ISSN 2829-4998

Assessment of safety and economic impact of boil-off-gas in LPG storage tanks

Nwadinobi Chibundo Princewill [a,1,*], Kanu Allwell Ubasom [a,2], Chukwudi Onyebuchi David [a,3]

[a] Department of Mechanical Engineering, Abia State University, Nigeria
[1] chibundop@gmail.com; [2] kanuallwell@yahoo.com; [3] davidkelvin1999@gmail.com
* corresponding author

ARTICLE INFO

Article history
Received July 03, 2023
Revised September 07, 2023
Accepted October 18, 2023
Available online November 29, 2023

Keywords
Safety
Economic assessment
Boil-off gas
Thermodynamic properties
LPG storage

ABSTRACT

This study was carried out to assess effect of boil-off gas (BOG) on the safety and economic effectiveness of LPG storage tank. It includes analysis of the thermodynamic properties of LPG; heat absorbed from ambient air by the storage tank that leaks into the LPG, and 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 supply chain, which amounted to 3335.9W/m2K and 21.058W/m2K, respectively, in the system under study. Analyzing the thermodynamic properties such as specific volume, entropy and enthalpy of the LPG, show that the entropy of LPG in the storage tank is negative, which suggested an endothermic process, validating that heat is added to the system from the surroundings. The heat absorbed in the LPG from the ambient air by the storage tank amounted to 1.785kW. The boil-off generation rate due to the storage tank heat leakage was 0.0049kg/s, which translates to a cost equivalent loss of 0.0069$/s at LPG selling price of 1.42$/kg. It was recommended that maintenance of insulation and other external factors such as wind speed, solar radiation, ambient temperature and thermal conductivity of the storage tank material are key factors in minimizing the heat leaks into LPG; hence BOG generation, which is of utmost importance in ensuring safety and economic loss in the LPG supply chain.

1. Introduction

Liquefied Petroleum Gas (LPG) is propane, butane, iso-butane, 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], [3]. The LPG stored in a tank exists in equilibrium between a thermodynamic liquid and vapor. The storage tank is surrounded by ambient air that causes heat leakage into the storage tank due to the temperature between the LPG and ambient air [4], [5]. The heat leakage into the tank causes portion of LPG to continue to evaporate, and generating a boil off gas (BOG) that causes changes in the thermodynamic properties of the LPG, and losses in the LPG supply chain over time [6], [7].

Different sources exist for the generation of BOG, these sources include heat leaks from ambient air around the storage tank, heat ingress due to the dissipation of pumping power inside the tanks, heat

https://doi.org/10.31763/aet.v2i3.1092 aet@ascee.org

leaks from pipelines, flash vapor generated by liquid rundown and displaced vapor from the tank due to liquid filling which is called the piston effect. The boil off of LPG causes excessive temperature and pressure build up in the tank, and as LPG is very sensitive to changes in temperature, an increase in its temperature leads to rapid evaporation and sudden increase of pressure in the storage tank [8], [9]. It is imperative to ascertain methods to reduce the temperature changes in the tank to prevent generation of the boil off in order to maintain the tank pressure within economic and safety ranges. LPG safety required that its storage tanks and other equipment are made of suitable materials with the proper design engineering.

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 [10]. In Nigeria, LPG is becoming even more useful, especially now that the government is positioning 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 [11]. These have resulted in the emergence of a lot of LPG skid plants, without proper boil-off gas (BOG) recovery system nationwide. Thus, raises safety and profitability concern [12], [13].

Even though, government is encouraging technology development and safety enhancement to support sustainable LPG business growth [14]. The generation of boil-off gas in the storage tank causes losses in the LPG supply chain over time [6]. BOG is the continuously evaporated or boiled LPG vapor that causes the pressure inside the tank to rise due to heat entering the tank during storage and transportation, which may change the quality of LPG over time. This BOG is generated primarily due to heat leakage, resulting from the temperature difference between the ambient air and LPG. BOG generation rate is one of the most important factors for safety and economic assessment of in LPG storage tank. This study took place at GMPP LPG storage tanks located in Okigwe and manufactured by Hubei Chusheng Ltd. as a case study to use the thermodynamic and heat transfer methods to analyze the temperature that may contribute to boil-off gas generation in the plant, and evaluate the economic implication of the boil-off of gas generation during the LPG storage process.

2. Method

The materials for this study include the LPG storage tank catalogue, Data of thermo-physical properties of LPG (Butane) and ambient air, data of ambient climate condition of the storage tank location (Okigwe, Imo State, Nigeria), and GMPP LPG storage tank facility inventory record. The data analysis method was used in the study. The processes are as outlined: Collection of Data; Thermodynamic Properties of LPG; Description of LPG Storage Tank; Description of the Boil off Gas Generation; Analysis of Heat Leakage through Storage Tank; Analysis of the Boil Off Gas Generation Rate. The schematic display is presented in equation.

The inventory record of the GMPP LPG storage tank facility offered vital perspectives on its operational history and trends, leading to a more nuanced comprehension of the system's dynamics. Employing this comprehensive methodology, we were able to evaluate not just the rate of boil off gas generation but also pinpoint potential areas for optimizing and improving the efficiency of LPG storage and utilization. The research flow is shown in the Fig. 1.

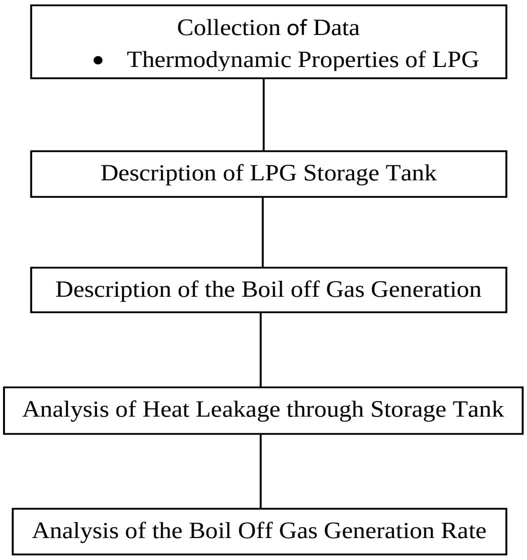

Fig. 1. Methodological process flow

2.1. Collection of Data

The data used in this study include the LPG skid plant technical parameters obtained from the LPG storage catalogue [15], thermo physical properties for the LPG (Butane) obtained from Beaton and Hewitt [16], thermo physical properties for the ambient air obtained from Cengel and Cimbala [17], ambient climate condition and other physical properties of the 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 storage used in this study is Okigwe, Nigeria, which has a tropical climate, with an average annual temperature of 26°C [18]. The annual average speed of air experienced in Okigwe is 2.32m/s [19].

2.1.1. Thermodynamic Properties of LPG

The heat leakage from the surroundings of the storage tank causes changes of temperature of the LPG, and consequently its composition vapor-liquid equilibrium which have a significant effect on its thermodynamic properties. The thermodynamic properties of the LPG include Pressure, Temperature, Specific Volume, Density, Enthalpy, Entropy and Heat Capacity [20], [21]. Equations of state which relate Pressure-Volume-Temperature (P-V-T) are commonly used to described the behavior of real pure substances and mixtures, and can be used for the Analysis of the Specific Volume, Density, Enthalpy and Entropy as functions of Temperature and Pressure [22].

- **Specific volume of the LPG**

  The changes in the temperature and pressure of the LPG in the storage tank also results in change in the volume and of the LPG. The volume of the LPG in the tank can be determined from the equation of state. There are different types of equations of states which are viral, cubic and complex, the greatest distribution was gained by the cubic equations of state for the simplicity of expression, ability with some degree of accuracy to describe thermodynamic properties of gases, the Van Der Waals equation of state that is useful for calculating the volume of gases below critical temperatures is used [23]. The Van der Waals equation of state is given in equation 1.

$$v^3 - \left(b + \frac{RT}{P}\right)v^2 + \frac{a}{P}v - \frac{ab}{P} = 0 \quad (1)$$

Where v = Specific volume (m3/mol), R = Specific gas constant (J/molK), T = Temperature (K), P = Pressure (N/m2). The value of the constants a and b for the Van der Waals equation of state for the gaseous elements and compounds contained in the LPG could be obtained from Cooper and Gold frank (1967). The specific volume can be expressed in cubic meter per kilogram (m3/kg) by the formula.

$$V = \frac{v}{M} \tag{2}$$

Where M = molecular weight of the gas (kg/Kmol).

- **Entropy of LPG**

Entropy is a property of a thermodynamic system that expresses the direction or outcome of spontaneous changes in the system. The change in entropy of a process can be expressed using Van der Waal equation of state as follows [24].

$$S - S_o = C_v \, In \, \frac{T}{T_o} + R \, In \, \frac{v-b}{v_o-b} \tag{3}$$

where Cv = Specific Heat at Constant Volume(kJ/kgK), To = Ambient Temperature (K), vo = volume of gas at ambient condition (m3/kmol). At standard temperature and pressure, volume of all gases is 22.4m3/kmol.

- **Enthalpy of LPG**

Enthalpy is a measure of the total energy of a thermodynamic system. It includes the internal energy, which is the energy required to create a system, and the amount of energy required to make room for it by displacing its environment and establishing its volume and pressure. Enthalpy change accounts for energy transferred to the environment at constant pressure through expansion or heating. The change in enthalpy of the gas can be calculated using the equation 4.

$$\Delta H = T(S - S_o) + V(P - P_o) \tag{4}$$

- **Energy Content of the LPG**

The energy content is the measure of equivalent energy released through combustion. The energy content of LPG is the central quantity upon which its economic value is determined and its value depends on the source of natural gas and the process used to liquefy the gas. The energy content (E) is expressed in Joule (J) and approximately given as.

$$E = E_{lpg} - E_{bog} \tag{5}$$

Where Elpg= Energy transferred in LPG (kJ), Ebog = Energy transferred in BOG (kJ). According Elengy [25], the energy transferred in BOG is approximately 0.1% of the energy transferred in the LPG. The energy transferred in LPG is given as.

$$E_{ipg} = \rho_{ipg} \, x \, V \, x \, \Delta H \tag{6}$$

Where V = Volume of LNG in the Tank (m3), H= Heating value of the LNG loaded in the tank (J/kg).

2.2. Description of LPG Storage Tank

LPG storage tanks are made from welded steel and are designed for the required pressures and heat expansion of the stored hydrocarbon gases, including propane and butane. LPG storage tank integrates components such as pump, valves, pipelines and dispensing unit, all self-contained on a frame. The storage tank is a double containment, a steel-in-steel cylindrical tank with hemispherical covers at both ends. The annulus is a vacuum with per lite insulation, as shown in Fig. 2.

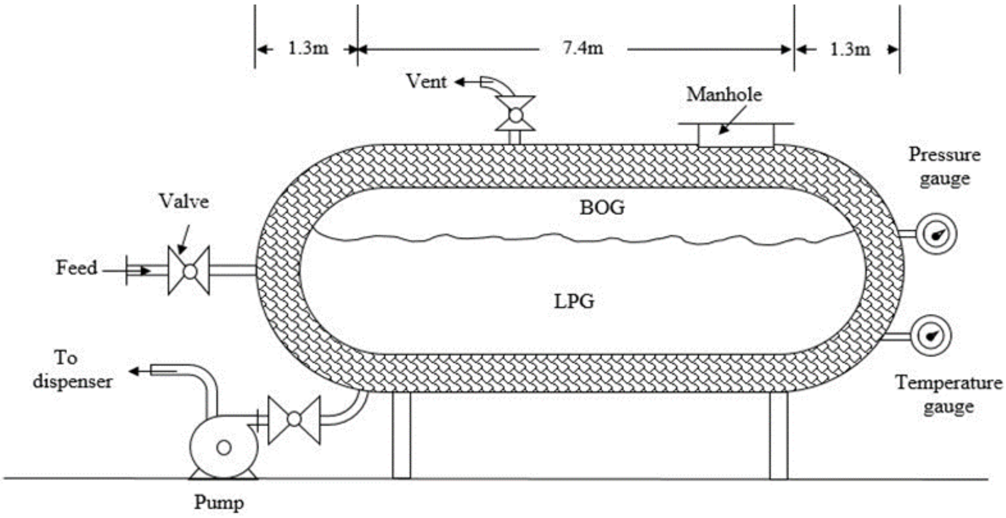

Fig. 2. Schematic diagram of an LPG skid plant [15]

- Vent: this an opening that allows air, gas or liquid to pass out of or into a confined space.
- Manhole: is an opening to a confined space such as a shaft, utility or large vessel. Manholes are often used as access point for an underground public utility, maintenance and system upgrades.
- Feed: This is a opening for supplying material to the LPG container.
- Pump: a pump is a device which moves fluids by mechanical action, from one place to another.
- Dispenser: This is where the desire amount of liquid, gas comes out from.
- Valve: A device for controlling the passage of liquid, gas, air through a pipe.
- Pressure gauges: they are devices that measure the internal pressure of media within a system.
- Temperature gauges: temperature gauges measure the thermal state of a homogenous substance.

2.2.1. Description of the Boil off Gas Generation

Boil off gas in the LPG storage tank is generated under the conditions that heat is absorbed from ambient air by the storage tank and leak 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].

2.2.2. Heat Leakage through Storage Tank

Heat is leak into the storage tank through the cylindrical shell and the hemispherical cover at both end of the cylinder as show in Fig. 3.

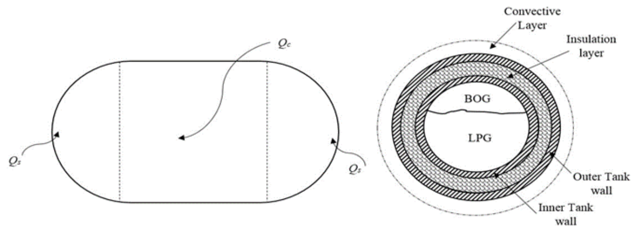

Fig. 3. Schematic diagram of axial and radial direction heat leakage into the storage tank [1]

Using Fig. 4, the heat leakage through the cylindrical shell and the hemispherical cover at both end of the storage tank, respectively, are given as [26].

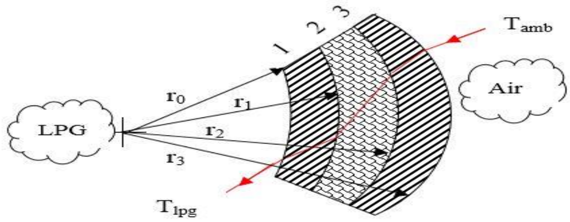

Fig. 4. Schematic diagram of the temperature distribution for the storage tank [26]

$$Q_c = \frac{2\pi l(T_{amb} - T_{lpg})}{\frac{1}{r_0 h_{lpg}} + \frac{1}{k_1} 1n\left(\frac{r_1}{r_0}\right) + \frac{1}{k_2} 1n\left(\frac{r_2}{r_1}\right) + \frac{1}{k_3} 1n\left(\frac{r_3}{r_2}\right) + \frac{1}{r_3 h_{air}}} \tag{7}$$

$$Q_s = \frac{2\pi r_0^2 (T_{amb} - T_{lpg})}{\frac{1}{h_{lpg}} + \frac{r_1}{k_1} + \frac{r_2}{k_2} + \frac{r_3}{k_3} + \frac{1}{h_{air}}} \tag{8}$$

where Qc = heat leakage through tank cylindrical shell (W), l = length of tank cylindrical \hemispherical end cover (W).

2.2.3. Convective Heat Transfer Coefficient through Storage Tank

The convective heat transfer coefficient for the airflow and LPG can be estimated using the Nusselt–Reynolds–Prandtl relation given as [27].

$$h = \left\{\frac{k}{d}\right\} \left\{ 0.3 + \frac{0.62\, Re^{\frac{1}{2}} Pr^{\frac{1}{3}}}{\left\{1 + \left(\frac{0.4}{Pr}\right)^{\frac{2}{3}}\right\}^{\frac{1}{4}}} \left\{1 + \left(\frac{Re}{28200}\right)^{\frac{5}{8}}\right\} \right\} \tag{9}$$

where Re = Reynolds number, Pr = Prandtl number, k = thermal conductivity (W/mK), d = tank diameter (m). The Reynolds numbers for the airflow and the LPG would be, respectively, calculated by [28].

$$Re_{air} = \frac{\rho_{air} V_{air} d_3}{\pi_{air}} \tag{10}$$

$$Re_{lpg} = \frac{4\rho_{lpg} q}{\mu\, d_0 \mu_{lpg}} \tag{11}$$

where ρair = density of air (kg/m3), Vair= air velocity (m/s), μair= viscosity of air (Ns/m2), ρlpg = density of LPG (kg/m3), q = flow rate of the LPG (m3/s), μlpg= viscosity of the LPG (Ns/m2).

2.2.4. Total Heat Leakage into the Storage Tank

From Fig. 2 and Fig. 3, the total heat leakage into the storage tank is given as [20].

$$Q_{Tank} = Q_c + Q_s + Q_s \quad (12)$$

2.2.5. Boil off gas generated due to storage tank heat leakage

The rate of BOG generated based on the heat leakage into the storage tank (mTank) is expressed in kilogram per second (kg/s) and is given as [22].

$$m_{Tank} = \frac{Q_{Tank}}{h_{fg}} \quad (13)$$

Where hfg = latent heat of vaporization (kJ/kg).

2.2.6. Cost Equivalent of LPG Loss

BOG generation resulted in losses of the LPG. The cost equivalent of loss LPG (CLoss) is expressed in the units of currency per second ($/s) and would be calculated using the formula.

$$C_{Loss} = C_{lpg} \times m_{Tank} \quad (14)$$

Where Clpg = unit cost of LPG ($/kg). Unit cost of LPG in Nigeria is 1.42$/kg [29].

3. Results and Discussion

Table 1 summarizes the collected data for the LPG parameters and the ambient air.

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

Fluid	Properties	Value
LPG (Butane)	Temperature	291K (18°C)
	Pressure	200kPa(2bar)
	Molecular weight	58.12kg/Kmol
	Liquid density	585kg/m^3
	Vapor density	5.17kg/m^3
	Liquid viscosity	175μNs/m^2
	Latent heat of vaporization	367kJ/kg
	Gas constant	0.1433kJ/kgK
	Specific Heat at Constant Pressure	1.7164kJ/kgK
	Specific Heat at Constant Volume	1.5734kJ/kgK
	Liquid thermal conductivity	109.2mW/mK
	Liquid Prandtl number	3.99
	Van der Waals constants:	
	a	1385kPa(m^3/kmol)^2
	b	0.1162m^3/kmol
Air	Temperature	299K (26°C)
	Pressure	103.3kPa(1bar)
	Speed	2.32m/s
	Density	1.18kg/m^3
	Viscosity	0.1854μNs/m^2
	Thermal conductivity	0.02558W/mK
	Prandtl number	0.7280

[a] **Source:** [15]–[17], [19], [30]

Table 2 summarizes the technical parameters of the LPG storage.

Table 2. Summary of LPG Storage Tank 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

[b.] **Source**: Hubei Chusheng Ltd. [15]

The thermodynamic properties of the LPG in the storage tank were analyzed using the temperature and pressure obtained for the LPG storage in Table 1.

2.2.7. Analysis of Specific Volume of LPG in the Storage Tank

Applying Equation 1, the specific volume of LPG in the tank was determined as follows: b = 0.1162m3/Kmol, R = 8314J/kmolK, T = 291K, P = 200kN/m2, a = 1385kPa (m3/kmol) 2 (from Table 1).

Also, applying Equation 2, the specific volume of LPG in the tank expressed in m3/kg was determined as follows: v = 11.62m3/kmol, M = 58.12kg/Kmol, V ≈ 0.2m3/kg.

3.2. Analysis of Entropy of LPG in the Storage Tank

Applying Equation 3, the entropy of LPG in the storage tank was determined as follows: Cv = 1.5734kJ/kgK, To = 298K, T = 291K, R = 0.1433 kJ/kgK, v = 11.62m3/kmol,b = 0.1162m3/kmol, vo= 22.4m3/kmol, .

The analysis showed that the entropy of LPG in the storage tank is negative, which suggested an endothermic process. That is, heat is added to the system from the surroundings.

3.3. Analysis of Enthalpy of LPG in the Storage Tank

Applying Equation 4, the enthalpy of LPG in the storage tank is determined as follows: T = 291K, S - So = 0.1325kJ/kgK, V = 0.2m3/kg,Po= 101.3kPa, P = 200kPa, .

The analysis showed that the enthalpy of LPG in the storage tank is greater than zero, which suggested that heat is added to the system from the surroundings.

3.4. Analysis of Energy Content of the LPG

Applying Equation 3.6, the enthalpy of LPG in the storage tank is determined as follows: T = 291K, S - So = 0.1325kJ/kgK, V = 0.2m3/kg, Po = 101.3kPa, P = 200kPa.

3.5. Analysis of the Heat Leakages

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

3.5.1. 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 8 and 9, whereρair = 1.18 kg/m3, Vair=

2.32m/s, μair= 0.1854 x 10-6 Ns/m2, ρlpg = 585kg/m3, μlpg= 175 x 10-6Ns/m2, q = 0.003 m3/s, d0 = 2.6m (from Table 2) .

Reair = 42,496,293 and Relpg = 49,111. Applying Equation 7, where kair = 0.02558W/mK, Prair = 0.7280 (from Table 1), d3 = 2.6 + 0.014 + 0.25 + 0.014 = 2.878m (from Table 2), Reair= 42,496,293, hair = 3335.9W/m2K.

Also, applying Equation 7, where klpg = 109.2 x 10-3W/mK, Prlpg = 3.99 (from Table 1), d0 = 2.6m (from Table 2), Relpg= 49,111, hlpg = 21.058W/m2K

Applying Equation 5 and 6, the heat leakage through the cylindrical shell and hemispherical end cover are thus determined, respectively, as follows: l = 7.4m (from Fig. 1), Tamb = 299K, Tlpg= 291K (from Table 1), r0 = 1.3m (from Table 2), r1 = 1.3+ 0.014 = 1.314, r2= 1.314 + 0.25 = 1.564m, r3 = 1.564 + 0.014 = 1.578m (from Table 2 and Fig. 4), k1 = k3 = 51.5W/mK k2= 0.95W/mK, hair = 3335.9W/m2K, hlpg = 21.058W/m2K.

Thus, applying Equation 10, we obtain the total heat leakage into the storage tank noting that: QC= 1687.39W, Qs= 48.54W and Qtank = 1.785kW. This analysis provides the total heat leak from the outside into the tank through the wall

3.6. Analysis of the BOG Generation Rate

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

3.6.1. Analysis of the BOG generation rate due to storage tank heat leakage

Applying Equation 11, where QTank= 1.785kW, hfg = 367kJ/kg (from Table 1), the BOG generation rate due to storage tank heat leakage is calculated as mtank = 0.0049kg/s.

3.6.2. Analysis of the Cost equivalent of loss LPG

Applying Equation 12, we obtain the cost equivalent loss of LPG, noting that Clpg= 1.42$/kg, mTotal = 0.0049kg/s. Therefore, Closs = 0.0069$/s.

From the analysis, The BOG generation rate of 0.0049kg/s, has a cost equivalent loss of 0.0069$/s at LPG selling price of 1.42$/kg.

4. Conclusion

This study was carried out to analyze the thermodynamic properties of LPG; heat absorbed from ambient air by the storage tank that leaks into the LPG, and consequently generates boil-off gas in the supply chain, by utilizing appropriate thermodynamic and heat transfer equations. Analyzing the thermodynamic properties of the LPG, shows that the entropy of LPG in the storage tank was negative, which suggested an endothermic process, validating that heat is added to the system from the surroundings. Considering the heat leakage into the skid plant, gave the convective heat transfer coefficient of the ambient air in the supply location and the LPG in the supply chain, as 3335.9W/m2K and 21.058W/m2K, respectively. Heat absorbed from the ambient air by the storage tank amounted to 1.785kW. Thus, the boil-off generation rate due to the storage tank heat leakage, was 0.0049kg/s, which translates to a cost equivalent loss of 0.0069$/s at LPG selling price of 1.42$/kg. Therefore, boil-off gas generation results from the heat leakages into the LPG through the tank wall. Thus, it is recommended for storage tank designers to provide perfect insulation to limit the admission of heat leakage that cause boil-off gas. In addition, a BOG Removing mechanism from the tanks would help storage of LPG at a stable temperature and pressure. These will ensure safety and economic effectiveness of the LPG supply chain.

References

[1] M. S. Zakaria, K. Osman, A. A. Yusof, M. H. Mohd Hanafi, M. N. A. Saadun, and M. Z. Abdul Manaf, "Parametric Analysis on Boil-Off Gas Rate inside Liquefied Natural Gas Storage Tank," *J. Mech. Eng. Sci.*, vol. 6, no. June, pp. 845–853, Jun. 2014, doi: 10.15282/jmes.6.2014.10.0080.

[2] N. C. Princewill, K. A. Ubasom, and O. Chibuike, "Liquefied Petroleum Gas (LPG) Storage Tanks Boil-off Gas Generation and Management– Review," *Int. J. Adv. Sci. Eng.*, vol. 10, no. 1, pp. 3294–3303, Aug. 2023, doi: 10.29294/IJASE.10.1.2023.3294-3303.

[3] M. S. Khan, M. A. Qyyum, W. Ali, A. Wazwaz, K. B. Ansari, and M. Lee, "Energy Saving through Efficient BOG Prediction and Impact of Static Boil-off-Rate in Full Containment-Type LNG Storage Tank," *Energies*, vol. 13, no. 21, p. 5578, Oct. 2020, doi: 10.3390/en13215578.

[4] D. Kim, C. Hwang, T. Gundersen, and Y. Lim, "Process design and economic optimization of boil-off-gas re-liquefaction systems for LNG carriers," *Energy*, vol. 173, pp. 1119–1129, Apr. 2019, doi: 10.1016/j.energy.2019.02.098.

[5] Z. Wang, F. Han, Y. Liu, and W. Li, "Evolution Process of Liquefied Natural Gas from Stratification to Rollover in Tanks of Coastal Engineering with the Influence of Baffle Structure," *J. Mar. Sci. Eng.*, vol. 9, no. 1, p. 95, Jan. 2021, doi: 10.3390/jmse9010095.

[6] M. Kang, J. Kim, H. You, and D. Chang, "Experimental investigation of thermal stratification in cryogenic tanks," *Exp. Therm. Fluid Sci.*, vol. 96, pp. 371–382, Sep. 2018, doi: 10.1016/j.expthermflusci.2017.12.017.

[7] S. Wu and Y. Ju, "Numerical study of the boil-off gas (BOG) generation characteristics in a type C independent liquefied natural gas (LNG) tank under sloshing excitation," *Energy*, vol. 223, p. 120001, May 2021, doi: 10.1016/j.energy.2021.120001.

[8] J. Thiaucourt, P. Marty, J.-F. Hetet, P. Robert, and E. Delaire, "A zonal non-equilibrium approach to model temperature gradients during ventless bottom filling of pressurized cryotanks for natural gas-powered ships," *Energy*, vol. 188, p. 116033, Dec. 2019, doi: 10.1016/j.energy.2019.116033.

[9] F. Huerta and V. Vesovic, "A realistic vapour phase heat transfer model for the weathering of LNG stored in large tanks," *Energy*, vol. 174, pp. 280–291, May 2019, doi: 10.1016/j.energy.2019.02.174.

[10] I. L. Maclaine-cross and E. Leonardi, "Performance and Safety of LPG Refrigerants," in *Proceedings of the 'Fuel for Change' Conference of the Australian Liquefied Petroleum Gas Association*, 2002, pp. 335–351, [Online]. Available at: https://www.es-refrigerants.com/resources/docs/PERFORMANCE AND SAFETY OF LPG REFRIGERANTS.pdf.

[11] O. Nnodim, "FG orders petroleum ministry vehicles to run on autogas - Punch Newspapers," *Punch Most Widely Ready Newspaper*, 2020. [Online]. Available at: https://punchng.com/fg-orders-petroleum-ministry-vehicles-to-run-on-autogas/.

[12] T. Olowu, "Starting A Liquified Petroleum Gas (Lpg) Business In Nigeria," *Mocacc*. [Online]. Available at: https://mocaccountants.com/starting-a-liquified-petroleum-gas-lpg-business-in-nigeria/.

[13] L. Morozyuk, B. Kosoy, V. Sokolovska-Yefymenko, and V. Ierin, "Analysis of Mixing Processes of LPG Gases in Tanks When Transporting by Sea," *Dynamics*, vol. 2, no. 3, pp. 219–233, Jul. 2022, doi: 10.3390/dynamics2030011.

[14] N. Bruce *et al.*, "The Government-led initiative for LPG scale-up in Cameroon: Programme development and initial evaluation," *Energy Sustain. Dev.*, vol. 46, pp. 103–110, Oct. 2018, doi: 10.1016/j.esd.2018.05.010.

[15] B. Gbaarabe and J. I. Sodiki, "Economic Implication of Boil-Off Gas Generation in Liquefied Petroleum Gas Economic Implication of Boil-Off Gas Generation in Liquefied Petroleum Gas Supply Chain," *Int. J.*

Mod. Res. Eng. Technol., vol. 8, no. June, p. 11, 2023, [Online]. Available at: https://www.researchgate.net/profile/Baribuma- .

[16] C. F. Beaton, G. F. Hewitt, and P. E. Liley, "Physical property data for the design engineer," *CiNii*, 1989. [Online]. Available at: https://cir.nii.ac.jp/crid/1130282272564983296.

[17] Y.-P. Jo, M. S. F. Bangi, S.-H. Son, J. S.-I. Kwon, and S.-W. Hwang, "Dynamic modeling and offset-free predictive control of LNG tank," *Fuel*, vol. 285, p. 119074, Feb. 2021, doi: 10.1016/j.fuel.2020.119074.

[18] T. Dorcas Mobolade and P. Pourvahidi, "Bioclimatic Approach for Climate Classification of Nigeria," *Sustainability*, vol. 12, no. 10, p. 4192, May 2020, doi: 10.3390/su12104192.

[19] Y. Shao, S. Yoon, and H. Kang, "Dynamic simulation of fuel tank aging for LNG-fueled ship apparatus in an X-DF Otto cycle engine," *Energy Sci. Eng.*, vol. 7, no. 6, pp. 3005–3019, Dec. 2019, doi: 10.1002/ese3.475.

[20] T. Włodek, "Analysis of boil-off rate problem in Liquefied Natural Gas (LNG) receiving terminals.," *IOP Conf. Ser. Earth Environ. Sci.*, vol. 214, no. 1, p. 012105, Jan. 2019, doi: 10.1088/1755-1315/214/1/012105.

[21] F. Ovidi, E. Pagni, G. Landucci, and C. Galletti, "Numerical study of pressure build-up in vertical tanks for cryogenic flammables storage," *Appl. Therm. Eng.*, vol. 161, p. 114079, Oct. 2019, doi: 10.1016/j.applthermaleng.2019.114079.

[22] Z. Duan, H. Xue, X. Gong, and W. Tang, "A thermal non-equilibrium model for predicting LNG boil-off in storage tanks incorporating the natural convection effect," *Energy*, vol. 233, p. 121162, Oct. 2021, doi: 10.1016/j.energy.2021.121162.

[23] V. L. Malyshev and E. F. Moiseeva, "Parallel computing applied to the molecular dynamics simulations," *J. Phys. Conf. Ser.*, vol. 1392, no. 1, p. 012055, Nov. 2019, doi: 10.1088/1742-6596/1392/1/012055.

[24] C. Yildiz, A. S. Semerciöz, B. H. Yalçınkaya, T. D. Ipek, E. O. Isik, and M. Özilgen, "Entropy generation and accumulation in biological systems," *Int. J. Exergy*, vol. 33, no. 4, p. 444, 2020, doi: 10.1504/IJEX.2020.111691.

[25] Elengy, "Elengy Better energy," *Energy, Oil & Gas magazine*, 2021. [Online]. Available at: https://energy-oil-gas.com/news/elengy/.

[26] F. P. Incropera, D. P. DeWitt, T. L. Bergman, and A. S. Lavine, "Fundamentals of Heat and Mass Transfer. *Sixth Edition*," *Wiley and Sons, Inc., Hoboken, New Jersey*, p. 1-1024 , 2011.[Online]. Available at: https://books.google.com/books/about/Fundamentals_of_Heat_and_Mass_Transfer..

[27] M. Kalikatzarakis, G. Theotokatos, A. Coraddu, P. Sayan, and S. Y. Wong, "Model based analysis of the boil-off gas management and control for LNG fuelled vessels," *Energy*, vol. 251, p. 123872, Jul. 2022, doi: 10.1016/j.energy.2022.123872.

[28] D.-H. Lee, S.-J. Cha, J.-D. Kim, J.-H. Kim, S.-K. Kim, and J.-M. Lee, "Practical Prediction of the Boil-Off Rate of Independent-Type Storage Tanks," *J. Mar. Sci. Eng.*, vol. 9, no. 1, p. 36, Jan. 2021, doi: 10.3390/jmse9010036.

[29] National Bureau of Statistics, "Liquefied Petroleum Gas (Cooking Gas) Price Watch," *Natl. Bur. Stat.*, no. January, 2021, [Online]. Available at: http://nigeria.opendataforafrica.org/oieqsne/cooking-gas-price-watch-2018.

[30] S. Z. S. Al Ghafri *et al.*, "Advanced boil-off gas studies for liquefied natural gas," *Appl. Therm. Eng.*, vol. 189, p. 116735, May 2021, doi: 10.1016/j.applthermaleng.2021.116735.