavoidable reality. While these are significant, few systematic studies on boil-off exist in the literature. In this work, we perform rigorous, realistic, detailed, and extensive dynamic simulation of boil-off during various steps of LNG transportation, study the effects of various factors such as nitrogen content, tank pressure, ambient temperature, voyage length, etc., and analyze the results. On the basis of our simulations, we determine optimal heels for several scenarios of lean LNG transportation. Our analysis shows that heel can be reduced by up to 40% for a typical long voyage of 20 days, compared to the usual industrial practice of 5% of the cargo, and the reduction is significantly more for the shorter voyages. Our computations suggest savings of millions of dollars from heel optimization alone in LNG transportation.

1. Introduction

Natural gas (NG) is a nontoxic, colorless, odorless, and noncorrosive fossil fuel. It contains mainly methane (about 90%), ethane, propane, butane, and trace amounts of nitrogen and carbon dioxide. Natural gas is the "natural" choice among fossil fuels. It is the cleanest fossil fuel with abundant proven reserves. Although it is a greenhouse gas with an effect that is 22 times greater than that of CO_2, it has the least CO_2 emission per unit energy and releases 1.9 times less CO_2 than coal.

Faced with the fast depletion of crude oil reserves, high oil prices in recent times, stringent environmental restrictions on CO_2 emissions, trends to diversify the energy supply, barriers to development of feasible renewable energy sources, etc., countries are now moving toward NG as their major and/or alternate source of fuel to supplement energy demand and curb the overdependency on oil. In the U.S. alone, about 10 000 companies explore, produce, transmit, and locally distribute NG, with a combined annual revenue of 100 billion USD.[1] The investment on NG will equal that of oil (19% of the total energy investment) and the cumulative spending on NG supply infrastructure will rise by 3.9 trillion USD over the course of 2001−2030.[2] Currently, NG is the world's fastest growing energy commodity and the third largest primary energy source after crude oil and coal.[3] In 2007, NG consumption was 2637.7 million tons oil equivalent, or about 23.8% of the total primary energy consumed worldwide.[3] The usage is projected to increase by nearly 52% between 2005 and 2030.[4] It is also the fastest-growing and second-largest energy source for electric power generation, producing 3.4 million GW in 2005 with a projection of 8.4 million GW in 2030.[4] NG-fired combined cycle generation units have an average conversion efficiency of 57%,[5] compared to 30−35% efficiency for coal.

Most NG reserves are offshore and away from demand sites. The storage and transportation of NG is a critical technology and cost issue. Pipelines pose a security risk and are not always feasible or economical. They are often limited by a "ceiling" amount of NG that can be transported. Alternately, an attractive option is to liquefy NG at −163 °C at the source and then transport it as liquefied natural gas (LNG) by specially built ships or tankers that are essentially giant floating flasks. When liquefied, the volume of natural gas reduces by a factor of about 600 at room temperature, which facilitates the bulk transport of NG. In fact, LNG is the most economical means of transporting NG over distances more than 2200 miles onshore and 700 miles offshore.[6] LNG provides an excellent example of design for logistics or DFL products.[7] Because major end-user markets of Asia, Europe, and North America are thousands of miles away from the foremost exporting countries such as Indonesia, Qatar, Trinidad, etc., LNG is becoming an increasingly global energy option and considered as the fuel for the future. In 2007, 226.41 billion m^3 of NG was transported as LNG,[3] accomplishing a total LNG movement of about 165.3 million tons per annum (mtpa). As an alternate fuel, the demand of LNG is doubling every 10 years. A growth rate of 6.5% per year[2] is expected for LNG in the near future, which would be the fastest growth for any energy activity or product worldwide. Singapore has already recognized the value of LNG with a receiving terminal in operation by 2012. The major factors behind recent increase in LNG demand include tendency to diversify energy sources for better energy security, decrease in LNG supply chain costs, new technology LNG tankers, increase in spot transactions, etc. More than 90% of the feed heating value in a modern LNG plant is shipped as product LNG.[8] With many higher throughput LNG trains being built in Qatar, Egypt, Iran, Russia, and Trinidad, global liquefaction and regasification capacity is expected to double between 2006 and 2010.[3]

The supply chain of LNG includes exploration and production of natural gas, liquefaction, marine transport of LNG, and LNG storage and regasification. Usually natural gas is produced at high pressure and then supplied to the liquefaction plant, where it is transformed into LNG. The liquefaction plant consists of several parallel processing modules called trains. Once LNG is produced, it is stored in cryogenic tanks from where it is loaded into LNG tankers. An LNG tanker is a ship with heavy insulation, and transports LNG to the customer side at its boiling point of −163 °C at atmospheric pressure. On arrival at the receiving terminal, LNG is stored and then regasified in regasification plants. Finally, it is supplied to the pipeline network for distribution among the consumers.

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The supply chain of LNG is capital intensive, mainly due to cryogenic liquefaction and transportation. These represent nearly 85% of the cost of delivering LNG to the customer's jetty. Although LNG supply chain has been considered[9] as costly and rigid since the early days, recent improvement in liquefaction technology and cryogenic transportation is transforming LNG into an increasingly favorable energy commodity for both developed and developing countries. Moreover, LNG tanker operation is getting more and more competitive, as there is a significant increase of ownership of tankers among LNG buyers, sellers, and third-party logistics providers (3PL) in recent years. An LNG tanker includes a cryogenic cargo containment system with proper tank support, double hull structure, secondary barrier, etc.[10] Two types (membrane and moss) of tankers are available at present.

Due to its cryogenic nature, LNG is continuously vaporized and lost as boil-off gas (BOG) during storage and transportation. The amount of BOG depends on the design and operating conditions of the LNG tanks and ships. Depending on the insulation and sea conditions, a boil-off rate of about 0.1−0.15% of the full cargo content per day is typical over a 21-day voyage.[11] While the boil-off rates vary significantly with different voyages,[12] the amount of BOG produced in a typical voyage can be as high as 2−6% of the total cargo depending on the voyage duration. Considering the total LNG movement of 165.3 mtpa in 2007, at least 3.3 mtpa of LNG were lost due to boil-off during transportation only. This amount is close to the annual capacity of a large base-load LNG train. At the average price of 7.73 USD per million BTU in 2007,[3] the cost of this cargo BOG loss exceeds 1.275 billion USD.

In addition to the loss during the voyage from an export to an import terminal, called the laden voyage, the return voyage of the tanker, called the ballast voyage, also incurs additional boil-off loss. During the ballast voyage, a small amount of cargo, called heel, is retained inside the cargo tanks to maintain them at their normal carrying temperature of −163 °C. The US Code of Federal Regulations (2008) defines the heel as the minimum quantity of LNG retained in an LNG ship after unloading at an LNG terminal to maintain temperature, pressure, and/or prudent operations. The heel may also be used to spray the tanks to cool them for the next loading of LNG. Without heel, the cargo tanks would get warm and excess flash boil-off would occur at the start of next loading. The boil-off losses can be 10−50% of the heel in a ballast voyage. Therefore, it is important to study the boil-off during LNG transportation.

The heel directly affects the revenue per trip, as it determines the amount of LNG delivered. It also influences the boil-off during loading, unloading, and ballast voyage. Although a common practice is to use 5% of the total cargo capacity[13] as the heel, it is not clear if this is the best or the only practice. Wide differences exist in heel management and boil-off rates, even for sister ships serving the same contract.[12] In fact, the total transport cost per unit of LNG can vary by as much as 100%. Grose and Flaherty[12] in their LNG carrier benchmarking work recommend that a potential for transporting an extra 3.5% LNG for each ship exists, depending on the LNG boil-off rates, cargo, and heel management. Clearly, both the US Code of Federal regulations and the benchmarking study of Grose and Flaherty[12] point to the need for optimum boil-off, cargo, and heel management. While the gas industry[14−16] is practicing optimization increasingly, no systematic approach exists in the open literature to address the boil-off and heel in LNG carriers to the best of our knowledge. In our opinion, it is crucial to understand how the boil-off changes under different conditions, how various factors influence it, what the optimum heel should be, how to minimize the boil-off losses, etc.

While research on the effect of boil-off of LNG cargo on the design of LNG[13] and designing systems for on-board reliquefaction of the BOG[11] has attracted considerable interest, virtually no literature deals with the boil-off itself or optimal heel. Hashemi and Wesson[17] investigated the influence of pressure on boil-off. Tanudjaja and Lanquetin[18] explored the reduction of fuel consumption on the LNG carrier "Ekaputra" by retaining a low heel onboard. Ait Ferhat et al.[19] conducted a thermal study on the interaction of an LNG tank system with the environment. However, all these studies are generally meant for the design of LNG storage tanks. The different factors and their interplays make it complex to estimate and/or compute the boil-off beforehand for different voyages and scenarios. The usual practice is to use a try-and-see approach to minimize or control boil-off from LNG tanks. However, a detailed simulation and/or optimization study on boil-off for LNG transportation is still missing in the literature to our knowledge.

In this article, we do extensive and detailed dynamic simulations to estimate boil-off in LNG transportation under different conditions. We identify and quantify the various factors that affect the boil-off and simulate the entire roundtrip journey of an LNG tanker from an export terminal to an import terminal. Using these extensive results, we determine the total boil-off as a function of heel and determine the optimal heel for any voyage. In addition, we study the interplays between and the effects of various factors, such as nitrogen content in LNG, tank pressure, ambient temperature, overall thermal conductance, voyage lengths, etc., on boil-off.

We begin with a discussion of the major factors affecting boil-off. Then, we present a detailed simulation study for the boil-off during LNG transportation and in other parts of the LNG supply chain. On the basis of this, we compute optimal heels for different scenarios of LNG transportation.

2. Boil-Off in LNG Supply Chain

LNG is stored and transported as an evaporating cryogen. It remains at its bubble point temperature (BPT) through a process known as autorefrigeration. As tanks cannot have perfect insulation, LNG cargo absorbs heat continuously due to the large temperature differential between the tank and the ambient. Because LNG is in a state of thermodynamic equilibrium inside the tank, the absorbed heat evaporates liquid at the surface with no visible bubble formation. This phenomenon is known as boil-off. BOG contains significant amounts of methane and nitrogen. BOG is generated at various places in the LNG supply chain because of LNG's cryogenic nature. Figure 1 shows the points producing BOG.

First, LNG is stored in atmospheric storage tanks at both LNG production plants and receiving terminals. As these tanks do not have perfect insulation, BOG produced during this storage is called tankage BOG (TBOG). In an LNG plant, it is usually compressed and exported to the plant fuel system. At receiving terminals, it is either flared or sent to the regasification plant using BOG compressors.[20]

LNG from a plant's storage tanks is loaded into tankers for delivery to receiving terminals. At the other end, it is unloaded from the tankers into the storage tanks, before it is regasified. BOG produced during the intermittent loading (LBOG) or unloading (UBOG) is commonly called jetty BOG (JBOG). JBOG is returned to the LNG storage tanks to combine with TBOG. BOG is produced during laden and ballast voyages due to the continuous leaking of heat into the cargo tanks. The BOG

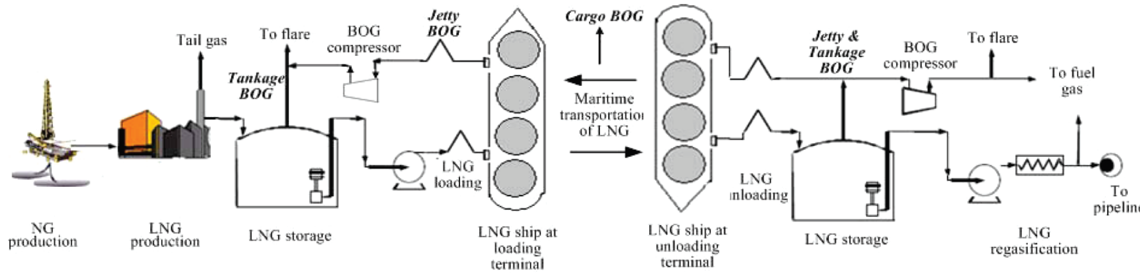

Figure 1. LNG supply chain with boil-off sources.

produced during the laden voyage is called cargo BOG or CBOG, and that produced during the ballast voyage is called ballast BOG (BBOG). The LNG tankers rarely have a reliquefaction system on board, and both these BOGs are usually vented to the atmosphere or used as a fuel to supplement bunker oil, when possible. However, since BOG is a part of the valuable LNG product and bunker oil is cheaper and more efficient, it is more economical to reduce BOG instead of using it as a fuel.

CBOG causes the cargo volume to decrease continuously throughout the laden voyage. This is a unique characteristic among commodity logistics. Furthermore, as LNG boils off, the composition, and hence the quality, of LNG changes due to weathering effect. This increases the BPT of LNG and consequently the tank temperature. The tank and the remaining cargo will then have to be cooled more during loading, which results in more JBOG.

Several factors affect the rate at which LNG boils off during a voyage.

2.1. Sea Condition. Hull motions arising from the sea waves induce sloshing in the partially filled tanks of cargo and ballast tankers. Sloshing in LNG tankers is the violent resonant of the free LNG surface. Sloshing transfers kinetic energy from the waves and swell into the tank, where friction causes additional heat effect and boil-off. However, sloshing is complex and stochastic in nature. It varies with voyage and sea conditions. While sea conditions do play a role, we neglect their effects and sloshing in this work.

2.2. Grade of LNG. LNG compositions vary with the processing plant and customer requirements. Two broad categories are lean and rich LNG. The typical composition of a lean LNG is roughly 90% methane and 10% ethane,[21] while rich LNG contains around 80% methane or more. Nitrogen content is another important factor in the quality of LNG, which usually varies from 0 to 4%. Clearly, an LNG tanker may transport LNG of various grades and compositions during different voyages. Since the compositions of both cargo and CBOG vary with time, CBOG contains more of nitrogen at the outset of a laden voyage. The nitrogen content decreases as the voyage continues. As lean LNG has relatively more volatile components as compared to rich LNG, its boil-off rate is greater. The boil-off rates for both rich and lean LNG drop with time due to the weathering effect, as it gets richer in heavier components.

As LNG boils off, methane is preferentially lost as compared to ethane and propane. Figure 2 shows the *xy* diagram for the methane−ethane binary system. For a methane content of more than 20 mol % overall, the vapor has more than 99 mol % methane. Thus, the boil-off is expected to be mainly methane for LNG, unless nitrogen is also present. For long voyages, operators sometimes inject nitrogen into an LNG cargo. This is because nitrogen is more volatile than methane and reduces the loss of valuable methane. As methane boils off, the composition and thermodynamic properties of the remaining LNG change. The concentration of heavier components increases gradually, which increases the BPT of the LNG. However, this also causes the temperatures of the bulk cargo and the heel to increase as well, which eventually affects the boil-off during loading.

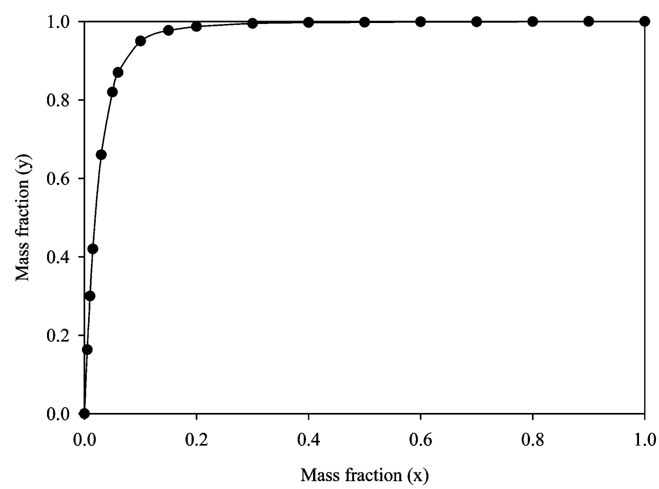

Figure 2. Plot of *xy* diagram for the methane−ethane binary system.

2.3. Ambient Temperature. The difference between the ambient and tank temperature directly determines the driving force for heat leakage into an LNG tank. A higher ambient temperature increases the boil-off rate. Apart from the sea conditions, the boil-off rate for an Atlantic voyage is different from that of a Pacific voyage, mainly because of the difference in ambient temperatures. Since it is difficult to estimate temperature profiles, we assume an average ambient temperature for each voyage in this study.

2.4. Overall Thermal Transmittance. The overall thermal transmittance (U) of storage tanks influences the amount of heat influx into a cargo tank, and hence the boil-off. U depends on two main factors. The first is the type and thickness of insulation. The second is the ratio of the support area connecting the inner and outer shells of a tank to its total area[22] with typical value of 0.0001. A typical double-wall LNG storage vessel uses a 9% nickel steel inner barrier and a carbon steel outer barrier with an insulating material (e.g., polyurethane foam) in between.[22] For such typical tank shells, U is about 0.411 kJ/h·m^2·°C, assuming that it only depends on the thermal conductivities of insulation and tank support, thickness of insulation, and ratio of support junction area to total surface area.

2.5. Tank Pressure. The tank design dictates the maximum allowable working pressure (MAWP) in a tank. While MAWP is generally about 10−14 atm and significantly greater than 1 atm, the standard practice is to transport LNG cargo at slightly above the atmospheric pressure. However, the tank pressure does affect the boil-off rate, and an optimum pressure with minimum boil-off may exist. As the tank pressure increases, the bubble point temperature of LNG increases. This favors less boil-off, as increased cargo temperature reduces the driving force for heat influx. However, an increase in pressure also decreases the latent heat of vaporization (H_v). This favors more boil-off, as LNG vaporization requires less energy. With these two conflicting factors in play, an optimum tank pressure that minimizes boil-off within the limits of the MAWP may exist.

2.6. Operating Modes. Unlike TBOG, JBOG is not produced continuously. It depends on the operating policies of the import and export terminals. A typical loading/unloading system consists of loading arms, circulation lines, pumps, etc., and the average time taken to load and discharge an LNG cargo is about 12−14 h. As shown in Figure 1, LNG from the storage tanks at an import terminal is loaded into the LNG carrier through a pipeline. At an export terminal, similar pipelines carry LNG from the ship to the storage tanks. These pipelines essentially constitute an LNG circulation system, which operates semicontinuously in two distinct modes, namely holding and loading/unloading. During the holding mode, no LNG tankers are loaded (unloaded) and the LNG inventory increases (decreases), but the circulating LNG maintains the pipelines at the cryogenic temperature. In the loading (unloading) mode, LNG is loaded (unloaded) via the loading arms attached to the pipeline. While circulating in the pipeline, LNG absorbs heat from the ambient and that generated from pumping, turbulent flow, and line friction.

The boil-off during loading is primarily due to two sources. The first is the heat gained through the pipes connecting the terminal to the LNG carrier, and the second is the cooling down of the tank shell and heel of the possibly warmer returning LNG tanker. While TBOG is produced during both holding and loading/unloading, JBOG is generated only during loading/unloading. However, the rate of JBOG is significantly higher during loading and unloading than that during storage. This amount increases, as the storage tanks are located further away from the LNG carrier. When a tanker returns from servicing or maintenance, extra cooling is required and excess JBOG is produced.

In what follows, we first dynamically simulate many tanker trips to estimate boil-off for a variety of parameters, conditions, and voyages. Later, we use these quantitative estimates to determine the optimum heel for any given voyage.

3. Simulating and Computing Boil-Off

We use Aspen HYSYS 2004.2 to simulate all the segments of a complete trip of an LNG tanker under a variety of parameters, conditions, and voyage lengths. Since the entire process is transient and involves nonlinear thermodynamic behavior, simulation is the only accurate means for this study. We use the Soave−Redlich−Kwong (SRK) equation of state as the fluid package, since it is found to be appropriate and applicable for the LNG system.[21] Quantitative simulation helps us observe the effects of various parameters and conditions on the boil-off and gives us the relative magnitudes of boil-off losses across the various segments of a trip.

Figure 3 gives an overview of our simulation procedure. The framework is generic and applicable for different scenarios. We simulate a single cargo tank only, since the treatment for all tanks would be identical and the results for one tank can be used for others. For each simulation run, we fix various parameters and conditions, and then simulate the four main steps of a typical trip. First, an LNG tanker with a given heel (amount and conditions) is loaded from the LNG storage tanks at an export terminal. Second, the tanker transports the LNG cargo in the laden voyage to an import terminal. Third, the LNG from the tanker is unloaded into the storage tanks at the receiving terminal except for the heel. Lastly, the tanker returns with the heel in the ballast voyage. We assume that the tanker is dedicated to making the same trip repeatedly. The simulation of each trip involves several iterations, as the heel composition and amount are unknown at the start of a trip. To obtain "stable" and pseudo-steady-state values for these, we guess them to begin with and then simulate several trips of the tanker, until the heel at the start of loading is identical (temperature, amount, composition, etc.) to that at the end of the ballast voyage for a given amount (percent) of heel at the start of the ballast voyage.

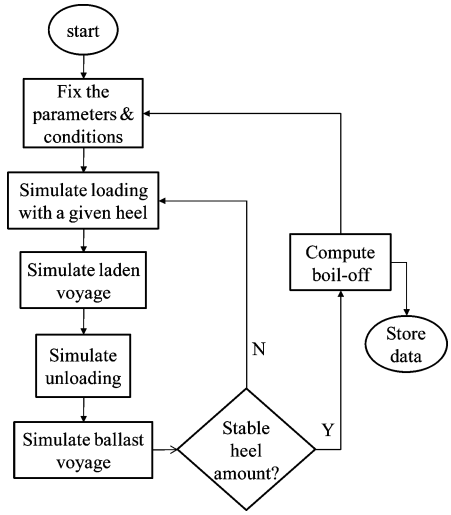

Figure 3. Overview of the simulation procedure.

3.1. Simulation Basis. Each simulation scenario requires two sets of parameters. One set is scenario-independent, fixed a priori, and the same for all runs, while the other is scenario-dependent and varies with each scenario.

We use the following as the scenario-independent parameters and assume values that represent real practice. We assume a tanker capacity of 145 000 m^3 with four spherical tanks. Each tank has an inner wall radius of 41.06 m and a capacity of 36250 m^3. Each tank is double walled with one inner and one outer barrier and a polyurethane foam insulation in between. As in real tanks, we use 0.05 m thick walls and 0.0381 m thick insulation. For both walls, we assume a density of 8000 kg/m^3 and a specific heat capacity of 0.486 kJ/kg·°C. For the insulation, we assume a density of 1050 kg/m^3 and a specific heat capacity of 2.1 kJ/kg·°C. The total heat capacity of the entire tank is taken as 2.52×10^6 kJ/°C. We consider 300 m pipelines for both loading and unloading with a thermal conductivity of 0.02 W/m·°C, an inner diameter of 84 in., and an insulation thickness of 1.5 in.

Each tank is filled to 98% of the tank capacity during loading. The 2% of the capacity is necessary to prevent any liquid from entering the vent pipes and spilling on to the surrounding hull structure.[21] For LNG with a density of 452 kg/m^3, a 36 250 m^3 tank filled to 98% of its total volume carries 16 062 tons of LNG. The rate of loading or unloading for a typical ship is 12 000 m^3/h with two pumps located at each cargo tank.[23] Thus, we use a loading/unloading rate of 3000 m^3/h or about 1356 ton/h for each cargo tank.

We use seven scenario-dependent parameters. These are voyage length, LNG grade, LNG composition, overall transmittance (U), ambient temperature, tank pressure, and heel. In this work, we use two grades (lean and rich) of LNG with the following three compositions for each grade.

lean-1: 90% methane, 10% ethane
lean-2: 90% methane, 9% ethane, 1% nitrogen
lean-3: 90% methane, 7% ethane, 3% nitrogen
rich-1: 82.5% methane, 8.5% ethane, 5% propane, 4% butane
rich-2: 81.5% methane, 8.5% ethane, 5% propane, 4% butane, 1% nitrogen
rich-3: 79.5% methane, 8.5% ethane, 5% propane, 4% butane, 3% nitrogen

To capture the possible variations in heel, ship design, ambient and operating conditions, supply contracts, and voyages, we use 3 U's (0.4, 0.5, and 0.6 kJ/h·m^2·°C), 5 ambient temperatures (−5, −10, 5, 15, and 25 °C), 9 pressures (101.3, 105, 110, 120, 140, 170, 200, 250, and 300 kPa), 4 voyage lengths (5, 10, 15, and 20 days), and 16 heel amounts (1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5, 5.0, 5.5, 6.0, 6.5, 7.0, 7.5, 8.0, and 8.5%). Since studying all possible combinations is nearly impossible, we select two sets of scenarios.

For first set (P1), we analyzed the effect of different parameters on the boil-off (CBOG) during a laden voyage. Since heel does not affect CBOG, it is an irrelevant parameter for P1. In P1, we used 3240 scenarios representing various combinations of six LNG compositions, three U's, five ambient temperatures, four voyage lengths, and nine different pressures. We also obtained quantitative insights into the effect of various factors that influence boil-off during a voyage.

The aim of our second set (P2) was to determine the optimal heel. We performed 114 simulations in P2 from selected combinations of 4 voyage lengths (5, 10, 15, and 20 days), 16 heel amounts (1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5, 5.0, 5.5, 6.0, 6.5, 7.0, 7.5, 8.0, and 8.5%), 2 U's (0.4 and 0.6 kJ/h·m^2·°C), and 2 ambient temperatures (5 and 25 °C). However, we did this only for a lean LNG with 90% methane and 10% ethane (lean-1) at 101.3 kPa.

We now present our methodology for computing boil-off during the four main steps in LNG transportation, namely loading, laden voyage, unloading, and ballast voyage.

3.2. Loading. While the loading process can be simulated dynamically, it is not necessary for BOG computation, as many of the factors affecting the BOG are relatively constant for a short duration of 12−14 h required for loading a tank.[23] Furthermore, the LNG composition in the transfer pipe as well as the tank can be safely assumed to be constant, which makes the H_v constant and simplifies boil-off computation considerably. We can simply consider an energy balance over the entire duration of loading. Neglecting the heat leak into the tanks during loading, the contribution to boil-off during loading consists of two parts.

The first part involves the flow of LNG to the tank via the transfer pipe, in which heat leaks into the pipe and heat is generated due to friction, pumping, and turbulence. We assume that the heat due to friction, pumping, and turbulence is negligible, and the transfer pipe supplies LNG of a fixed composition at a constant rate. This enables estimation of the rate of heat leak (q) into the pipeline by means of the following equation.[24]

$$q = \frac{2\pi kL(T_\infty - T_C)}{2.3\log\left(\dfrac{D + 2t}{D}\right)} \tag{1}$$

where, k, D, and L are the thermal conductivity, inner diameter, and length of the transfer pipe, t is the thickness of insulation, T_∞ is the ambient temperature, and T_C is the temperature of LNG. Knowing the LNG composition, we compute its H_v from Aspen Hysys and compute the boil-off from the transfer pipe as LTq/H_v, where LT is the loading time.

The second part involves the cooling of the resident LNG heel and the cargo tank to the supply temperature of LNG. We estimate the BOG produced due to this by computing the total heat lost by the heel and the tank based on their heat capacities. We assume that the temperatures of the tank and the heel are identical. This gives us the total BOG production during loading as

$$\mathrm{LBOG} = \frac{\mathrm{LT}q + (\mathrm{HC_T} + C_P M_H^i)(T_H^i - T_C)}{H_v} \tag{2}$$

where, C_P is the isobaric specific heat capacity (kJ/kg·°C) of LNG, $\mathrm{HC_T}$ is the total heat capacity (kJ/°C) of the tank, M_H^i is the heel in kilograms retained at the start of loading, and T_H^i is the heel temperature in degrees celcius at the start of loading. LT (h) is given by

$$\mathrm{LT} = \frac{M_C^i - M_H^i + \mathrm{LBOG}}{r} \tag{3}$$

where, M_C^i is the amount of LNG in the tank at the end of loading and r is the pumping rate (kg/h).

3.3. Laden Voyage. In contrast to loading, we must use dynamic simulation for a laden voyage, as the composition of the cargo and the temperature vary with time. For this simulation, we use a step size of 1×10^{-18} and an acceleration of 1×10^{13} in Hysys and record the relevant results at an interval of 5 min. These simulations give us the boil-off amounts, cargo composition, cargo amount, and temperature with respect to time, from which we compute the total boil-off losses for a laden voyage (CBOG).

3.4. Unloading. For unloading, the computation is very similar to that of loading. We neglect the heat leak into the tanks during unloading. Assuming that the LNG composition and temperature remain constant during unloading, there is no change in the heat content of the tank. The heat gain in the transfer pipe is the main source for BOG production, and we can use eq 1 for that. If the LNG left in the tank at the end of a laden voyage is M_C^f, then the unloading time (UT) and boil-off during unloading are given by

$$\mathrm{UT} = \frac{M_C^f - M_H^f}{r} \tag{4}$$

$$\mathrm{UBOG} = \frac{\mathrm{UT}q}{H_v} \tag{5}$$

where M_H^f is the heel left for the ballast voyage and r is the pumping rate, which we assumed same as the loading rate. Note that loading produces more boil-off than unloading.

3.5. Ballast Voyage. Again, as for a laden voyage, we need dynamic simulation for a ballast voyage to obtain BBOG. We use the same simulation procedure. As we discuss later, we find that CBOG is almost equal to BBOG, as long as sufficient heel is provided. This is not surprising, because the aim for both is to keep the tank temperature constant and the heat capacity of the tank is the same for both voyages.

The total boil-off for a complete round trip for a tanker is given by

$$\mathrm{BOG} = \mathrm{LBOG} + \mathrm{CBOG} + \mathrm{BBOG} + \mathrm{UBOG} \tag{6}$$

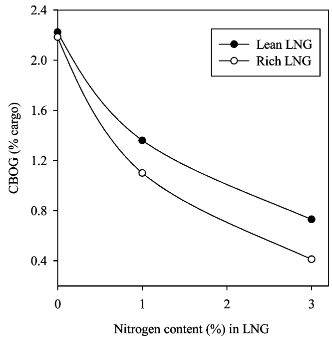

Figure 4. Effect of nitrogen content on CBOG for lean-1, 2, and 3 and rich-1, 2, and 3 for a voyage length of 20 days, ambient temperature of 25 °C, U of 0.4 kJ/h·m^2·°C, and at atmospheric pressure.

3.6. Simulation Results. It is not possible to present the results of all scenarios, so we present some key results instead. Figure 4 shows the variation of CBOG (weight percent of initial cargo load) with nitrogen content for lean and rich LNG for a voyage length of 20 days, ambient temperature of 25 °C, U of 0.4 kJ/h·m^2·°C, and pressure of 101.3 kPa. The three data points in Figure 4 are from lean-1 (rich-1), lean-2 (rich-2), and lean-3 (rich-3). Clearly, the effect of nitrogen content on boil-off is significant. Boil-off decreases nonlinearly with nitrogen content for both lean and rich LNG. Although lean and rich LNG have significantly different methane contents, boil-off is almost the same for zero nitrogen content. However, boil-off decreases more sharply with nitrogen content for rich LNG than lean LNG. Note that although more nitrogen seems good for boil-off, it does decrease the heating value and BPT. However, it should be possible to optimize nitrogen content for any given voyage or in general. Therefore, designing nitrogen content in LNG for long voyages is an interesting and nonintuitive problem that deserves attention.

For a given nitrogen content, boil-off is greater for lean LNG than that for rich LNG. This is reasonable, as the presence of more methane in lean LNG reduces the BPT or cargo temperature. Note that H_v is constant for a fixed nitrogen content. In contrast, as nitrogen content varies, H_v varies. In such a case, the boil-off involves a nonlinear and complex interplay between the conflicting effects of the BPT and H_v. As the nitrogen content increases, BPT decreases and heat influx increases. This tends to increase boil-off. However, H_v also increases and tends to decrease boil-off. Simulation results indicate that the effect of H_v outweighs that of BPT, thus boil-off reduces as nitrogen content increases.

Figure 5a shows CBOG (weight percent cargo) for lean-3 (90% methane, 7% ethane, and 3% nitrogen) at different pressures and voyage lengths, $U = 0.4$ kJ/h·m^2·°C, and ambient temperature = 15 °C. Interestingly, CBOG increases nonlinearly with pressure. In fact, the nonlinearity is stronger for longer voyages. Thus, the effect of pressure is opposite that of nitrogen content. As pressure increases, the BPT increases, but H_v decreases. However, as stated earlier, the effect of H_v is much stronger, and hence, the boil-off increases with pressure. For a voyage length of 20 days, a pressure of 300 kPa would produce 60.84 tons more of CBOG as compared to 101.3 kPa. However, the trend interestingly indicates that boil-off can be reduced further by using a pressure lower than 101.3 kPa.

Figure 5b shows CBOG (weight percent cargo) at different pressures for lean-1, lean-2, lean-3, rich-1, rich-2, and rich-3 for an ambient temperature = 15 °C and $U = 0.4$ kJ/h·m^2·°C. Interestingly, boil-off does increase with pressure as in Figure 5a for all grades except lean-1 and rich-1. Both of these grades have zero nitrogen. This also indicates an interesting effect of nitrogen on boil-off. For lean-1 and rich-1, boil-off seems to decrease slightly with pressure.

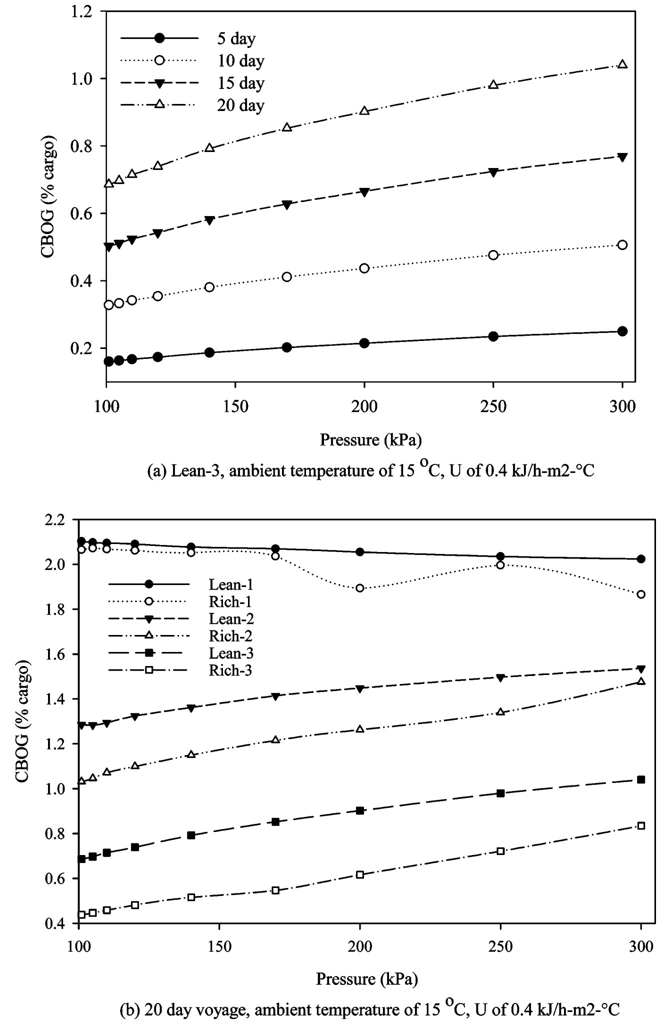

Figure 5. Effect of pressure on CBOG for various voyage lengths and LNG grades at an ambient temperature of 15 °C and U of 0.4 kJ/h·m^2·°C.

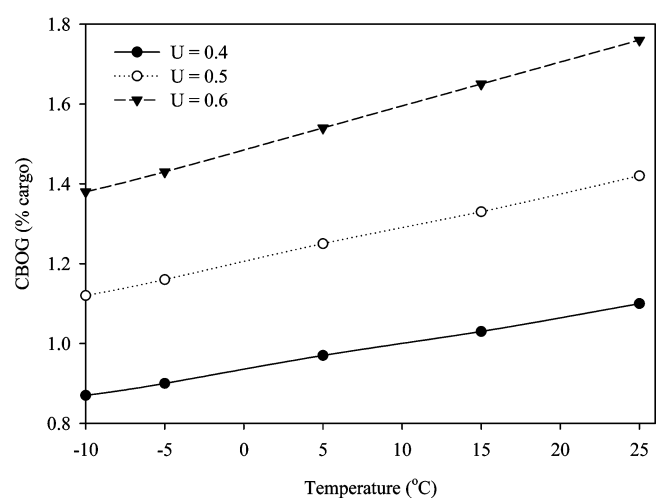

Figure 6. Effect of temperature and U on CBOG for rich-2 LNG with a voyage length of 20 days and at atmospheric pressure.

Figure 6 shows CBOG (weight percent cargo) for rich-2 at 101.3 kPa at different temperatures and U's. The voyage length is 20 days. As expected, CBOG increases with ambient temperature and U. However, the change is linear rather than

Table 1. Boil-Off Results for the Scenarios in P2

scenario	voyage length (days)	overall U (kJ/h·m^2·°C)	ambient temperature (°C)	heel	LBOG (ton)	CBOG (ton)	BBOG (ton)	UBOG (ton)	total boil- off (ton)	boil-off (wt % of cargo)
S1	5	0.4	5	1.0	45.56	79.95	79.06	36.51	241.09	1.501
	5	0.4	5	1.5	35.70	79.95	79.01	36.32	230.99	1.438
	5	0.4	5	2.0	37.90	79.15	79.07	36.13	232.26	1.446
	5	0.4	5	2.5	36.48	79.95	79.90	35.94	232.28	1.446
	5	0.4	5	3.0	38.79	79.95	79.72	35.76	234.22	1.458
	5	0.4	5	3.5	38.39	79.95	79.84	35.57	233.75	1.455
	5	0.4	5	4.0	38.07	79.95	79.91	35.38	233.30	1.453
	5	0.4	5	4.5	37.78	79.95	79.97	35.19	232.89	1.450
	5	0.4	5	5.0	37.54	79.95	80.06	35.00	232.54	1.448
	5	0.4	5	5.5	37.30	79.95	80.13	34.81	232.19	1.446
	5	0.4	5	6.0	37.08	79.95	80.23	34.62	231.88	1.444
	5	0.4	5	6.5	36.88	79.95	80.29	34.43	231.55	1.442
	5	0.4	5	7.0	37.37	79.95	80.36	34.24	231.92	1.444
	5	0.4	5	7.5	37.40	79.95	80.43	34.05	231.84	1.443
	5	0.4	5	8.0	37.30	79.95	80.48	33.86	231.60	1.442
	5	0.4	5	8.5	37.12	79.95	80.58	33.67	231.33	1.440
S2	5	0.6	25	1.5	48.46	134.79	133.00	36.20	352.45	2.194
	5	0.6	25	2.0	39.09	134.79	133.56	35.00	342.45	2.132
	5	0.6	25	2.5	40.70	134.79	133.94	35.02	344.45	2.145
	5	0.6	25	3.0	40.67	134.79	134.21	35.63	345.30	2.150
	5	0.6	25	3.5	39.96	134.79	134.42	35.44	344.62	2.146
	5	0.6	25	4.0	39.44	134.79	134.50	35.25	343.98	2.142
	5	0.6	25	4.5	39.02	134.79	134.45	35.06	343.32	2.137
	5	0.6	25	5.0	38.65	134.79	134.30	34.87	342.62	2.133
	5	0.6	25	5.5	38.34	134.79	134.46	34.68	342.27	2.131
	5	0.6	25	6.0	38.06	134.79	134.52	34.49	341.86	2.128
	5	0.6	25	6.5	37.80	134.79	134.62	34.30	341.52	2.126
	5	0.6	25	7.0	37.56	134.79	134.64	34.12	341.11	2.124
	5	0.6	25	7.5	37.34	134.79	134.72	33.93	340.78	2.122
	5	0.6	25	8.0	37.12	134.79	134.80	33.94	340.65	2.121
	5	0.6	25	8.5	37.70	134.79	134.83	34.55	341.87	2.128
S3	10	0.4	5	1.0	226.05	159.71	141.42	36.33	563.51	3.508
	10	0.4	5	1.5	55.94	159.71	157.58	36.14	409.37	2.549
	10	0.4	5	2.0	43.00	155.71	156.99	35.95	391.64	2.438
	10	0.4	5	2.5	43.08	159.71	159.36	35.76	397.90	2.452
	10	0.4	5	3.0	41.69	159.71	159.66	35.57	396.63	2.469
	10	0.4	5	3.5	40.80	159.71	160.02	35.38	395.90	2.465
	10	0.4	5	4.0	40.13	159.71	160.01	35.19	395.04	2.459
	10	0.4	5	4.5	39.63	159.71	159.87	35.00	394.21	2.454
	10	0.4	5	5.0	39.21	159.71	159.89	34.81	393.63	2.451
	10	0.4	5	5.5	38.86	159.71	159.98	34.63	393.17	2.448
	10	0.4	5	6.0	38.54	159.71	160.14	34.44	392.83	2.446
	10	0.4	5	6.5	38.26	159.71	160.27	34.25	392.48	2.444
	10	0.4	5	7.0	38.00	159.71	160.40	34.06	392.17	2.442
	10	0.4	5	7.5	37.75	159.71	160.61	33.87	391.94	2.440
	10	0.4	5	8.0	37.52	159.71	160.74	33.68	391.65	2.438
	10	0.4	5	8.5	37.30	159.71	160.91	33.49	391.41	2.437
S4	10	0.6	25	2.0	117.69	269.65	257.66	35.70	680.70	4.238
	10	0.6	25	2.5	57.71	269.65	265.42	35.51	628.29	3.912
	10	0.6	25	3.0	49.32	269.65	264.96	35.32	619.24	3.855
	10	0.6	25	3.5	44.80	269.65	264.79	35.13	614.37	3.825
	10	0.6	25	4.0	43.56	269.65	263.26	34.70	611.18	3.805
	10	0.6	25	4.5	42.93	269.65	268.50	34.75	615.84	3.834
	10	0.6	25	5.0	42.09	269.65	268.64	34.56	614.94	3.829
	10	0.6	25	5.5	41.43	269.65	268.88	34.37	614.34	3.825
	10	0.6	25	6.0	40.89	269.65	269.03	34.18	613.75	3.821
	10	0.6	25	6.5	40.43	269.65	269.09	33.99	613.17	3.818
	10	0.6	25	7.0	40.02	269.65	268.86	33.80	612.34	3.812
	10	0.6	25	7.5	39.66	269.65	268.95	33.62	611.88	3.809
	10	0.6	25	8.0	39.34	269.65	269.08	33.43	611.50	3.807
	10	0.6	25	8.5	39.04	269.65	269.15	33.24	611.08	3.804
S5	15	0.4	5	1.5	256.20	239.22	213.55	35.96	744.92	4.638
	15	0.4	5	2.0	70.47	239.22	235.38	35.77	580.84	3.616
	15	0.4	5	2.5	47.79	239.22	232.97	35.58	555.56	3.440
	15	0.4	5	3.0	46.47	239.22	239.17	35.39	560.25	3.468
	15	0.4	5	3.5	44.15	239.22	239.68	35.20	558.26	3.476
	15	0.4	5	4.0	42.80	239.22	240.02	35.01	557.05	3.468
	15	0.4	5	4.5	41.91	239.22	240.41	34.82	556.36	3.464
	15	0.4	5	5.0	41.24	239.22	240.77	34.63	555.86	3.461
	15	0.4	5	5.5	40.68	239.22	240.68	34.44	555.02	3.455
	15	0.4	5	6.0	40.20	239.22	240.64	34.25	554.32	3.451
	15	0.4	5	6.5	39.79	239.22	240.33	34.06	553.41	3.445
	15	0.4	5	7.0	39.45	239.22	240.53	33.87	553.07	3.443
	15	0.4	5	7.5	39.13	239.22	240.74	33.69	552.77	3.442

Table 1. Continued

scenario	voyage length (days)	overall U (kJ/h·m^2·°C)	ambient temperature (°C)	heel	LBOG (ton)	CBOG (ton)	BBOG (ton)	UBOG (ton)	total boil- off (ton)	boil-off (wt % of cargo)
	15	0.4	5	8.0	38.83	239.22	240.86	33.50	552.41	3.439
	15	0.4	5	8.5	38.56	239.22	241.04	33.31	552.13	3.459
S6	15	0.6	25	3.0	126.08	403.48	387.90	35.01	952.47	5.930
	15	0.6	25	3.5	58.51	403.48	391.48	34.82	888.29	5.530
	15	0.6	25	4.0	48.35	403.48	387.37	34.63	873.83	5.440
	15	0.6	25	4.5	48.78	403.48	397.72	34.44	884.42	5.506
	15	0.6	25	5.0	47.59	403.48	402.24	34.25	887.56	5.526
	15	0.6	25	5.5	45.90	403.48	402.75	34.06	886.20	5.517
	15	0.6	25	6.0	44.69	403.48	403.19	33.87	885.23	5.511
	15	0.6	25	6.5	43.78	403.48	403.47	33.68	884.41	5.506
	15	0.6	25	7.0	43.08	403.48	403.90	33.50	883.95	5.503
	15	0.6	25	7.5	42.49	403.48	404.19	33.31	883.47	5.500
	15	0.6	25	8.0	41.98	403.48	404.38	33.12	882.95	5.497
	15	0.6	25	8.5	41.54	403.48	404.47	32.93	882.41	5.494
S7	20	0.4	5	2.0	277.82	318.57	285.43	35.58	917.40	5.712
	20	0.4	5	2.5	69.83	318.57	307.46	35.39	731.26	4.553
	20	0.4	5	3.0	47.86	318.57	303.82	35.20	705.45	4.392
	20	0.4	5	3.5	48.29	318.57	314.57	35.02	716.44	4.460
	20	0.4	5	4.0	46.90	318.57	319.66	34.83	719.96	4.482
	20	0.4	5	4.5	44.98	318.57	320.10	34.64	718.29	4.472
	20	0.4	5	5.0	43.71	318.57	320.44	34.45	717.16	4.465
	20	0.4	5	5.5	42.83	318.57	320.91	34.26	716.56	4.461
	20	0.4	5	6.0	42.15	318.57	321.39	34.07	716.18	4.459
	20	0.4	5	6.5	41.59	318.57	321.81	33.88	715.84	4.457
	20	0.4	5	7.0	41.09	318.57	321.80	33.69	715.15	4.452
	20	0.4	5	7.5	40.66	318.57	321.58	33.50	714.31	4.447
	20	0.4	5	8.0	40.27	318.57	321.11	33.31	713.26	4.441
	20	0.4	5	8.5	39.92	318.57	320.80	33.12	712.41	4.435
S8	20	0.6	25	3.0	357.02	537.19	437.16	34.70	1396.07	8.692
	20	0.6	25	3.5	266.33	537.19	489.93	34.51	1327.96	8.268
	20	0.6	25	4.0	73.66	537.19	510.57	34.32	1155.74	7.196
	20	0.6	25	4.5	49.18	537.19	515.61	34.13	1122.11	6.986
	20	0.6	25	5.0	48.60	537.19	518.72	33.94	1129.45	7.032
	20	0.6	25	5.5	49.02	537.19	520.22	33.75	1140.18	7.099
	20	0.6	25	6.0	49.45	537.19	530.84	33.57	1151.05	7.166
	20	0.6	25	6.5	48.88	537.19	537.31	33.38	1156.76	7.202
	20	0.6	25	7.0	47.36	537.19	537.94	33.19	1155.67	7.195
	20	0.6	25	7.5	46.20	537.19	538.37	33.00	1154.76	7.189
	20	0.6	25	8.0	45.27	537.19	538.71	32.81	1153.98	7.185
	20	0.6	25	8.5	44.51	537.19	538.94	32.62	1153.26	7.180

nonlinear as was the case with pressure. We observed similar trends for other simulation scenarios.

Table 1 gives the results for the 114 scenarios of P2. It shows individual and total boil-offs and the total loss of LNG due to various boil-offs in transportation (weight percent of M_C^i) for different scenarios for lean-1 at 101.3 kPa. We used M_C^i = 16 062 ton for each tank. It is clear that the total boil-off losses increase with voyage length, ambient temperature, and U. The total boil-off losses with 5% heel for voyage lengths of 5, 10, 15, and 20 days are 1.45%, 2.45%, 3.46%, and 4.47%, respectively, of M_C^i for ambient temperature = 5 °C and U = 0.4 kJ/h·m^2·°C, and 2.13%, 2.83%, 5.53%, and 7.03%, respectively, of M_C^i for ambient temperature = 25 °C and U = 0.6 kJ/h·m^2·°C.

Figure 7 shows the distribution of boil-off for lean-1 at various steps in its transportation for four voyage lengths (5, 10, 15, and 20 days) at pressure = 101.3 kPa, heel = 5%, U = 0.4 kJ/h·m^2·°C, and ambient temperature = 5 °C. The total boil-off increases almost linearly with voyage length, as CBOG and BBOG increase almost linearly with time, and LBOG and UBOG are nearly constant. CBOG and BBOG are almost equal and much greater than LBOG and UBOG. As voyage length increases, the relative contributions of CBOG + BBOG rise in comparison to LBOG + UBOG. For instance, the contributions of CBOG + BBOG and LBOG + UBOG (Figure 7) are (34.4 + 34.4)% and (16.1 + 15.1)%, respectively, for 5 days, (40.6 + 40.6)% and (10 + 8.8)%, respectively, for 10 days, (43 + 43.3)% and (7.4 + 6.2)%, respectively, for 15 days, and (44.4 + 44.7)% and (6.1 + 4.8)%, respectively, for 20 days. LBOG is slightly greater than the UBOG, since LBOG includes additional boil-off due to the cooling of the tanks and heel.

4. Optimal Heel

Figure 8 shows the various boil-offs and the total boil-off in tons as a function of heel for a scenario with lean-1, U of 0.6 kJ/h·m^2·°C, ambient temperature of 25 °C, voyage length of 20 days, and a pressure of 101.3 kPa. Although heel can be expressed in terms of total tank volume, level, or cargo capacity, we define heel as $100M_H^f/M_C^i$, which is in line with practice. While CBOG and UBOG do not change with heel, BBOG and LBOG do change up to a certain heel, after which they remain nearly constant. As heel increases, BBOG increases and LBOG decreases. This is because smaller heel increases the tank temperature, which causes more LBOG. If the heel is below a certain value, then the tank temperature will increase significantly. To decrease this tank temperature, as heel increases, BBOG must increase too. Clearly, a tradeoff exists between LBOG and BBOG up to a certain heel.

The effect of heel on the total boil-off increases with voyage length. Scope exists for decreasing the boil-off significantly by adjusting the heel during the ballast voyage. Figure 9 shows the total boil-off (weight percent of M_C^i) for various voyages for eight (S1−8) major scenarios shown in Table 1. The boil-off decreases initially with an increase in heel, until it reaches a minimum. This is the optimum heel that minimizes the boil-

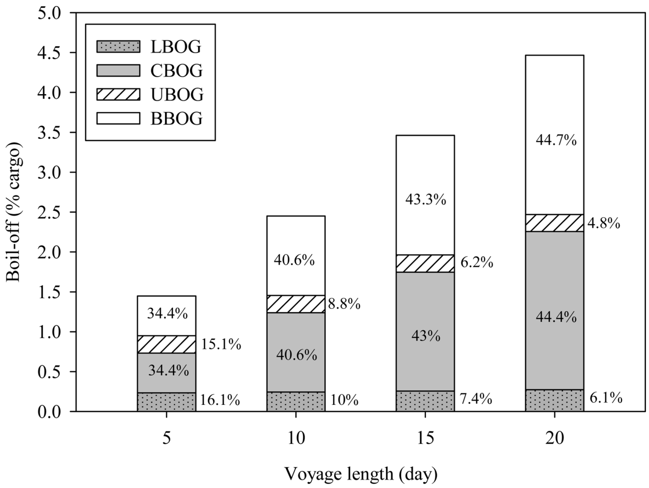

Figure 7. Distribution of boil-off in LNG supply chain with 5% heel, U of 0.4 kJ/h·m^2·°C, ambient temperature of 5 °C, and at atmospheric pressure.

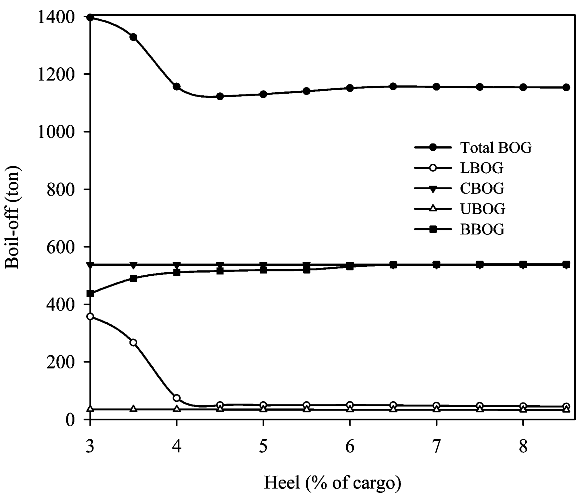

Figure 8. Various boil-offs and the total boil-off as a function of heel for lean-1 LNG with U of 0.6 kJ/h·m^2·°C, ambient temperature of 25 °C, voyage length of 20 days, and at atmospheric pressure.

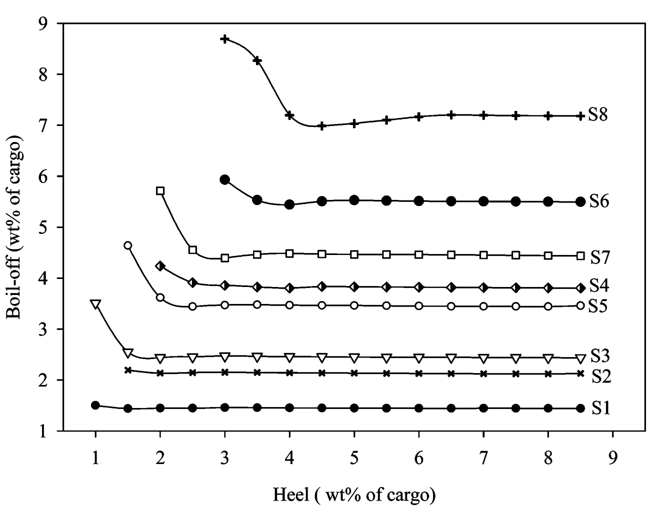

Figure 9. Boil-off as a function of heel for S1−8.

off losses for a given scenario. For instance, the optimal heel is 3% for a voyage of 20 days (S7) with an ambient temperature of 5 °C and U of 0.4 kJ/h·m^2·°C. This is 40% less than the usual industry practice of 5%. Clearly, even a smaller heel would be optimal for a shorter voyage. Figure 10 shows the optimal heels for S1−8. The optimal heels are 1.5%, 1.65%, 2.5%, and 3% (2.25%, 3.75%, 4%, and 4.5%) for voyage lengths of 5, 10, 15, and 20 days, respectively, with an ambient temperature of 5 °C and U of 0.4 kJ/h·m^2·°C (25 °C and 0.6 kJ/h·m^2·°C). Clearly, the optimal heel increases with voyage length (day), and the industry practice of 5% for all trips seems quite conservative and offers significant room for savings. Note that these results are only for lean-1 with no nitrogen content. For the LNG compositions with nitrogen, the optimal heels would be even less. For higher U and ambient temperature, both the optimal heel and boil-off are higher than those for lower U and ambient temperature. Moreover, the changes in optimal heels with temperatures are more at low ambient temperatures than they are at high ambient temperatures.

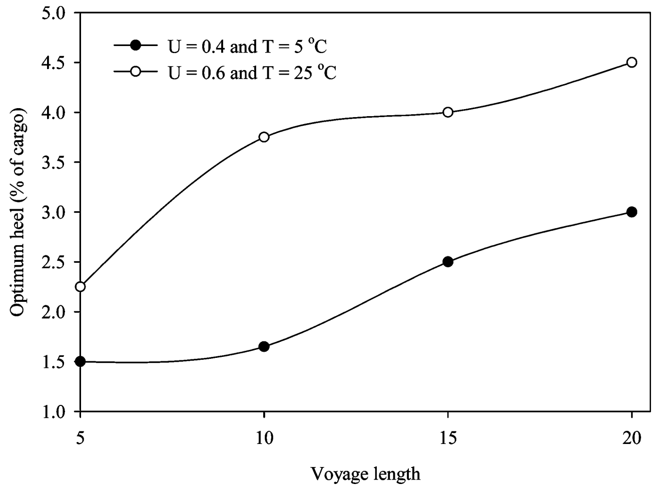

Figure 10. Optimal heel for different voyages.

The corresponding total boil-offs in weight percent of cargo at optimal heels for voyage lengths of 5, 10, 15, and 20 days are 1.44%, 2.44%, 3.44%, and 4.39%, respectively, of M_C^i for ambient temperature = 5 °C and U = 0.4 kJ/h·m^2·°C, and 2.13%, 3.80%, 5.44%, and 6.99%, respectively, of M_C^i for ambient temperature = 25 °C and U = 0.6 kJ/h·m^2·°C. With an optimal heel of 3% for S7, the boil-off loss is reduced by 11.71 ton per tank, or 46.84 ton per ship. For an LNG cost of 7.73 USD per million BTU or 386.5 USD per ton, 18,100 USD per tank is saved for a single voyage. Furthermore, the saving of 2% heel adds 1285 tons to LNG delivery. Both these factors together contribute 514,700 USD to the revenue from a single voyage. The savings in boil-offs and the reductions in heels (or increase in total LNG delivered to the customer jetty) adds revenues of 872,900, 704,100, 837,480, 331,600, 621,250, 305,500, 514,700, and 135,500 USD, respectively, for S1−8 for a single trip of a typical ship with four cargo tanks. Note that a ship typically may make several such trips during a year, thus the benefits are on the order of millions of USD annually.

It is also clear from the simulation results that although boil-off does not vary much with heel after it reaches the minimum value for shorter voyages with low ambient temperatures and/or U, optimum heel becomes significant as the voyage durations and ambient temperatures increase. For long voyages with high ambient temperatures, the boil-off with heel shows a clear minimum. Most LNG trade movements occur in the Asia−Pacific region. The LNG-producing Persian Gulf countries such as Qatar experience ambient temperatures as high as 45−50 °C, especially during summer. Moreover, except for a few spot transactions, most long-term LNG supply involves voyage durations of 20 days or even more. Therefore, choosing an optimal heel is crucial for such voyages.

5. Conclusion

We simulated the boil-off in LNG transportation using realistic data and studied the effects of several factors such as LNG composition, ambient temperature, nitrogen content, tank pressure, heel, etc. On the basis of our detailed computations, we determined the optimal heel as a function of voyage length for at least one LNG composition. Our results show that, even for a typical long voyage of 20 days (one-way), a heel of 5% is conservative compared to the optimal heel. Since shorter voyages do require smaller heels, optimizing heel using a case-by-case analysis is beneficial for the LNG industry and can result in savings of millions of USD annually. Although certain factors such as ambient temperature and insulation thickness are beyond control, other factors such as heel, tank pressure, and nitrogen content can be adjusted to minimize boil-off losses. However, the effect of sea condition on boil-off may be worth studying in the future.

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Nomenclature

q = heat leak into the pipeline
k = thermal conductivity
D = inner diameter of the transfer pipe
L = length of the transfer pipe
T = thickness of insulation of the transfer pipe
T_∞ = ambient temperature
T_C = temperature of LNG
H_v = latent heat of vaporization
LT = loading time
UT = unloading time
C_P = isobaric specific heat capacity of LNG
HC = total heat capacity of the tank
M_H^i = heel at the start of loading
T_H^i = heel temperature at the start of loading
M_C^i = LNG in the tank at the end of loading
M_C^f = LNG left in the tank at the end of a laden voyage
M_H^f = heel left for the ballast voyage
r = pumping rate

Literature Cited

(1) *Natural Gas Production and Distribution*, First Research, Inc.: Austin, TX, 2008.

(2) *World Energy Outlook*; IEA: Paris, 2006.

(3) *Statistical Review of World Energy*; BP: London, 2008.

(4) *International Energy Outlook*; **2008**.

(5) Kjärstad, J.; Johnsson, F. Prospects of the European Gas Market. *Energy Policy* **2007**, *35*, 869–888.

(6) Thomas, S.; Dawe, R. A. Review of Ways to Transport Natural Gas Energy from Countries which do not need the Gas for Domestic Use. *Energy* **2003**, *28*, 1461–1477.

(7) Lee, H. L. Design for Supply Chain Management: Concepts and Examples. In *Perspectives in Operations Management: Essays in Honor of Elwood S. Buffa*; Sarin, R. K., Ed.; Kluwer Academic Publishers: Boston, 1993; pp 44−66.

(8) Liu, Y.; Lucas, C. E.; Bower, R. W.; Bronfenbrenner, J. C. Reducing LNG Costs by Better Capital Utilization. Presented at the *13th International Conference and Exhibition on Liquefied Natural Gas (LNG13)*, Seoul, Korea, May 14−17, 2001.

(9) Michel, V.; Marie-Françoise, C.; Thierry, L. World LNG prospects: Favorable parameters for a new growth era. Presented at the *18th Congress of the World Energy Council*, Buenos Aires, October 2001.

(10) Abe, A.; Nakamura, M.; Sato, I.; Uetani, H.; Fujitani, T. Studies of the Large-Scale Sea Transportation of Liquid Hydrogen. *Int. J. Hydrogen Energy* **1998**, *23*, 115–121.

(11) Gerdsmeyer, K. D.; Isalski, W. H. On-board Reliquefaction for LNG Ships. *GASTECH*, Bilbao, Spain, March 2005.

(12) Grose, I.; Flaherty J. LNG Carrier Benchmarking. Presented at *LNG15*, Barcelona, Spain, April 24−27, 2007; Poster PO-01.

(13) Wilson, J. J. An Introduction to the Marine Transportation of Bulk LNG and the Design of LNG Carriers. *Crogenics* **1974**, 115–120.

(14) Hasan, M. M. F.; Karimi, I. A.; Alfadala, H. E.; Grootjans, H. Operational Modeling of Multistream Heat Exchangers with Phase Changes. *AIChE J.* **2009**, *55*, 150–171.

(15) Javanmardi, J.; Nasrifar, Kh.; Najibi, S. H.; Moshfeghian, M. Feasibility of Transporting LNG from South-Pars Gas Field to Potential Markets. *Appl. Therm. Eng.* **2006**, *26*, 1812–1819.

(16) Kuwahara, N.; Bajay, S. V.; Castro, L. N. Liquefied Natural Gas Supply Optimization. *Energy Convers. Manage.* **2000**, *41*, 153–161.

(17) Hashemi, H. T.; Wesson, R. Cut LNG Storage Costs. *Hydrocarbon Process.* **1971**, *50*, 117–120.

(18) Tanudjaja, R.; Lanquetin, B. High Flexibility and Effective Voyage Cost Improvement for LNG Carrier 'Ekaputra' due to Low Boil-Off Rate. Presented at the *14th International LNG/LPG Conference and Exhibition - GASTECH 90*, Amsterdam, Netherlands, December 4−7, 1990.

(19) Ait Ferhat, S.; Benbrik, A.; Lemonnier, D. Thermal Study by a Nodal Model of the Unit Tank-LNG in Interaction with Environment. Presented at the *7th World Congress of Chemical Engineering*, Glasgow, Scotland, July 10−14, 2005.

(20) Shin, M. W.; Shin, D.; Choi, S. H.; Yoon, E. S.; Han, C. Optimization of the Operation of Boil-Off Gas Compressors at a Liquefied Natural Gas Gasification Plant. *Ind. Eng. Chem. Res.* **2007**, *46*, 6540–6545.

(21) Valencia-Chavez, J. A.; Reid, R. C. The Effect of Composition on the Boiling Rates of Liquefied Natural Gas for Confined Spills on Water. *Int. J. Heat Mass Transfer* **1979**, *22*, 831−838.

(22) Chen, Q. S.; Wegrzyn, J.; Prasad, V. Analysis of Temperature and Pressure Changes in Liquefied Natural Gas (LNG) Cryogenic Tanks. *Crogenics.* **2004**, *44*, 701–709.

(23) Tarlowski, J.; Sheffield, J. LNG Import Terminals - Recent Developments. http://www.cheresources.com/lng_terminals.pdf (accessed Jan 26, 2007).

(24) Kern D. Q. *Process Heat Transfer*; McGraw-Hill: New York, 1950.

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