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Economic Implication of Boil-Off Gas Generation in Liquefied Petroleum Gas Supply Chain

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ABSTRACT : *This study is carried out to analyze the economic cost of boil-off gas generation rate in the liquefied petroleum gas (LPG) supply chain. It includes analysis of the heat absorbed from ambient air by the storage tank and pipelines, and heat produced by the operation of the transfer pump that leaks into the LPG in the skid plant, which consequently generates boil-off gas in the supply chain, by utilizing appropriate thermodynamic and heat transfer equations. Analyzing the heat leakage required the estimations of the convective heat transfer coefficient of the ambient air in the supply location and the LPG in the supply chain, which amounted to 3335.9W/m^{2}K and 21.058W/m^{2}K, respectively, in the system under study. The heat absorbed in the LPG from the ambient air by the storage tank and pipelines amounted to 1.785kW and 0.0368kW, respectively, and the heat produced by the operation of the transfer pump that leak into the LPG, amounted to 3.214kW. The total boil-off generation rate due to the storage tank heat leakage, pipeline heat leakage, heat produced by the operation of pump and vapor displacement in the storage tank is 0.0293kg/s, which translates to a cost equivalent loss of 15.14₦/s at LPG selling price of 516.4₦/kg.*

KEYWORDS -*Boil-off gas, Boil-off gas generation rate, Cost equivalent of loss LPG, Heat leakage via convection, conduction and radiation, LPG skid plant*

I. INTRODUCTION

Liquefied petroleum gas (LPG) is propane, butane, isobutane, or mixtures of these gases, which are extracted from natural gas production fields or produced during the refining of petroleum (crude oil). LPG is stored and transported in steel cylindrical tanks as liquid under sufficiently high pressure [1]. To allow for thermal expansion, these tanks are typically filled to between 80% and 85% of their capacity [2]. The approved Nigeria LPG composition, for domestic consumption is 100% butane or a mixture of 85% butane and 15% propane [3].

LPG is used as fuel gas in heating appliances, cooking equipment, and vehicles. It also powers many business and agricultural processes. LPG is increasingly used as an aerosol propellant and a refrigerant, replacing chlorofluorocarbons in an effort to reduce damage to the ozone layer [4]. In Nigeria, LPG has received increasing attention, especially now that the government has positioned LPG as an alternative for the eventual replacement of firewood and kerosene as domestic cooking fuel, and also canvassing the use of LPG as vehicle fuel (auto gas) for transportation [5]. These have resulted in the emergence of a lot of LPG skid plants nationwide, without proper boil-off gas (BOG) recovery system. Thus, rises safety and profitability concern [6].

However, government is encouraging technology development and safety enhancement to support sustainable LPG business growth [7]. The generation of boil-off gas in the storage tank continued causing losses in the LPG supply chain over time [8]. BOG is the continuously evaporated or boiled LPG vapor that causes the pressure inside the storage tank to rise due to heat leakage during transportation, storage, loading and dispensing, which may also change the quality of LPG over time [9]. The heat leakage result from the temperature difference between the ambient air and LPG supply system. BOG generation in LPG supply chain is one of the most important factors for safety and economic assessment of LPG skid plant [10].Thus, has become one the most significant research interest.

Reference [11] studied the effect of surrounding temperature on liquefied petroleum gas behavior inside a storage cylinder during exhaustion process. The study was experimentally carried out at surrounding temperatures of 10°C to 35°C. The results show that LPG exhaustion operation at the surrounding temperature of 25°C or higher, exhibited significant temperature and pressure profiles which explained a considerable reduction of the LPG residue. Also, radial and axial thermal distribution analysis inside the cylinder indicated that sensible heat needed for the evaporation process was derived mainly in the axial direction at the regions adjacent to the internal wall.

Reference [10] examined the problem of evaporation of liquefied petroleum gas occurring at different places in the supply chain. Having identified evaporation losses in the liquefied petroleum gas supply chain as one of the key factors for safety and economic assessment, they presented the general methods of handling and utilizing the BOG at different points in the liquefied petroleum gas supply chain.

Reference [12]carried out a parametric analysis on BOG rate inside LPG storage tanks to determine the relationship between thermal transmittance and ambient condition for both the steady and unsteady behavior of the heat transfer mechanisms using ANSYS Fluent software. Results from the dynamic transient simulation that took effect on the first five days of a voyage show that there is a linear relationship between the investigated parameters, which include volume and temperature, and BOG rate.

Reference [13] presented a paper on maintaining higher efficiency of LPG butane boil-off gas re-liquefaction in LPG butane storage tanks using unsteady state process simulation. In the paper, hypothesis was made that by continuously venting small amounts of non-condensable gas (NCG), higher reliability of the storage tank pressure control performance was achieved. A strategy to improve the NCG butane BOG venting control system was also formulated using unsteady state analysis of LPG butane tanks and butane BOG re-liquefaction. HYSYS simulator software in dynamic condition was employed to analyze the unsteady state tank behavior, and the result showed that the LPG Butane Storage and Loading efficiency was dramatically improved from 91.42% to 99.96%. This improvement reduced the annual production loss, which was 200,000 USD of 500 Million USD LPG product value, for the facility under study.

Reference [14]carried out performance analysis of LPG storage tanks in refueling stations. In their analysis, time-dependent thermodynamic models were developed to evaluate the LPG holding time in the storage tanks before BOG releases to the atmosphere. Factors such as the thermal mass of the tanks and the actual operating conditions at refueling stations, were included explicitly in the models. The results showed that the thermal mass of the storage tanks had direct impact on LPG holding time and BOG generation rate.

Reference [15] worked on optimization of propane reliquefaction cycle in an LPG Plant, which was aimed at minimizing BOG on propane tanks. The optimization work was conducted on the compressor cooler exit unit, and it involving varying heat flux and heat transfer surface area which affect the investment cost. The optimization resulted in decrease in the compressor work from 213.04kJ/kg to 179.92 kJ/kg and recovered the coefficient of performance of the reliquefaction cycle to 2.16 from 1.90.

Reference [16] carried out an optimization study on the reliquefaction of boil-off gas from a liquefied petroleum gas storage tank. The study compared single and two-stage refrigeration cycles, using propane as a refrigerant for a vapor recompression refrigeration cycle. Soave-Redlich-Kwong equation of state model with Twu's alpha function was selected for the modeling and optimization of the refrigeration cycle for the reliquefaction of BOG coming out from the tank. The result obtained from the optimization work shows that in the two-stage refrigeraton cycle, 24.8% of compressor power was reduced compared to that of single-stage refrigeration cycle.

Reference [17]presented an article on LPG accounting specificity during its storage and transportation. The article considered the measurement and calculation of LPG volume in a tank, to estimate the resulting errors from the calculation. They reported that the errors that impact the LPG volume calculation includes the reservoir graduation error, the level measurement error, the temperature measuring error, which have to be reduced to the standard temperature conditions of 15°C while calculating volume of quantity of LPG, and the incorrect data of LPG liquid/vapor phase composition.

Reference [18] presented a paper on energy saving through efficient BOG prediction and impact of static boil-off-rate in full containment-type LPG storage tanks. The paper investigated the impact of static boil-off rate on BOG predictions, and the results suggested that boil-off rate is a strong function of liquid level in a tank. Also, total heat leakage rate in a tank rate practically remains constant, and the unequal distribution of heat in vapor and liquid at lower and higher liquid levels gives variations in the boil-off rate. They reported that the boil-off rate varies from 0.012wt% per day for an 80% tank fill to 0.12wt% per day at 10% tank.

Reference [19] carried out a study to develop and evaluate various handling schemes to minimize and/or recover the generated BOG from an actual baseload LPG export terminal with a capacity of 554 million standard cubic feet per day of natural gas feed. Three scenarios were assessed for the study which include jetty BOG re-liquefaction, LPG sub-cooling, and lean fuel gas reflux. Steady state models for these scenarios were simulated using Aspen Plus computer software to determine the promising options that should be considered for further rigorous analysis. The results indicated that the flow of attainable excess LPG was 0.07, 0.03, and 0.022 million metric tons per annum for LPG sub-cooling, lean fuel gas refluxing and jetty boil-off gas re-liquefaction, respectively, which in turn resulted in a profit of 24.58, 12.24 and 8.14 million dollars per year, respectively.

Reference [20] studied practically, the prediction of boil-off rate of independent-type storage tanks. In their study, experimental and numerical analyses were conducted to predict the boil-off rate of a cubic International Maritime Organization Type C independent tank for small ships. In the experiment, the boil-off rate was measured using a weighing scale and thermocouples which were welded on the tank, and used to analyze the surface temperature according to the filling ratio. They concluded that under high filling ratios, the amount of boil-off generation was smaller, and the boil-off rate of the designed cubic tank was slightly larger than that of the storage tank for commercial ships by approximately 35%. They further concluded that the rate of BOG as predicted through finite element analysis was within 1% of error when compared to an empirical correlation applied to the designed fuel tank.

Having reviewed literatures, one of the crucial factors in the LPG supply chain is the generation of BOG which continued to cause evaporation losses, that would determine the safety and economic assessment of the LPG in a skid plant. This present study takes the PEL Gas LPG skid plant located in Port Harcourt, and manufactured by Hubei Chusheng Limited, as a case study to analyze the heat leakages via convection, conduction and radiation that may contribute to boil-off gas generation in the skid plant, and the economic cost of the boil-off gas generation.

II. MATERIALS AND METHODS

The materials for this study include the LPG skid plant catalogue, data of thermophysical properties of LPG (butane) and the ambient air, data of ambient climate conditions of the plant location (Port Harcourt), and PEL Gas LPG skid plant facility inventory record. The methods that have been used in the study are discussed in the following sections:

2.1 Data Collection

The data used in this study include the LPG skid plant technical parameters obtained from the LPG skid plant catalogue [21], thermophysical properties for the LPG (butane) obtained from reference [22],thermophysical properties for the ambient air obtained from reference [23], ambient climate condition and other physical properties of the skid plant obtained from the various measuring and monitoring instruments fitted to the plant and recorded in facility inventory record. The operational environment of the LPG skid plant used in this study is Port Harcourt, Nigeria, which has a tropical climate, with an average annual temperature of 26°C The annual average speed of air experienced in Port Harcourt is 2.32m/s. Table 1 summarizes the collected data.

Table 1: Thermophysical Properties of LPG (Butane) and Ambient Air

Fluid	Properties	Value
LPG (Butane)	Temperature	291K (18ºC)
	Pressure	200kN/m^2 (2bar)
	Liquid density	585kg/m^3
	Vapor density	5.17kg/m^3
	Liquid viscosity	175$\mu Ns/m^2$
	Latent heat of vaporization	367kJ/kg
	Liquid thermal conductivity	109.2mW/mK
	Liquid Prandtl number	3.99
Air	Temperature	299K (26ºC)
	Pressure	103.3kN/m^2(1bar)
	Speed	2.32m/s
	Density	1.18kg/m^3
	Viscosity	0.1854$\mu Ns/m^2$
	Thermal conductivity	0.02558W/mK
	Prandtl number	0.7280

Source: [24]

2.2 Description of LPG skid plant

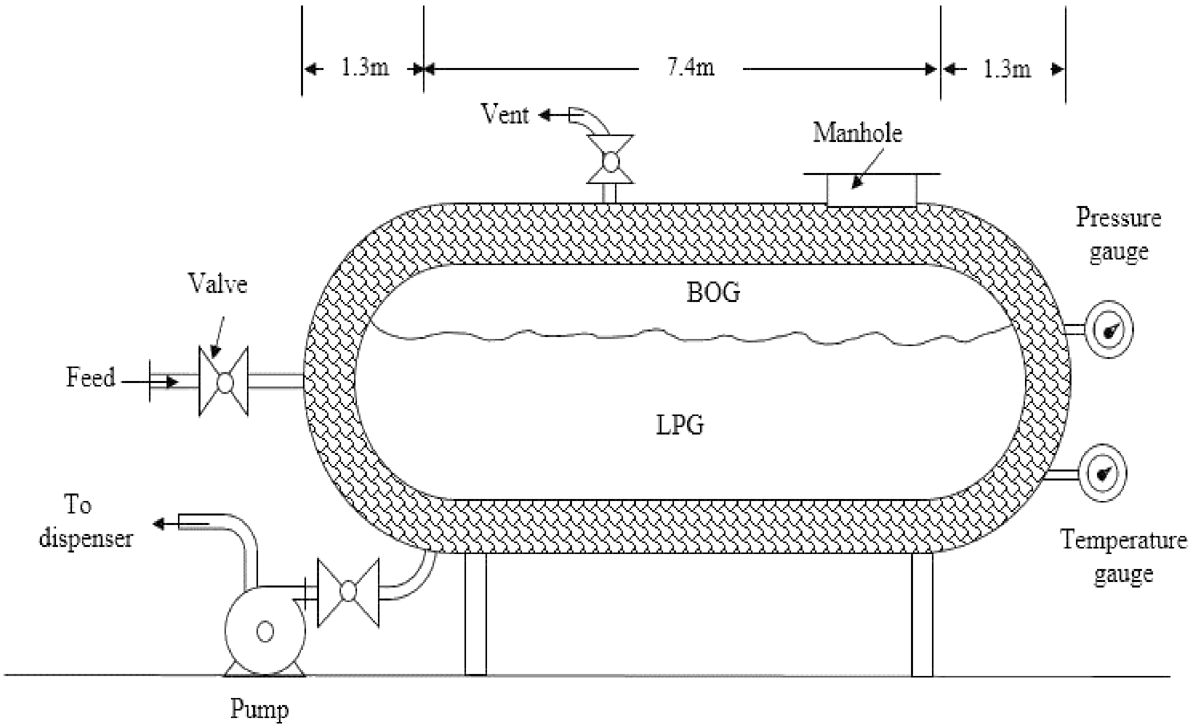

Figure 1: Schematic of an LPG skid plant [21]

LPG skid plant is a complete set of LPG filling station equipment, which integrates components such as storage tank, pump, valves, rundown pipes and the dispensing unit, all self-contained on a skid or frame. The storage tank is a double containment steel-in-steel cylindrical tank with hemispherical covers at both ends. The annulus is a vacuum with perlite insulation, as shown in Fig. 1. Table 2 summarizes the technical parameters of the LPG skid plant.

Table 2: Summary of LPG Skid Plant Technical Parameters

Component	**Parameter**	**Value**
Storage tank	Tank length	10*m*
	Tank diameter	2.6*m*
	Thickness of tank shell	14mm
	Thickness of end plate	14mm
	Thickness of insulation	250mm
	Tank material	Carbon steel (Q345R)
	Insulation material	Perlite
Pump	Power	7.5*kW*
	Flow rate	0.003m^3/s
	Efficiency	75%
Pipe	Length	5.5*m*
	Diameter	12.7*mm*
	Thickness	3*mm*
	Material	Mild steel

Source: [21]

2.3 Description of the BOG generation

Boil-off gas (BOG)in the LPG skid plant is generated under the conditions that heat is absorbed from ambient air by the storage tank and the pipeline, and heat which is produced by the transfer pump leaks into the LPG. A difference in temperature between the LPG and ambient air provides the driving force for heat transfer, and any temperature above the boiling point, LPG would immediately boil off into vapor [1]

2.3.1 Heat Leakage through storage tank

Heat leaks into the storage tank through the cylindrical shell and the hemispherical covers at both ends of the cylinder as shown in Fig.2.

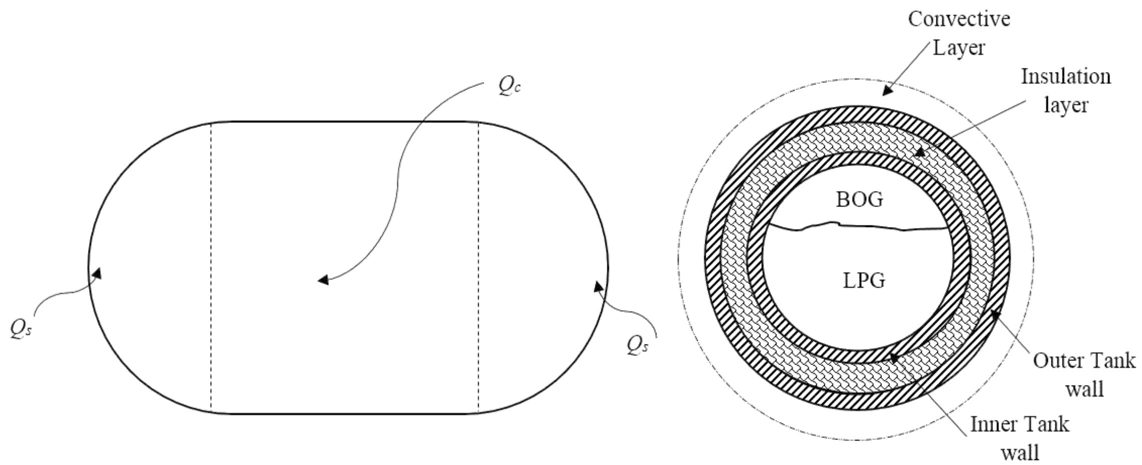

Figure 2: Schematic of heat leakage into the storage tank [1]

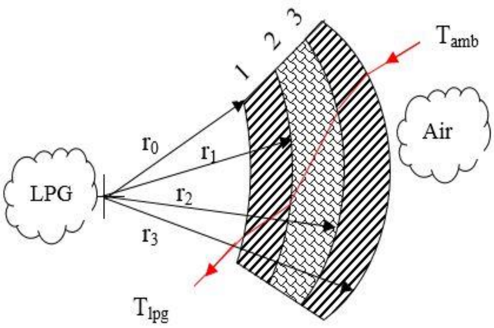

Figure 3: Schematic of temperature distribution for the storage tank [25].

Using Fig.3, the heat leakage through the cylindrical shell and the hemispherical covers at both ends of the storage tank, respectively, are given as [25]:

$$Q_c = \frac{2\pi l (T_{amb} - T_{lpg})}{\frac{1}{r_0 h_{lpg}} + \frac{1}{k_1}\ln\left(\frac{r_1}{r_0}\right) + \frac{1}{k_2}\ln\left(\frac{r_2}{r_1}\right) + \frac{1}{k_3}\ln\left(\frac{r_3}{r_2}\right) + \frac{1}{r_3 h_{air}}} \quad (1)$$

and

$$Q_s = \frac{2\pi r_0^2 (T_{amb} - T_{lpg})}{\frac{1}{h_{lpg}} + \frac{r_1}{k_1} + \frac{r_2}{k_2} + \frac{r_3}{k_3} + \frac{1}{h_{air}}} \quad (2)$$

where Q_c = heat leakage through tank cylindrical shell (W), l = length of tank cylindrical shell (m), T_{amb} = ambient temperature (K), T_{lpg} = temperature of LPG (K), r_0= tank radius (m),h_{lpg}= convective heat transfer coefficient of LPG (W/m^{2}K), $k_{1,2,3}$= thermal conductivity of the layers (W/mK), $r_{1,2,3}$= radius of subsequent tank layers (m), h_{air}= convective heat transfer coefficient of air (W/m^{2}K), Q_s = heat leakage through tank hemispherical end cover (W). The thermal conductivity of carbon steel (Q345R) used for the storage tank is 51.5W/mK[26]. The thermal conductivity of perlite used for the storage tank insulation is 0.95W/mK[27]

The convective heat transfer coefficient for the airflow and LPGcan be estimated using the Nusselt–Reynolds–Prandtl relation given as [28]:

$$h = \left\{\frac{k}{d}\right\}\left\{0.3 + \frac{0.62\,\mathrm{Re}^{\frac{1}{2}}\,\mathrm{Pr}^{\frac{1}{3}}}{\left\{1 + \left(0.4/\mathrm{Pr}\right)^{\frac{2}{3}}\right\}^{\frac{1}{4}}}\left\{1 + \left(\frac{\mathrm{Re}}{28200}\right)^{\frac{5}{8}}\right\}\right\} \quad (3)$$

where k = thermal conductivity (W/mK), d = tank diameter (m), Re =Reynolds number, Pr = Prandtl number. The Reynolds numbers for the airflow and the LPG would be, respectively, calculated by [29]:

$$\mathrm{Re}_{air} = \frac{\rho_{air} V_{air} d_3}{\mu_{air}} \quad (4)$$

$$\text{and } \mathrm{Re}_{lpg} = \frac{4\rho_{lpg} q}{\pi d_0 \mu_{lpg}} \quad (5)$$

where ρ_{air} = density of air (kg/m^3), V_{air}= air velocity (m/s), μ_{air}= viscosity of air (Ns/m^2), ρ_{lpg} = density of LPG (kg/m^3), q = flow rate of the LPG (m^3/s), μ_{lpg}= viscosity of the LPG (Ns/m^2),

From Fig.3, the total heat leakage into the storage tank is given as:

$$Q_{Tank} = Q_c + Q_s + Q_s \quad (6)$$

2.3.2 Heat leakage through transfer pump

A pump is required for transferring LPG from the storage tank to the dispensing unit in the skid plant. Energy is transferred to the pump to move the quantity of the LPG. Part of this energy would be lost as heat due to deficiency, and results in BOG generation. The heat generated due to the pump deficiency and leaked into the LPG is given as [30]:

$$Q_{Pump} = P\left(\frac{1}{\eta} - 1\right) \quad (7)$$

where Q_{pump}= heat generated in the pump (W), P = pump power (W), η = pump efficiency (%). Many smaller centrifugal pumps offer efficiencies of 50 to 70% [31].

2.3.3 Heat leakage through pipeline

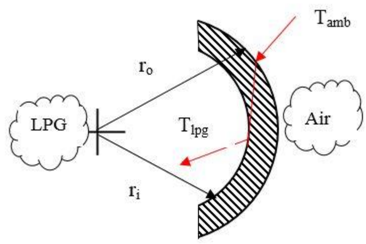

Figure 4: Schematic diagram of the temperature distribution for the rundown pipe [25].

LPG flow from the storage tank through the rundown pipes to the dispensing unit during sale. Thus, heat is leak into the pipe as a result of the temperature different between the ambient and LPG. The heat is leak through the wall of the pipes as shown in Figure 4, and is given as [25]:

$$Q_{pipe} = \frac{2\pi L\left(T_{amb} - T_{lpg}\right)}{\frac{1}{r_i h_{lpg}} + \frac{1}{k_o}\ln\left(\frac{r_o}{r_i}\right) + \frac{1}{r_o h_{air}}} \quad (8)$$

where Q_{pipe} = heat leakage through pipe (kW), L= total length of pipe (m), r_i= Inner pipe radius (m), k_o= thermal conductivity of the pipe material (W/mK), r_i= inner radius of the pipe (m), r_o= outer radius of the pipe (m). The thermal conductivity of the pipe material (mild steel) is 51.9W/mK[32]

2.4 Boil off gas generation rate

The BOG generation in the LPG skid plant is contributed by the heat leakages via storage tank, pipelines and transfer pump

2.4.1 Boil off gas generated due to storage tankheat leakage

The rate of BOG generated based on the heat leakage into the storage tank (m_{Tank}) is expressed in kilogram per second (kg/s) and is given as [33]:

$$m_{Tank} = \frac{Q_{Tank}}{h_{fg}} \quad (9)$$

where h_{fg} = latent heat of vaporization (kJ/kg)

2.4.2 Boil off gas generated due to pump deficiency

The rate of BOG generated based on the dispensing pump deficiency (m_{pump}) is expressed in kilogram per second (kg/s) and is given as [6]:

$$m_{pump} = \frac{Q_{pump}}{h_{fg}} \quad (10)$$

2.4.3 Boil off gas generated due to pipelines heat leakage

The rate of BOG generated based on the heat leakage into the rundown pipes (m_{pipe}) is expressed in kilogram per second (kg/s) and is given as [30]:

$$m_{pipe} = Q_{pipe}\left(\frac{\beta}{h_{fg}}\right) \quad (11)$$

where β = safety factor (1.05)

2.4.4 Boil off gas generated due to vapor displacement

The inflow LPG into emptied storage tank would displace vapor and add-on to BOG generation. The BOG generated due to the vapor displacement (m_{vapor}) is expressed in kilogram per second (kg/s) and is given as [9]:

$$m_{vapor} = q \times \rho_{vap} \quad (12)$$

where q= pump flow rate (m^3/s), ρ_{vap} = vapor density (kg/m^3)

Total BOG generation rate (m_{Total}) is expressed in kilogram per second (kg/s) and is given as [30]:

$$m_{Total} = m_{Tank} + m_{pump} + m_{pipeline} + m_{vapor} \quad (13)$$

2.5 Cost equivalent of loss LPG

BOG generation resulted in losses of the LPG. The cost equivalent of loss LPG (C_{Loss}) is expressed in the units of currency per second (₦/s) and would be calculated using the formula:

$$C_{Loss} = C_{lpg} \times m_{Total} \quad (13)$$

where C_{lpg} = unit cost of LPG (₦/kg). Unit cost of LPG in Nigeria is 450.57₦/kg [34]

III. RESULTS AND DISCUSSION

The results of the study are presented and discussed as follows:

3.1 Analysis of the heat leakages

The heat leak into the LPG through the storage tank, pump and pipeline are determined as follow:

3.1.1 Analysis of the heat leakages through the storage tank wall

Analyzing the heat leakage into the storage tank, is associated with estimations of the convective heat transfer coefficient of the ambient air and LPG supply as follows:

The Reynolds number for the ambient air and LPG are calculated, respectively, using equations

4 and 5, where ρ_{air} = 1.18 kg/m^3, V_{air}= 2.32m/s, μ_{air}= 0.1854 x 10^{-6} Ns/m^2, ρ_{lpg} = 585kg/m^3, μ_{lpg}= 175 x 10^{-6}Ns/m^2(from Table 1), q = 0.003 m^3/s, d_0 = 2.6m (from Table 2)

$$\mathrm{Re}_{air} = \frac{1.18 \times 2.32 \times 2.878}{0.1854 \times 10^{-6}} = 42{,}496{,}293$$

and

$$\mathrm{Re}_{lpg} = \frac{4 \times 585 \times 0.03}{\pi \times 2.6 \times 175 \times 10^{-6}} = 49{,}111$$

Applying equation 3, where k_{air} = 0.02558W/mK, Pr$_{air}$ = 0.7280(from Table 1), d_3 = 2.6 + 0.014 + 0.25 + 0.014 = 2.878m (from Table 2), Re$_{air}$= 42,496,293

$$h_{air} = \left\{\frac{0.02558}{2.878}\right\}\left\{0.3 + \frac{0.62 \times 42496293^{\frac{1}{2}} \times 0.7280^{\frac{1}{3}}}{\left\{1+\left(0.4/0.7280\right)^{\frac{2}{3}}\right\}^{\frac{1}{4}}}\left\{1+\left(\frac{42496293}{28200}\right)^{\frac{5}{8}}\right\}\right\}$$

= 3335.9W/m^{2}K

Also, applying equation 3, k_{lpg} = 109.2 x 10^{-3}W/mK, Pr$_{lpg}$ = 3.99 (from Table 1), d_0 = 2.6m (from Table 2), Re_{lpg}= 49,111

$$h_{lpg} = \left\{\frac{109.2 \times 10^{-3}}{2.6}\right\}\left\{0.3 + \frac{0.62 \times 49111^{\frac{1}{2}} \times 3.99^{\frac{1}{3}}}{\left\{1+\left(0.4/3.99\right)^{\frac{2}{3}}\right\}^{\frac{1}{4}}}\left\{1+\left(\frac{49111}{28200}\right)^{\frac{5}{8}}\right\}\right\}$$

= 21.05W/m^{2}K

Applying equation 1 and 2, the heat leakage through the cylindrical shell and hemispherical end cover are thusdetermined, respectively, as follows: l = 7.4m (from Fig. 1), T_{amb} = 299K, T_{lpg}= 291K, r_0 = 1.3m (from Table 1), r_1 = 1.3+ 0.014 = 1.314, r_2= 1.314 + 0.25 = 1.564m, r_3 = 1.564 + 0.014 = 1.578m (from Table 1 and Fig. 4), k_1 = k_3 = 51.5W/mKk_2= 0.95W/mK, h_{air} = 3335.9W/m^{2}K, h_{lpg} = 21.058W/m^{2}K

$$Q_C = \frac{2 \times \pi \times 7.4 \times (299-291)}{\frac{1}{1.3 \times 21.058} + \frac{1}{51.5}\ln\left(\frac{1.314}{1.3}\right) + \frac{1}{0.95}\ln\left(\frac{1.564}{1.314}\right) + \frac{1}{51.5}\ln\left(\frac{1.578}{1.564}\right) + \frac{1}{1.578 \times 3335.9}}$$

= 1687.39W

and

$$Q_S = \frac{2 \times \pi \times 1.3^2 \times (299-291)}{\frac{1}{21.058} + \frac{1.314}{51.5} + \frac{1.564}{0.95} + \frac{1.578}{51.5} + \frac{1}{3335.9}}$$

= 48.54W

Thus, applying equation 6, we obtain the total heat leakage into the storage tank noting that: Q_c= 1687.39W, Q_s= 48.54W

$$Q_{Tank} = 1687.39 + 48.54 + 48.54 = 1784.46W$$

≈ 1.785kW

This analysis provides the total heat leak from the outside into the tank through the wall.

3.1.2 Analysis of the Heat leakage through pump

Applying equation 7, we obtain the heat leakage in the LPG through the dispensing pump, noting that P = 7.5kW, η = 70% (from Table 2)

$$Q_{Pump} = 7.5 \times \left(\frac{1}{0.7} - 1\right) = 3.214\text{kW}$$

3.1.3 Analysis of the heat leakage through pipeline

Applying equation 8, the heat leakage through pipeline is calculated thus: T_{amb} = 299K, T_{lpg}= 291K (from Table 1), L = 5.5m, r_i = 0.00635m, r_o= 0.00635 + 0.003 = 0.00935m (from Table 2), k_o = 51.9W/mK, h_{lpg} = 21.058W/m^{2}K, h_{air} = 3335.9W/m^{2}K

$$Q_{pipe} = \frac{2 \times \pi \times 5.5 \times (299-291)}{\frac{1}{0.00635 \times 21.058} + \frac{1}{51.9}\ln\left(\frac{0.00935}{0.00635}\right) + \frac{1}{0.00935 \times 3335.9}}$$

= 36.77W ≈ 0.0368kW

3.2 Analysis of the BOG generation rate

BOG generation rate due to storage tank, pump and pipeline heat leakages are analyzed as follows:

3.2.1 Analysis of the BOG generation rate due to storage tankheat leakage

Applying Equation 9, where Q$_{Tank}$= 1.785kW, h_{fg} = 367kJ/kg (from Table 1), the BOG generation rate due to storage tank heat leakage is calculated as

$$m_{Tank} = \frac{1.785}{367} = 0.0049\text{kg/s}$$

3.2.2 Analysis of the BOG generation rate due to heat produced by the operation of dispensing pump

Applying Equation 10, the BOG generation rate due to heat produced by the operation of dispensing pump is determined as follows: Q_{Pump}= 3.214kW, h_{fg} = 367kJ/kg (from Table 1)

$$m_{Pump} = \frac{3.214}{367} = 0.0088\text{kg/s}$$

3.2.3 Analysis of the BOG generation rate due to rundown pipes heat leakage

Applying Equation 11, where Q_{Pipe}= 0.0368kW, β = 1.05, h_{fg} = 367kJ/kg (from Table 1), the BOG generation rate due to rundown pipes heat leakage is calculated as

$$m_{pipe} = 0.0368 \times \left(\frac{1.05}{367}\right) = 0.00011\text{kg/s}$$

3.2.4 Analysis of the BOG generation rate due to vapor displacement

Applying Equation 12, where q= 0.003m^3/s (from Table 2), ρ_{vap} = 5.17kg/m^3 (from Table 1), the BOG generation rate due to vapor displacement is calculated as

$$m_{vapor} = 0.003 \times 5.17 = 0.01551\text{kg/s}$$

Thus, applying Equation 13, we obtain the BOG generation rate:

$$m_{Total} = 0.0049 + 0.0088 + 0.00011 + 0.01551$$
$$= 0.0293\text{kg/s}$$

3.3Analysis of the Cost equivalent of loss LPG

Applying Equation 14, we obtain the cost equivalent loss of LPG, noting that C_{lpg}= 516.4₦/kg, m_{Total} = 0.02932kg/s.

$$C_{Loss} = 516.4 \times 0.0293 = 15.14\text{₦/s}$$

From the analysis, The BOG generation rate of 0.0293kg/s, has a cost equivalent loss of 15.14₦/s at LPG selling price of 516.4₦/kg.

IV. VI. CONCLUSION

This study is carried out to analyze the economic cost of boil-off gas generation rate in the liquefied petroleum gas supply chain. It includes analysis of the heat absorbed from ambient air by the storage tank and pipelines, and heat produced by the transfer pump that leaks into the LPG, and consequently generate boil-off gas in the supply chain, by utilizing appropriate thermodynamic and heat transfer equations. Thekey conclusions of the analysis carried out in this study were summarized as follows:

(i) Analyzing the heat leakage into the skid plant, required the estimations of the convective heat transfer coefficient of the ambient air in the supply location and the LPG in the supply chain, which amounted to 3335.9W/m^{2}K and 21.058W/m^{2}K, respectively in the system under study.

(ii) The heat absorbed from the ambient air by the storage tank and pipelinesby the LPG amounted to 1.785kW and 0.0368kW, respectively, and the heat produced by the operation of transfer pump in the plant that leak into the LPG amounted to 3.214kW.

(iii) The total boil-off generation rate due to the storage tank heat leakage,pipelines heat leakage, heat produced by the transfer pump and vapor displacement in the storage tank is 0.0293kg/s, which translates to a cost equivalent loss of 15.14₦/s at LPG selling price of 516.4₦/kg.

In conclusion therefore, boil-off gas generation results from the heat leakages into the LPG through the tank wall, pipelines and operation of the transfer pump. Thus, maintenance of insulation and other external factors such as wind speed, solar radiation, ambient temperature and thermal conductivity of the skid plant's material are key factors in minimizing the heat leaks into LPG, hence BOG generation, which is of utmost importance in ensuring safety and economic operation of the LPG supply chain.

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