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Simulation study on boil-off gas minimization and recovery strategies at LNG exporting terminals

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HIGHLIGHTS

- Various strategies to recover BOG are explored with energy requirement comparison.
- BOG can be recovered to increase revenue of LNG plant and benefit the environment.
- BOG generation can be decreased economically by sub-cooling LNG.
- Heat leaks through LNG equipment are calculated.

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ABSTRACT

Liquefied natural gas (LNG) is becoming one of the prominent clean energy sources with its abundance, high calorific value, and low emission and price. Vapors generated from LNG due to heat leak are called boil-off gas (BOG). As world-wide LNG productions are in an increasingly growth, BOG generation and handling problems become more critical subject to more intense global competitions and stricter environmental regulations. In this study, typical C3-MR process, storage facilities, and loading facilities are modeled and simulated to study BOG generation at LNG exporting terminals, including LNG processing, storage, and berth loading areas. Factors causing BOG are presented, and quantities of BOG generated due to each factor at each location are calculated under different LNG temperatures. Various strategies to minimize, recover, and reuse BOG are also studied for their feasibility and energy requirements. The study would help proper handling of BOG problems in terms of minimizing flaring at LNG exporting terminals, and thus reducing waste, saving energy, and protecting surrounding environments.

1. Introduction

With a continuous increase in clean energy demands, the world-wide production capacity of liquefied natural gas (LNG) is expanding very fast, and LNG is actually becoming the world's fastest growing energy sector. United States Energy Information Administration (EIA) 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 [1]. 285 million tons per year (MTPA) of liquefaction capacity has been proposed in North America alone [2]. New LNG terminals, which are currently under construction, will increase the LNG production by 125 MTPA [3]. In 2014 only, over 297 MTPA world-wide LNG operating capacity was recorded [4].

Over long distances, it is more economical to transport natural gas in the form of LNG, because LNG has over 600 times lower volume compared with the gas phase of the same mass. However, its

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Abbreviations: BOG, boil-off gas; C3, propane; FBOG, boil-off gas from depressurization of LNG after MCHE; FBOG2, boil-off gas from depressurization of liquefied BOG; FL, BOG generated due to depressurization (flashing) of inlet stream; HE, BOG generated due to heat added by equipment like pumps; HL, BOG generated due to heat leak from surrounding into container/pipeline; HT, BOG generated due to hot tank/container; JBOG, boil-off gas from jetty (while loading a Cargo); LIN, liquid nitrogen; LNG, liquefied natural gas; MCXB, main cryogenic heat exchanger bottom section; MCHE, main cryogenic heat exchanger; MCXT, main cryogenic heat exchanger top section; MR, mixed refrigerant; N_2, nitrogen; NG, natural gas; NRU, nitrogen removal unit used for LNG; NRU2, nitrogen removal unit used for BOG; TBOG, boil-off gas from LNG storage tanks; VD, BOG generated due to vapor displacement caused by inlet stream; VRA, vapor return arm.

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bubble point is below −161 °C, which requires a huge amount of energy for liquefaction operations. Note that the huge difference between LNG processing temperature and the ambient temperature can easily cause heat leak in spite of careful insulations. The heat leak makes some LNG vaporize, where the vapors generated are called boil-off gas (BOG). To avoid the overpressure in LNG containers, it is necessary to relieve BOG periodically. BOG mainly contains the lightest compounds from LNG, i.e., methane and nitrogen. Not having proper BOG recovery facility will lead to flaring of BOG, which will result in wastage of material and energy, and environmental pollutions. Limiting climate change [5] would require substantial and sustained reductions in greenhouse gas (GHG) emissions [6]. A range of policies have been made for mitigation of GHG emissions in different sectors, and these policies are being implemented effectively by many countries [7]. Various tools for reduction of GHG emissions include: (a) increase of shares of renewables, (b) increase of energy efficiency, (c) flare minimization through proper planning and scheduling operations, avoiding process upsets, using better process control, utilizing end flash gases, (d) minimize venting and fugitive emissions, (e) use of cleaner fuels, and (f) Carbon capture and sequestration [8]. Methane has about 26 times higher radiative efficiency than CO_2, thus it is more dangerous to release methane into environment [9]. The global CO_2 emissions from flaring of unused gas (natural gas) during oil production was about 250 million tonnes in 2011 [10]. Methane was the second-highest contributor to total GHG emissions during 1990 and 2012 [11]. Therefore, it is important to avoid venting and flaring of boil-off gas.

LNG industries are actually facing BOG problems in different sectors of the LNG supply chain: during LNG production, storage, loading, transportation, and unloading processes. BOG generation during transportation [12–14] and during unloading [15–18] have been addressed in many literatures. However, based on the literature search, it seems that BOG generation at exporting terminals are still lacking systematic studies. Roughly, BOG generations at exporting terminals range from 1% to over 3% of the produced LNG. If they were not recovered and reused, the total amount of material lost world-wide would be at least equivalent to the capacity of one mid-scale LNG plant. Furthermore, due to more intensive global competitions and stricter environmental regulations, BOG flaring is becoming more unacceptable. If this BOG issue at LNG exporting terminals is not addressed properly and in time, losses of valuable materials and energy plus air pollutions would be significantly greater than ever due to the LNG industry expansions worldwide. Therefore, BOG minimization at LNG exporting terminals needs special considerations.

In this study, typical C3-MR process, storage facilities, and loading facilities are modeled and simulated to study BOG generation at LNG exporting terminals, including LNG processing, storage, and berth loading areas. Factors causing BOG are presented, and quantities of BOG generated due to each factor at each location are calculated under different LNG temperatures. Various strategies to minimize, recover, and reuse BOG are also studied for their feasibility and energy requirements. The study would help proper handling of BOG problems in terms of minimizing flaring at LNG exporting terminals, and thus reducing waste, saving energy, and protecting surrounding environments.

2. BOG minimization and recovery strategies and process simulation

There are several main LNG processes used in industries: (1) C3-MR process developed by Air Products & Chemicals Inc.; (2) Cascade process developed by ConocoPhillips; (3) Duel Mixed Refrigerant process by Shell; and (4) Mixed Fluid Cascade process by Linde Engineering. The C3-MR process is used in most LNG plants [19,20]. Therefore, the C3-MR process is used in this study. Steady-state simulation tool Aspen Plus v8.2 software is used to simulate NG liquefaction, LNG loading, and BOG recovery processes.

2.1. Base case simulation

In the base case of C3-MR process, propane is used to precool natural gas while mixed refrigerant is used for chilling process for liquefaction. The simulated C3-MR process is partly based on process flow and process conditions described by Ravavarapu et al. [21]. Soave–Redlich–Kwong (SRK) cubic equation of state is used as the property method based on the suggestion of Aspen Plus for gas processing and hydrocarbon systems. Fig. 1 shows the process flow diagram for this liquefaction process. An LNG plant with 4.3 MTPA capacity is simulated using Aspen Plus v8.2. The feed flow rate is calculated to be 600,000 kg/h. The feed composition is given in Table 1. The sweet natural gas enters the plant at 50 bar and 25 °C. The ambient temperature is set as 15 °C. The natural gas is precooled to −34 °C using propane refrigeration cycle. The mixed refrigerant (MR) cycle is also precooled using propane refrigeration cycle. MR's model composition includes 40% methane, 35% ethane, 15% propane, and 10% nitrogen. After the NG is dried and sent to Scrubber for heavy hydrocarbon removal, it is directed to nitrogen removal unit (NRU) to separate excess nitrogen. There are different methods to remove nitrogen from NG [22–24]. For NRU units in the simulation, it is assumed that 75% of nitrogen from NRU-feed is removed to fuel gas stream coming out of the NRU, and 1.3% of methane from the feed is lost in the fuel gas stream. After NRU, sweet, dry, and pure NG meeting specification requirements is sent to bottom section of main cryogenic heat exchanger (MCHE). It is cooled to −112 °C using heavier part of mixed refrigerant. At this point, natural gas has been in the liquid form at 49.3 bar. However, this temperature is still higher than the bubble point of LNG at the storage pressure. Thus, it is further chilled in top portion of MCHE by the lighter part of MR.

Finally, the LNG exits the main cryogenic heat exchanger at −162 °C and 49 bar with the flow rate of 505,262 kg/h. The composition of this effluent stream is given in Table 1. The LNG flash, storage, and loading sections are simulated as shown in Fig. 2, where the LNG stream from MCHE is flashed to depressurize down to the storage pressure of 1.06 bar at "DEPRESS" tank. The flashing creates BOG, named as FBOG for the flash tank BOG. The pumping and piping system is also simulated in order to include hydraulic calculations, and heat added to LNG by the pumps. The liquid from the flash tank is then pumped to storage tanks through a 12 in. pipeline represented by blocks P1 and P2. The equivalent pipe length from flash tank to storage tanks is assumed to be 1000 m, with an elevation of 60 m (based on the overall height of the storage tank). The total LNG volumetric flow rate fed to storage tanks is calculated as 1133 m^3/h at 1.06 bar.

Two storage tanks ("STORAGE1" and "STORAGE2" in Fig. 2) with LNG storage capacity 168,000 m^3 each are considered in the study. The settings of the inner diameter of the storage tanks is 70 m; the inner height is 43.75 m, such that the D/H ratio 1.6. Above ground full-containment type LNG storage tanks is considered. The tank design, insulation scheme, and heat leak calculations are explained in Section 2.3.1. The produced LNG is equally divided and fed to each storage tanks ("STORAGE1" and "STORAGE2" in Fig. 2). During the storage, BOG generated from storage tanks is named as TBOG.

The LNG ship cargo is considered to have four moss type spherical tanks ("SHIP-T1" through "SHIP-T4") with a total 143,000 m^3 storage capacity. The geometry of the tanks and calculation of heat leak through these tanks are explained in Section 2.3.2. Note that each LNG plant can be different in several aspects such as feed