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Estimation of Boil-off-Gas BOG from Refrigerated Vessels in Liquefied Natural Gas Plant

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ABSTRACT

This research describes techniques for estimating the boil-off gas generation rate from refrigerated vessels of liquefied natural gas plant. Appropriate thermodynamic, heat transfer due to heat-ingress in radiation, convection and conduction and displacement functional equations were utilized to bring the research to fruition. The BOG computing process was made possible by considering the heat leaks into loading and circulation pipelines, heat ingress from loading and circulation pumps and vapourized products from flashing refrigerated product. The aggregate results from these five points of BOG losses stood at 35,458.20 kg/hr and its cash equivalent loss at $16,636.88/hr @ $9 per MMBtu of LNG.

Keywords: *BOG generation, Heat-ingress via radiation-convection-conduction, Refrigerated storage vessel, liquefied natural gas, and Thermodynamic equations*

1. INTRODUCTION

Petroleum consists of many components of which natural gas NG is one of the components. In Nigeria, estimated natural gas reserve capacity is 187 trillion cubic feet and United States Geological Survey USGS study estimates the gas reserves potentiality in Nigeria could be as high as 600 trillion cubic feet**.** And Nigeria is the seventh largest producer of natural gas in the world **[1]**. Natural gas has been proved to be the cleanest burning fossil fuel and more economical world-wide. This is because, when combusted it emits less emission particles and pollutants to the atmospheres. Therefore, it is accepted as being of immense energy sources for domestic and industrial purposes. During its processing a lot of gas is being vaporized and displaced from storage vessels or containers .The minimization of vaporization and displacement losses from storage vessels become very imperative for investigations **[2]**. Natural gas is being processed into liquefied natural gas (LNG) because it is more economical to transport it in this form to prospective buyers. Since pipeline transportation is not feasible for long distances natural gas is liquefied stored in containers for ship loading. Another alternative to liquefied natural gas is liquefied petroleum gas produced by refining petroleum during the refining of crude oil or separating gas streams obtained from reservoirs. The LPG includes C_3 and C_4 -fractions and can be transported as pure C_3 , pure C_4 or a mixed LPG i.e a blend of C_3 plus C_4 at specified ratio to meet standard specifications i.e 70 percent C_3 and 30 percent C_4. Liquefied petroleum gas can evaporate at normal temperatures and pressures. It is also stored in refrigerated specially designed vessels in the refineries. Its storage is near its bubbling temperature at almost atmospheric pressures.

As it is expected from process plant point of view, a storage vessel is not pumped completely dry when emptied. The vapours above the remaining liquid will expand to fill the void space at the liquids vapour pressure at storage temperature. As the vessels fill, vapours are compressed into smaller void space until the set pressure on the relief system is reached. Some filling losses are associated with the liquid expansion into the vessel. The vapors emitted from storage vessel relief valves are generated in two ways:

- Vapours which are generated by liquid vaporization stored in storage vessel.
- Storage vessel vapours forced out during filling operations (Displacement losses)

The vaporization and displacement losses are basically sources of BOG generations of interest for gas processing activities. Essentially, there are two types of storage classifications, above ground and underground. Categories include; Atmospheric, Low pressure (0 to 17 KPa), Medium pressure (17 to 100 KPa), High Pressure (at Pressures above 100 KPa) **[2]** and underground.

Atmospheric are cylindrically designed tanks for content storage at atmospheric pressure. They range from small shop-welded tanks to field-erected tanks. They are bolted tanks and, usually, rectangular welded tanks are also used for atmospheric storage purpose. Low pressure is applied for storage of intermediates and product that require an internal gas pressure from close to atmospheric. They are cylindrical in shape with flat or dished bottoms and sloped or domed roofs. Also, bolted tanks are often applied for operating pressures near atmospheric. Many refrigerated storage vessels operate at approximately 3.5KPa. Medium pressure used for storage of higher volatility intermediates and products that cannot be stored in dished bottoms and sloped or domed roofs. High pressure storage tanks are generally used in the refineries for the storage of refined products or fractionated components of petroleum ex-crude distillation unit at pressures above 100 KPa (ga). Finally, underground storage is applied for liquids used for gas processing. There are no standard procedures for this type of storage except there some publications and books on the subject in detail.

1.1 Conceptual Framework

Vaporization Losses are encountered through vapors generated by heat gained through the shell, bottom and roof vessels. The total heat input is the algebraic sum of the three modes of heat transfer which are radiant, conductive and convective heat transfer. This type of loss is especially prevalent where light HC liquids are stored in full pressure or refrigerated storage. They are less prevalent but still quite common in crude oil and finished product tanks. This vapor can be recovered by using the vapor recovery systems.

Displacement losses are losses made up of combined loss from filling and emptying is considered a working loss or displacement loss. As liquid level increase, the pressure inside the vessel exceeds the relief pressure and vapors are then expelled from the vessel. During emptying of liquids product evaporative loss occurs, and air is drawn into the tank during liquid removal, it become saturated with organic vapors and expands, thereby exceeding the vapor space capacity.

1.2 BOG LNG in Process Plant

Ideally, BOG is tenaciously associated with process plant operations/activities. Because, LNG and LPG are stored at cryogenic temperatures, there is continuous boil-off of small fraction or portion of LNG due to warming during transport and storage. This boil-off gas is generated primarily due to heat leakage from the atmosphere through tank insulation, unloading and recirculation-line insulation. As stated earlier, heat leakage also occurs from the loading and recirculation-pumps energy and gas displacement from LNG storage tanks during filling or unloading of ship tanks. BOG is also generated intermittently during cooling of loading pipelines which must be chilled to loading temperatures.

2. MATERIALS AND METHOD

The material concepts for implementing of the research are obtained from Nigerian Liquefied Natural Gas process plant located at Bonny, Rivers State. The material data are in respect of heat leak sources stated as follows: Heat leak into storage tank, heat leak into loading and circulation pipelines, heat-ingress from loading and circulation pumps, vapour displaced during loading and vaporized product from flashing refrigerated product. These heat leak sources are considered in calculating BOG rates.

However, calculating BOG rates and determining BOG Compressor capacity involves the chemical engineering principles of radiation, convection and conduction of heat transfer modes **[3,5]** , in estimating the quantity of BOG given-off from LNG storage vessels due to heat-ingress will be determined using appropriate mathematical equations stated in (2) to (3). As earlier stated, that BOG-vapours' generated is as a result of heat leakages (heat in-leak) from refrigerated vessel facilities. The re-liquefaction system capacity i.e BOG compressor capacity can be determined from the various sources of heat leaks into the system, product loading activities and feed conditions. The BOG rates and compressor capacity can be designed on the conditions defined for specific refrigerated storage vessels. The main scenarios considered for LNG vessels are the unloading, holding with no cooling of loading line and holding with cooling of loading line. Therefore, BOG rates depend on the following identified scenarios:

2.1 Heat Leak into Storage Vessel

Theoretical model equations for application are based on the heat transfer through the storage vessels shell, bottom and roof (top). To calculate/estimate the generated BOG flow rate in storage vessels, effects of radiant, conductive and convective heat inputs to the storage vessel are combined for adequate estimates. Although, some assumptions of proper design and selection of insulation materials to prevent or minimize heat leaks or losses from storage vessels are made, still heat can be transferred to the refrigerated product contained in the vessel, and from the environment due to ambient temperature, solar and wind speed. An approximate BOG generation value can be calculated by dividing the total heat input by the latent heat of the refrigerated product at fluid temperature. A typical BOG rate can be estimated by the model equation (1), by the application of the coefficients for percentage of the refrigerated storage vessel working volume per day **[3,4] .** Generally stated as,

BOG Rate due to Heat Ingress to Storage Tanks.

$$BOG_T\ (kg/hr) = \frac{\alpha \rho_{product} V_{tank}}{24} \quad (1)$$

Heat Leak into Loading and Circulation Pipelines.

$$P_r = \frac{c_{p\,air}\mu_{air}}{k_f} \quad (2)$$

$$R_e = \frac{u \times D \times \rho_{air}}{\mu_{air}} \quad (3)$$

$$Q_L = \frac{2\pi L\left[\left(\frac{T_\infty + T_S}{2} - T_i\right)\right]}{\frac{1}{h_0\, r_0} + \ln \frac{\frac{r_0}{r_i}}{k_{ins}}} \quad (4)$$

$$NU_D = \frac{h_0 D}{k_f} = 0.3 + \frac{0.62 Re^{\frac{1}{2}} Pr^{\frac{1}{3}}}{\left[1+\left(\frac{0.4}{\mathrm{Pr}}\right)^{\frac{2}{3}}\right]^{\frac{1}{4}}}\left[1+\left(\frac{Re}{282000}\right)^{\frac{5}{8}}\right]^{\frac{4}{5}} \quad (5)$$

$$\mathrm{BOG_L} = 3.6 Q_L \left(\frac{\beta}{\lambda}\right) \quad (6)$$

Heat Ingress from Loading Pumps.

$$Q_p = \frac{mgH}{3600}\left(\frac{1}{\xi} - 1\right) \quad (7)$$

$$BOG_P = 3.6 \frac{Q_P}{\lambda} \quad (8)$$

The main conditions considered when calculating the BOG for LNG storage tanks are unloading, holding without cooling of loading path and holding with cooling of loading path. Hence, BOG rate depends on the following identified parameters and constants in table1: [6]

Table 1: Nigeria LNG Process Plant Data and Constants for Liquefied Natural Gas

Plant Data and Constants	Values
Storage tank operating pressure	90m barg
Density	$455.5 kg/m^3$
Operating pressure at ship inlet	$70m\ barg$
Ship tank's operating pressure	$0\ barg$
Run down operating pressure	$28\ barg$
Run down temperature	$-161°C$
BOG pressure at storage tank inlet	$6\ barg$
BOG temperature at storage tank inlet	$-127\ °C$
Ambient temperature	25.3°C
Sunlit temperature	23.61°C
Thermal conductivity of ambient air	0.027W/m°K
Specific heat ambient air	1005J/kg°K
Viscosity of ambient air	$1.9 \times 10^{-5} kg/m.s$
Density of ambient air	1.127kg/m^3
Tank capacity	$84{,}200 \times 4\ \ tanks$
LNG Storage tank filling rate	1000 m^3/hr
LNG Ship's tank loading rate	10000 m^3/hr
Diameter of run down line	16 inches = 0.41m
Length of run down line	400m
Diameter of loading line	24 inches = 0.61m
Length of loading line	1000m
Insulation thickness	0.23m
Thermal conductivity of insulation	0.04W/m°K
Pump head of LNG pumps	146.2 m
Efficiency of LNG pumps	80%
Latent heat of LNG	510 kJ/kg
Design margin	1.1
Safety factor	1.05

For LNG: $\alpha = 0.04\% - 0.06\%$,

For LPG (Propane, Butane and their mixture): $\alpha = 0.06\% - 0.1\%$ **[2]**

Heat leak into loading and circulation pipelines.

The other main heat in-leak to refrigerated facilities that contributes to BOG generation is heat leak via piping and pipe lines through insulation. Loading pipelines, BOG and run down lines are some of the main pipes to consider when calculating BOG rate.

The equations below can be used to calculate the heat ingress into the above ground pipes:

$$P_r = \frac{C_{p\,air}\mu_{air}}{kf}$$

$$P_r = \frac{1{,}005 \times 1.93 \times 10^{-5}}{0.0027} = 0.71$$

$$R_e = \frac{u \times D \times \rho_{air}}{\mu_{air}}$$

$$R_{e\,0.41-m.} = \frac{6.5 \times 1.127(0.41 + 4 \times 0.23)}{1.9 \times 10^{-5}} = 393{,}263.7$$

$$R_{e\,0.61-m} = \frac{6.5 \times 1.127(0.61 + 4 \times 0.23)}{1.9 \times 10^{-5}} = 453{,}765.8$$

$$h_{0,0.41-m.} \frac{0.027}{1.33}\left[0.3 + \frac{0.62 \times .393363.7^{\frac{1}{2}} \times 0.71^{\frac{1}{3}}}{[1 + (0.4/0.7)^{\frac{2}{3}}]^{\frac{1}{4}}}\left[1 + \left(\frac{393{,}263.7}{282000}\right)^{\frac{5}{8}}\right]^{\frac{4}{5}} K\right] = 11.59W/m^2K$$

$$h_{o,0.61-m.} \frac{0.027}{1.53} = \left[0.3 + \frac{0.62 \times 453{,}765.8^{\frac{1}{2}}.15 \times 0.71^{\frac{1}{3}}}{\left[1 + (0.4/0.7)^{\frac{2}{3}}\right]^{\frac{1}{4}}}\left[1 + \left(\frac{453{,}765.8}{282{,}000}\right)^{\frac{5}{8}}\right]^{\frac{4}{5}}\right] = 11.46W/m^2K$$

$$Q_L = \frac{2\pi L\left[\left(\frac{T_\infty + T_s}{2} - T_i\right)\right]}{\frac{1}{h_0\, r_0} + ln\ \frac{\frac{r_0}{r_i}}{k_{ins}}}$$

$$Q_{L,0.41-m.} = \frac{2 \times 3.142 \times 400[24.5-(-161)]}{\frac{1}{11.59 \times 0.435} + ln\ \frac{0.435}{0.205}/0.04} = 24{,}583.11\ W$$

$$Q_{L,0.61-m} = \frac{2 \times 3.14 \times 1000[24.5-(-161)]}{\frac{1}{11.46 \times 0.535} + ln\ \frac{0.535}{0.305}/0.04} = 82{,}207.29W$$

$$NU_D = \frac{h_0 D}{k_f} = 0.3 + \frac{0.62 Re^{\frac{1}{2}} Pr^{\frac{1}{3}}}{\left[1 + \left(\frac{0.4}{P_r}\right)^{\frac{2}{3}}\right]^{\frac{1}{4}}}\left[1 + \left(\frac{Re}{282000}\right)^{\frac{5}{8}}\right]^{\frac{4}{5}}$$

$$NU_{D,0.41-m.} = \frac{h_0 D}{k_f} = 0.3 + \frac{11.59 \times 0.26}{0.027} = 112.0$$

$$NU_{D,0.61-m.} = \frac{h_0 D}{k_f} = 0.3 + \frac{11.46 \times 0.26}{0.027} = 111.0$$

$$\mathrm{BOG_L} = 3.6Q_L\left(\frac{\beta}{\lambda}\right)$$

$$\mathrm{BOG_L} = 3.6(24583.11 + 82207.0)\left(\frac{1.05}{510}\right) = 791.51\ Kg/hr$$

Heat ingress from loading pumps.

The equations below estimate the quantity of BOG generated based on the heat ingress from loading pumps

$$Q_p = \frac{mgH}{3600}\left(\frac{1}{\xi} - 1\right)$$

$$Q_p = \frac{10300 \times 455.5 \times 9.8 \times 146.2}{3600}\left[\frac{1}{0.80} - 1\right] = 466{,}806.14W$$

$$BOG_P = 3.6\frac{Q_p}{\lambda}$$

$$BOG_p = 3.6\left[\frac{466{,}806.14}{510}\right] = 38295.10\ kg/hr \times 3\text{pumps} = 9855.31\ kg/hr$$

BOG Rate due to Vapour Displacement

ρ_{vapour} at storage tank/ ship's tank = $1.77/1.78 kg/m^3$

$$\text{From Ship's tank } BOG_v = 1.78 \times 10300 = 18{,}334.0\ Kg/hr$$

$$*From\ Storage\ Tank\ 1-4\ BOG_v = (1.77 \times 1095) \times 4 = 7752.6 kg/hr$$

BOG rate due to flashing of run down methane in storage tank by simulation, is assumed to be;

$BOG_f = 10000 Kg/hr$ at minimum operating pressure

Total generated BOG rate (kg/hr)

$$\mathrm{BOG} = (BOG_T + BOG_L + BOG_P + BOG_V + BOG_F)$$

$$\mathrm{BOG} = (3835.31 + 791.51 + 9855.31 + 7752.6 + 10000) kg/hr \times 1.1$$

Total BOG = $35{,}458.20\ kg/h$. Its cash equivalent is given as 35,458.20 Kg/hour and $16,636.88 (@ $9 per mmBtu.

3. RESULTS AND DISCUSSION

This research investigated BOG loss in liquefied storage tanks facilities which is a function of two major sources that is displacement BOG loss and heat ingress (radiation, convection and conduction modes) to storage vessels which results in vaporizations forces. The displacement loss, heat ingress, and loading facilities are dependent on operating parameters. These parameters are the primary state functions upon which BOG studies are based. The results of the research are based on the heat leaks into loading and circulation pipelines, heat-ingress from loading and circulation pumps, vapour displaced during loading and vaporized products from flashing refrigerated product, and are presented in quantity of Boil-off gas in kilogram per hour and its cash equivalent in the spot LNG market as 35,458.220 Kg/hour and $16,636.88 (@ $9 per mmBtu).

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NOMENCLATURE

BOG: Boil- off gas rate due to heat ingress , kg/hr.
d: Insulation thickness, m.
D: Outside diameter of pipe plus insulation thickness, m.
h_0: Heat transfer coefficient,$W/m^2/K$.
k_f : Thermal conductivity of ambient air,$W/m/K$.
k_{in} : Thermal conductivity of insulation,$W/m/K$.
L: Length of pipe, m.
NU_D: Nusselt number.
Pr: Prandtle number.
Q_L: Heat ingress to pipes, W.
Re: Reynolds number.
r_i: Radius of pipe,$D/2$, m.
r_0: Radius of pipe plus insulation thickness, $r_i + d/2, m$.
T_∞: Ambient temperature, °C.
T_i: Fluid temperature, °C.
T_s: Sunlit temperature, °C.
β: Safety Factor.
λ: Latent heat of product, kJ/kg.
g: gravity acceleration , m/s^2.
m: Pump capacity, kg/hr.
Q_p: Heat ingress from pump.
ξ: Pump efficiency.