Simulasi Dinamik Fasilitas Terminal LNG untuk Meminimalisir Boil-Off Gas

Dynamic Simulation of LNG Terminal Facilities to Minimize Boil-Off Gas

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ABSTRAK

Gas alam dicairkan menjadi LNG (Liquefied Natural Gas) untuk mengurangi volume guna mempermudah transportasi. Pada berbagai tahapan rantai pasokan LNG, terutama pemuatan atau pembongkaran, seringkali terbentuk boil-off gas (BOG) akibat penguapan sebagian cairan LNG yang terjadi karena penyerapan panas dari lingkungan sekitarnya. Penelitian ini membahas strategi untuk meminimalkan dan memulihkan BOG di terminal ekspor LNG. Penelitian menggunakan simulasi dinamis berbasis plant-wide untuk menganalisis pembentukan BOG selama mode loading dan unloading, dengan mempertimbangkan berbagai suhu subcooling LNG. Studi ini mengidentifikasi suhu LNG yang optimal untuk mengurangi konsumsi energi total melalui berbagai strategi pemulihan BOG. Dari hasil pengolahan data suhu BOG pada LNG, maka dapat disimpulkan bahwa suhu BOG pada LNG yang tepat di kisaran suhu -162°C. Nilai efisiensi BOG adalah 0,15%. Kompresi BOG untuk digunakan sebagai bahan bakar mesin menghasilkan efisiensi termal hingga 60%. Selain itu untuk meminimalkan BOG pada LNG, gunakan insulasi tangki super efisien, terapkan teknologi Re-Liquefaction (mencairkan kembali BOG), manfaatkan BOG sebagai bahan bakar kapal (terutama dengan mesin dual-fuel), dinginkan tangki sebelum memuat, serta optimalkan operasi dan tekanan pompa saat transfer untuk mengurangi energi panas masuk.

Kata kunci: *Boil-Off Gas, Emisi, Energi, Liquefied Natural Gas, Simulasi Dinamik*

ABSTRACT

Natural gas is liquefied into LNG (Liquefied Natural Gas) to reduce the volume to make transportation easier. At various stages of the LNG supply chain, especially loading or unloading, boil-off gas (BOG) often forms due to partial evaporation of the LNG liquid which occurs due to heat absorption from the surrounding environment. This research discusses strategies to minimize and recover BOG at LNG export terminals. The research uses plant-wide dynamic simulations to analyze BOG formation during loading and unloading modes, taking into account various LNG subcooling temperatures. This study identifies the optimal LNG temperature to reduce total energy consumption through various BOG recovery strategies. From the results of processing BOG temperature data on LNG, it can be concluded that the correct BOG temperature on LNG is in the temperature range of -162°C. The BOG efficiency value is 0.15%. Compressing BOG for use as engine fuel achieves thermal efficiency of up to 60%. Apart from that, to minimize BOG in LNG, use super efficient tank insulation, apply Re-Liquefaction technology (re-liquefy BOG), use BOG as ship fuel (especially with dual-fuel engines), cool the tank before loading, and optimize pump operation and pressure during transfer to reduce incoming heat energy.

Keywords: *Boil-Off Gas, Dynamic Simulation, Emissions, Energy, Liquefied Natural Gas*

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INTRODUCTION

Natural gas production and consumption has increased significantly throughout the world because it is more environmentally friendly than other fossil fuels. Global LNG trade volume continues to set new records every year, as occurred in 2016 when it reached 258 million tons. Natural gas is liquefied into LNG to reduce its volume to 1/600 of normal gas, making it more economical for long-distance transportation. LNG plays an important role in the global energy supply chain.

In the process of liquefying, storing, transporting and loading LNG, BOG (gas that evaporates due to the addition of heat) becomes a significant problem. BOG that is not handled properly causes energy waste, greenhouse gas emissions, and increases operational costs. With increasingly stringent environmental regulations, flaring (burning BOG) is no longer considered an environmentally friendly option. Therefore, efficient methods are needed to minimize and recover BOG. Most previous research focuses on LNG regasification terminals, while studies on the effect of LNG subcooling temperature on BOG reduction at export terminals are still limited.

According to Sugiono (2016), demand for natural gas will increase with an average growth of 5.6% every year, and it is estimated that by 2030, natural gas consumption will reach a quarter of total energy consumption worldwide. Liquefied natural gas or also called Liquified Natural Gas (LNG) is a type of natural gas that is currently in the development stage and is currently widely used. According to Fadel (2022), LNG is natural gas that has been cooled to a temperature of -160°C at a pressure of 1 atmosphere, so that its volume is reduced to 1/600 of its original size when in gas form. According to Nuswantara, et. al (2014), the LNG receiving terminal has several facilities, such as LNG storage tanks, regasification units (BOG), energy supplies, support units for ships entering the port during transportation, as well as other facilities that support the system at the LNG terminal.

According to Ikhwan, et. al (2014), Boil off gas is gas that is formed due to the evaporation process of LNG liquefied gas under atmospheric pressure and as a result of expansion in storage spaces such as tanks. If this gas exceeds the design pressure in the tank, the condition of the tank can become dangerous. To keep the pressure within safe limits, this BOG is usually burned and channeled to the flare. In other words, the plant has discharged clean gas without costing anything. Therefore, a better option is to use the BOG as fuel for factory operations with the help of a compressor. Process modeling is carried out using existing features in HYSYS, then continued with real-time dynamic simulation. According to Prasetya (2021), Aspen HYSYS (Hypothetical System) is a chemical process simulation currently being developed by AspenTech, used to model chemical processes mathematically, from operating units to complete chemical factories and refineries.

According to Muhammad and others in 2023, their study titled "Analysis of the Utilization of the BOG K-6801B/B Compressor at the LNG Hub Facility" found that the Boil Off gas (BOG) coming from the LNG tank enters the compressor at a temperature of -145.5 °C and a pressure of 0.00054 kg/cm^{2}G. After being compressed, the BOG exits the compressor at a temperature of 51.6 °C and a pressure of 15.4 kg/cm^{2}G. After the calculation guide, efficiency dropped by 13% from 98% of the design data to 85%, and efficiency fell by 21% using Hysys, reaching 77%. According to Bouabidi and others in 2021, their study looked at ways to reduce and use Boil-off Gas (BOG) at a real LNG export terminal. The research found that the extra LNG flow that could be achieved was 0.07, 0.03, and 0.022 million metric tons per year for three different methods: standalone LNG sub-cooling, LNG sub-cooling in the main cryogenic heat exchanger, and LFG reflux and boiling gas liquefaction dock. This leads to annual profits of 24.58, 12.24, 8.14, and 7.63 million dollars for an LNG price of 7 dollars per Metric Million British Thermal Unit (MMBtu) LNG. According to Zakaria, et al.(2012), their 2012 study titled "Boil-Off Gas Formation inside Large Scale Liquefied Natural Gas (LNG) Tank Based on Specific Parameters" explains that selecting the right boundary conditions and proper parameters was used to estimate how much BOG evaporates in a particular LNG tank. A three-dimensional cargo model of a ship that can carry 160,000 cubic meters of LNG was chosen as the case for calculations. This model was simulated using ANSYS Fluent with an ambient air temperature of 5 degrees Celsius and an ambient seawater temperature of 0 degrees Celsius. The goal was to calculate the total heat transfer rate and the Boil-Off Rate (BOR). The results indicate that the calculation and simulation model works well with standard LNG ship designs and follows the rules set by the International Marine Organization.

MATERIALS AND METHODS

This type of research is quantitative with simulation techniques using dynamic simulation software Aspen Hysys. According to Giffary, et. al (2024), Aspen Hysys software is a tool that can be used to simulate processes in syngas production. A quantitative approach utilizing the Peng-Robinson (PR) model was employed. According to Petropoulou and Voutsas (2022), the Peng-Robinson (PR) model is an equation of state widely used in hydrocarbon systems due to its ability to accurately predict vapor-liquid phase equilibrium across various pressure and temperature conditions. The materials and tools used to conduct this research are Boil of Gas temperature data on LNG is Aspen Hysys. According to Lande and Kartohardjono (2019), therefore the Dynamic Simulation method was chosen because the Dynamic Simulation method can describe the temperature conditions of the Boil of Gas in LNG. This research method is used to minimize and recover boil-off gas (BOG) at LNG export terminals. The simulation process in the research was carried out using the Aspen Hysys application.

RESULTS AND DISCUSSION

This research was carried out using the Aspen Hysys application. The data used was Boil of Gas temperature data on LNG. Starting from collecting data, identifying data, classifying data, analyzing data and presenting data. This research is used to minimize and restore boil-off gas (BOG) at LNG export terminals. The simulation process in the research was carried out using the Aspen Hysys application.

The Peng-Robinson approach to dynamic Boil-Off Gas (BOG) modeling is a thermodynamic simulation used to calculate the evaporation rate and pressure changes of cryogenic gases (such as LNG) resulting from heat transfer from the environment. It accurately accounts for compressibility factors and real-gas characteristics. This approach employs the Peng-Robinson Equation of State (EoS):

$$P = \frac{R.T}{v-b} - \frac{a(T)}{v(v+b)+b(v-b)} \quad (1)$$

to determine volumetric properties and phase equilibrium. Dynamic inputs include ambient temperature, tank pressure, and cargo composition (methane, ethane, etc.), while dynamic outputs comprise liquid/vapor density, enthalpy, entropy, and vapor fraction as they vary over time. The heat leakage scenario models how ambient heat penetrates the tank's insulation system (e.g., perlite or vacuum insulation). Based on the formula:

$$Q = U.A.\Delta T \quad (2)$$

this heat flux causes the liquid to boil slowly, with daily BOG volumes typically ranging from 0.10% to 0.25% of the total cargo. Regarding the pressure rise and BOG accumulation scenario, a closed-tank condition (such as during storage or transit) triggers a dynamic pressure surge. Mass accumulation: The rate of BOG formation is directly proportional to the heat transfer rate divided by the latent heat of vaporization. Pressure rise: The buildup of vapor in the headspace increases the system pressure, a process modeled in a step-by-step manner over time. Operational Scenario (BOG Release & Handling): To maintain tank integrity and prevent overpressure, dynamic scenarios are typically simulated through mitigation measures such as re-liquefaction, where BOG is compressed and cooled back into a liquid to be returned to the tank and use as ship engine fuel (via a Gas Combustion Unit/GCU), where BOG serves as an energy source to drive turbines or main engines. The simulation duration (t) for the BOG process in this Aspen Hysys simulation is set to 24 hours.

The following is the LNG feed composition data in Table 1, as follows:

Table 1. LNG Feed Composition Data

Composition	Mole Fraction
Nitrogen	0,0027
Carbon Monoxide	0,0000
Methane	0,9511
Ethane	0,0461
Propane	0,0002
i-Butane	0,0000
n-Butane	0,0000
i-Pentane	0,0000
n-Pentane	0,0000
n-Hexane	0,0000
Total	1,0000

The following is Boil of Gas Temperature data for LNG in Table 2, as follows:

Table 2. Boil of Gas Temperature Data on LNG

Simulation	Temperature (^{0}C)
1	-158
2	-159
3	-160
4	-161
5	-162
6	-163
7	-164
8	-165
9	-166
10	-167
11	-168

The following is a dynamic simulation diagram for Aspen Hysys in Figure 1, as follows:

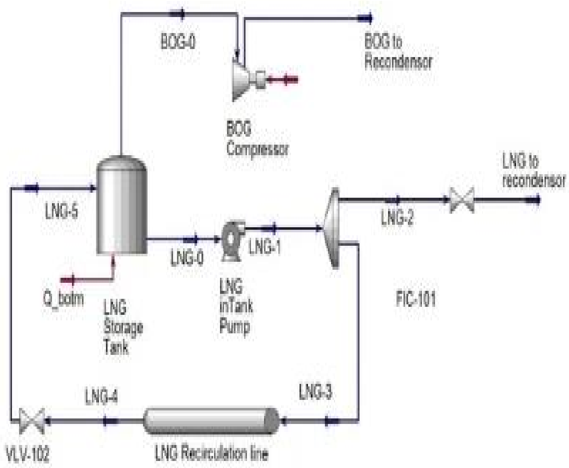

Figure 1. Dynamic simulation diagram on Aspen Hysys

The table shows the tank size and other important details needed to calculate the Boil-Off Gas (BOG). The main assumptions that are used when calculating Boil-Off Gas are listed below :

a. It is assumed that the temperature along the tank walls and the insulation stays the same.
b. Temperature does not vary with tank height;
c. The heat coming in from solar radiation through convection or conduction is not considered.
d. The liquid (LNG) and vapor (BOG) phases are considered to be thoroughly mixed with no layering.
e. Mass and heat are transferred between the storage stages, which include LNG and BOG.

The following is LNG storage tank model parameters and simulation basis in Table 3, as follows:

Table 3. LNG storage tank model parameters and simulation basis.

Tank Dimensions and Heat Transfer Parameters	Values	Units
Volume	260000	m^3
Diameter	90	m
Height	41	m
Top Side HTC	0,02371	W/m^2-K
Shell Vapour Side HTC	0,02121	W/m^2-K
Shell Liquid Side HTC	0,02136	W/m^2-K
Vapour-Liquid Interface HTC	4,0	W/m^2-K
Tank Bottom Temperature Maintained	5	^{0}C
Ambient Temperature	25	^{0}C
Tank Pressure	1,17	Bar
LNG Density	455,5	kg/m^3
Latent Heat of Vaporization of LNG	510	KJ/kg
Methane	0,9984	mole fraction
Nitrogen	0,0015	mole fraction

Using the assumptions and the chosen parameters from Table 3, the model in Figure 1 calculates a steady heat leak rate. It's important to note that the BOG in an LNG tank happens because heat enters the tank and the recirculation lines, plus the pump inside the tank works harder due to the recirculation. When the recirculation rate stays the same, a little bit of heat is slowly added to the tank.This amount of heat is very small compared to the heat that escapes from the tank.The heat created by the pump is removed from the tank by moving the LNG through it. So, the main reason BOG forms in the tank is because heat from the surroundings leaks into it. The Aspen Hysys tank module, along with some theoretical adjustments, is used to model heat leaks. From the diagram above, it is explained that in the dynamic simulation using Aspen Hysys for the boiling temperature of gas in LNG, the correct temperature range is -162 degrees Celsius.

The following graph shows the fluctuations in tank pressure and boil-off gas rate over the course of operations :

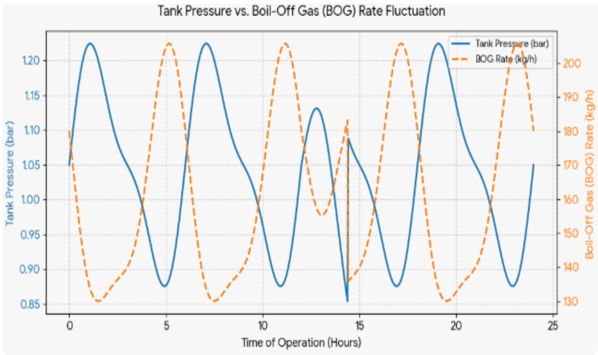

Figure 2. The tank pressure and boil-off gas rate graphs fluctuate over the course of operations.

Total BOG mass flow rate per day is 161 kg/h, so per day is 3864 kg/day, and the recovered BOG mass flow rate is 58 kg/day. The Boil-Off Gas (BOG) efficiency value is calculated as follows: BOG Efficiency = (Recovered BOG mass flow rate / Total BOG mass flow rate) x 100% = 58 kg/day / 3864 kg/day = 0,15%. The results obtained apart from setting the right temperature at -162^{0}C, there are other ways to minimize Boil-Off Gas (BOG) in LNG, namely using super efficient tank insulation, applying Re-Liquefaction technology (re-liquefying BOG), using BOG as ship fuel (especially with dual-fuel engines), cooling the tank before loading, and optimizing pump operation and pressure during transfer to reduce incoming heat energy. The simulation duration (t) for the BOG process in this Aspen Hysys simulation is set to 24 hours. Boil-Off Gas (BOG) efficiency refers to the utilization ratio of liquefied natural gas vapors that evaporate naturally within storage tanks or vessels. Compressing BOG for use as engine fuel (such as for ship generators) achieves thermal efficiency of up to 60%. This reduces operational costs by converting waste gas into a primary energy source. In Technology and Systems, you can apply Re-Liquefaction, namely a system that captures BOG and returns it to liquid LNG, then flows back to the main tank, reducing cargo loss significantly. In Cryogenic Tank Insulation, the storage tank is very well insulated to maintain very low temperatures and minimize heat transfer from the outside. The BOG Compressor is compressing BOG for use as fuel in terminals or on ships (such as in DFDE engines), or sent to high pressure gas pipes. In operational practice, tank cooling can be applied, namely cooling the cargo tank before loading LNG to reduce the initial evaporation rate. In Pump and Compressor Optimization, namely reduce the discharge pressure of the pump when loading and the BOG compressor to reduce the incoming energy and cause evaporation. In Ship Management, namely Use BOG as fuel for the ship's main engines (for example, dual-fuel diesel electric / DFDE engines) to save LNG cargo, increase efficiency and reduce emissions. Calculation and Design by means of Design Simulation, namely by designing the tank by simulating the heat entering from the atmosphere (dome, walls, bottom) to ensure the BOG rate is within safe and economical limits. By utilizing BOG, compressed BOG fuel can be used as fuel for power plants, for ship internal purposes, or sent to gas pipeline networks.

CONCLUSION

Based on the results of processing Boil of Gas temperature data on LNG. So it can be concluded that the correct Boil of Gas temperature for LNG is in the temperature range of -162^{0}C. Apart from that, to minimize Boil-Off Gas (BOG) in LNG, use super efficient tank insulation, apply Re-Liquefaction technology (re-liquefying BOG), use BOG as ship fuel (especially with dual-fuel engines), cool the tank before loading, and optimize pump operation and pressure during transfer to reduce incoming heat energy. The Boil-Off Gas (BOG) efficiency value is 0,15%. Boil-Off Gas (BOG) efficiency refers to the utilization ratio of liquefied natural gas vapors that evaporate naturally within storage tanks or vessels. Compressing BOG for use as engine fuel (such as for ship generators) achieves thermal efficiency of up to 60%. This reduces operational costs by converting waste gas into a primary energy source. In order to minimize and restore boil-off gas (BOG) at the LNG export terminal, the following activities that can be carried out are to get used to following operational standards when loading and unloading LNG, check the condition of LNG temperature, tank temperature and ambient temperature and ensure that human resources and all equipment are functioning properly. The results obtained are expected to provide benefits for environmental sustainability, in the form of reducing emissions and for the LNG industry in the form of saving raw materials and energy as well as increasing productivity.

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