REVIEW ARTICLE

Liquefied Petroleum Gas (LPG) Storage Tanks Boil-off Gas Generation and Management– Review

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ABSTRACT: This study is to review works on Liquefied petroleum gas (LPG) storage tanks, in order to assess boil-off gas generation and management. Liquefied petroleum gas (LPG) is used as fuel in heating appliances, cooking equipment, and vehicles. It also powers many business and agricultural processes. In Nigeria, LPG is becoming 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 for transportation. These have resulted in the emergence of a lot of LPG skid plants, without proper boil-off gas (BOG) recovery systems, thus raising safety and profitability concerns. The generation of boil-off gas in the storage tank causes losses in the LPG supply chain over time. 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 the safety and economic assessment of LPG storage tanks.

KEYWORDS: Liquefied petroleum gas (LPG) storage tanks, safety, profitability, boil-off gas, fuel

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1. INTRODUCTION

The Nigerian government announced the decade of gas, an initiative designed to ensure that Nigeria can take advantage of the global energy transition. National stakeholders seemingly renewed their resolve to optimize Nigeria's gas resources throughout the new decade. This resolve was accompanied by a call to boost the widespread utilization of all forms of gas products, from compressed natural gas (CNG) to liquefied petroleum gas (LPG), in Nigeria [1]. 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. These have resulted in the expansion of LPG Markets, and emergence of a lot of LPG skid plants nationwide, without proper boil-off gas (BOG) recovery system, which rises safety and profitability concern in the domestic LPG markets. BOG generation in LPG supply chain is one of the most important factors for safety and economic assessment of LPG skid plant. Thus, has become one the most significant research interest.

2. OVERVIEW OF LPG PROCESSES AND STORAGE

Chen et al., [2] analyzed the temperature and pressure changes in Liquefied Petroleum gas storage tanks. In their analysis, thermodynamic and heat transfer methods were used to analyze the pressure and temperature changes in LPG tanks. The thermodynamic properties and composition of the LPG fuel inside tanks as a function of time were simulated and the LPG fuel loss rate due to venting was discussed, and certain approaches to prevent the loss were also proposed. Gorieuet al.,[3] introduced how to operate LPG terminals flexibly and safely under the condition of different LPG producing areas and diversified LPG quality. The strict requirements and solutions of the above conditions to the injection objects were analyzed by using the experimental data of manufacturers. They reported that the comprehensive stratification predictive model should help gas companies optimized the handling of different LPGs in their storage tanks.

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Khelifi et al., [4] studied laminar natural convection in a storage tank filled with LPG using a numerical method based on the two-dimensional approach. These researchers aimed to understand the evaporation problem occurring in an LPG tank by conducting a parametric study. Their main finding was that the increase of the Rayleigh number at constant aspect ratio, or the reduction of aspect ratio at a constant Rayleigh, enhanced the heat transfer. In addition, due to this heat gain, it was observed that the evaporative flux was maximum near the wall and minimum at the free surface center; Furthermore, in the light of the steady state study.

Gronhauget al.,[5] expressed the LPG inventory and routing problem in their study with inventory management and port constraints. They introduced a method to solve sub-problems for ship routes. In the study, a solution methodology was proposed to solve the problem much faster than commercial optimization software and to solve larger samples than the previous examples. Jang [6] designed an algorithm for the optimal operation of BOG compressors. The authors investigated an optimal pressure between the steady-state and desired tank pressure based on the simulation of the dynamic behavior of the LPG tank. Their proposed algorithm exemplified a superior performance in comparison to previous research and routine process algorithms. Li et al.,[7]analyzed and optimized the BOG condensation system in China's first receiving terminal and provided a flexible and cost-effective optimization method to facilitate designing and improving other BOG re-condensation processes. The research indicated that for 6.69 tons/h BOG with an LPG output between 49 and 562 tons/h, the optimization results were successful at decreasing the process energy by 91.2 kW, while 1.28 tons/h would be recovered. Dobrota et al., [8] presented a paper on the problem of boil-off in the LPG supply chain. The paper examined the problem of evaporation of LPG occurring at different places in the LPG supply chain and presented the general methods of handling and utilizing BOG at different points in the LPG supply chain, having considered evaporation losses in the LPG supply chain as one of the key factors for LPG safety and economic assessment.

Roh & Son [9] investigated the natural convection in a Liquefied Petroleum Gas (LPG) tank using the commercial computational fluid dynamic software FLUENT. Their major results revealed that heat transfer rate was strongly related to liquid-solid contact area. In addition, this heat transfer was essentially caused by the liquid region rather than by the vapor region. Zakaria et al., [10] carried out a parametric analysis on boil-off gas rate inside Liquefied Petroleum Gas storage tanks. The analysis was carried out to determine the relationship between heat thermal transmittance and ambient condition, and the boil-off rate for a specific 40,447m^3 LPG tank for both the steady and unsteady behavior of heat transfer mechanisms using ANSYS Fluent software. Results show that dynamic transient simulation only takes effect on the first five days of a voyage and that there is a linear relationship between the investigated parameters of the boil-off rate of LPG. Sharafian et al.,[11] presented a study on performance analysis of Liquefied Petroleum Gas storage tanks in refueling stations. In the study, time-dependent thermodynamic models were developed to study the LPG holding time of storage tanks in refueling stations before BOG releases to the atmosphere. Previously overlooked factors, such as the thermal mass of storage tanks and the actual operating conditions at refueling stations, were included explicitly in the models. The effect of the thermal mass of storage tanks on holding time is illustrated by an analysis of 57.20 m^3 storage tanks filled with LPG at -150 °C and -126.5 °C. The modeling of the 57.20 m^3 storage tank with a heat transfer coefficient of 0.022 W/m^{2}K shows that fuel delivery rates as low as 1.89 m^3/day are sufficient to maintain the tank pressure within allowable limits.

Mianaet al.,[12] predicted the LPG weathering in LPG carriers. Their results showed that the constant and variable evaporation rates led to the more accurate prediction of the LPG weathering at a destination. Comparing the numerical and experimental data to predict the LPG weathering showed that the average error between the two sets of data was minimized by increasing the voyage length and ship storage capacity. Zakaria et al., [10] analyzed the heat and pressure distribution of LPG during heat leakage. The simulation involves heat leakage from static storage tanks, bottom and sidewalls. The results show that the maximum pressure point is on the circumference connecting the tank top and the tank sidewall. Kurle et al.,[13] performed dynamic simulations of an LPG vessels loading process to obtain the jetty boil-off gas Recovery generation profile. The researchers also studied the effect of the holding mode heat leak, initial ship-tank temperature, tank cooling rate, and jetty boil-off gas compressor capacity. The work also examined several jetty boil-off gas utilization strategies.

Effendy et al., [14] studied an atmospheric LPG storage tank of a degasification terminal using a non-equilibrium thermodynamic model. Their numerical results showed that during 15 days of operation, the liquid phase temperature remained constant, while the vapor phase temperature increased by about 15°C.Calogero et al., [15] developed a non-equilibrium thermodynamic model to predict the LPG weathering in atmospheric storage tanks. Their numerical results showed that the vapor temperature maintained about 8°C higher than the boiling temperature of LPG during the course 11 of a year. Also, the BOG generation rate calculated by their non-equilibrium thermodynamic model decreased by 25% compared with the equilibrium thermodynamic model reported in their previous study [16] experimentally carried out an investigation of thermal stratification in storage tanks. They investigated the thermodynamic behavior that occurs when cryogenic liquids, such LPG and liquid hydrogen, are stored. The experiment was conducted with liquid nitrogen and cryogenic liquid under 0.024 W/mK using vacuum insulation characterized by a thermal conductivity coefficient similar to that of the polyurethane foam commonly installed in LPG storage tanks. The experimental results indicated different behaviors because of thermal stratification. They concluded that the thermodynamic behaviors resulting from thermal stratification are significantly different from those predicted by the homogeneous model.

Krikkis [17] used the non-equilibrium thermodynamic modeling to calculate the LPG weathering during ship transportation and compared the results with the experimental data. Krikkis experimental measurements showed that the LPG temperature in atmospheric storage tanks did not change significantly, while the vapor phase temperature varied from -143°C to -72°C. Comparing the results of the non-equilibrium thermodynamic modeling and the experimental data of a laden voyage showed that the modeling results predicted the BOG generation rate with good accuracy in comparison with the measured amount of vapor removed from the tank. Włodek [18] analyzed the boil-off rate problem in LPG receiving terminals. The results of the analysis show that boil-off rate increases with increase in ambient temperature. Performed analysis for bi-component mixtures methane-ethane and methane-nitrogen showed that boil-off rate as percentage of LPG volume in the tank decreases with increase of ethane molar fraction, in case of nitrogen there is opposite. Huerta & Vesovic [19] provided a rule of thumb for estimating the temperature of evaporated gas in industrial storage tanks and developed an unbalanced model related to LPG evaporation from large storage tanks at constant pressure that treats the heat influx from the surroundings into the vapor and liquid phases separately and allows for heat transfer between the two phases.

Federica et al., [20] used CFD technology to simulate the self-pressurization behavior of storage tanks. The evaporation of ethylene and methane in storage tanks was studied. Ethylene was found to pressurize and vaporize faster than methane. Due to more effective natural convection, the liquid thermal stratification of methane is wider than that of ethylene.

Quet al.,[21] used a non-equilibrium thermodynamic modeling to study the BOG generation rate in a 160,000m^3 LPG ship tank during the laden voyage and ballast phase. The average daily BOG generation rate was about 0.14%. For the self-pressurization, the steep pressurization occurred at the initial phase, while the saturation temperature was almost constant. They reported that using the tank pressure and sea conditions as the input parameters, their model accurately predicted the vapor temperature in the LPG tank and the average daily BOG generation rate during the laden voyage and ballast phase. Khan et al., [22] presented a study on energy saving through efficient BOG prediction and impact of static BOG rate in full containment-type LPG Storage tank. The study investigated the impact of static BOG predictions and the result showed that BOG is a strong function of liquid level in a tank. Total heat leakage in a tank practically remains constant; nonetheless the unequal distribution of heat in vapor and liquid gives variation in BOG.

Lee et al., [23] performed dynamic simulation to estimate the collected amount of BOG produced during ship-to-ship LPG bunkering and assessed the contribution of each parameter, including temperature variation, transportation rate, and pipe insulation performance. By combining the approaches of the two previously described studies, several simulations and cycle assessments have been conducted to suggest useful environmental indicators. Wang et al., [24] presented an article on evolution process of Liquefied Petroleum Gas from stratification to rollover in storage tanks with the influence of baffle structure. The article theoretically analyzed the causes and inducing factors of the LPG stratification and rollover phenomenon in the storage tank. Computational fluid dynamics was used to establish a numerical model for the heat and mass transfer of LPG multi-component materials in the imaginary layered interface of the storage tank, and the evolution process of LPG from spontaneous stratification to rollover was simulated. The accuracy of the mathematical model was verified by comparing numerical results with experimental data from open literature. The effects of the density difference between upper and lower layers, layering parameters, heat leakage parameters, and the baffles structure on the rollover process were studied. The results show that different baffle structures formed different boundary velocity fields and the baffle structure that has the best suppression of rollover and the minimum boundary velocity is at 0.5 m above the stratified interface with the installation of the baffle at 5 degrees. Lee et al.,[23] 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 was used to analyze the surface temperature according to the filling ratio. They concluded that under high filling ratios, the amount of BOG generation was the smallest, 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 also that the rate of boil-off generation was predicted through finite element analysis within 1% of minimum error when compared to an empirical correlation applied to the designed fuel tank.

Al Ghafri et al., [25] reported series of experiments that have been conducted for LPG-like binary mixtures of methane and ethane to measure the BOG production and resultant pressure change under various industrially relevant conditions. Experimental data and observations made in the work are compared with both the available literature and with the predictions of a new non-equilibrium model that uses the GERG-2008 equation of state to calculate relevant LPG and BOG properties. The data revealed three distinct stages of BOG evolution, labeled as self-pressurization, transient, and homogenous. It was observed that, in the self-pressurization stage, the thickness of a thermally stratified layer adjacent to the liquid–vapor interface increases with time. The transient stage is defined to commence when the system reaches the specified relief pressure and the homogeneous stage is reached upon the effective elimination of thermal stratification in the LPG. They observed that good agreement exists between the new model and the experimental and literature data acquired during the self-pressurization and homogeneous stages. In the transient stage, the model does not accurately quantify the BOG rate indicating a need to incorporate the effects liquid thermal stratification in future model development.

Bouabidiet al.,[26] presented a study on analysis of the processes in the components of the LPG (propane/ butane) re-liquefaction plant under the conditions of co-mingling in tanks when transporting by sea. In the analysis, energy analysis of the mixture-based re-liquefaction plant has been performed using the monitoring data of an LPG cargo operation. The analysis considered the characteristics of the mixture in the tanks, operating conditions of the re-liquefaction plant, and the performance of the system. The method of equivalence was applied for thermodynamic analysis. The result of the substitution of actual processes with equivalent ones allows for the accomplishment of the parameters control of each working fluid within the mixture as a pure working fluid. It is showed that the low-boiling component determines the operating parameters of the entire re-liquefaction plant. The method of equivalence and visualization of the processes within the LPG as a mixture using the thermodynamic diagrams of pure working fluids is recommended to shorten the path to set up the appropriate re-liquefaction plant management strategy. The energy analysis performed using the method of equivalent cycles was validated with the existing re-liquefaction plant characteristics with inaccuracies in the limit of 4%.

3. DOMESTIC CONSUMPTION AND RETAIL MARKETING OF LPG

LPG has a wide variety of uses, ranging from automotive fuel to chemical feedstock. Despite this, its primary use in Nigeria has been domestic. LPG currently constitutes about five per cent of Nigeria's household energy mix, and this figure continues to increase rapidly. Nigeria's domestic consumption of LPG increased from 250,000 metric tons in 2013 to over one million metric tons in 2020, which represent an increase of over 300 per cent within seven years. This rapid increase in LPG adoption is a major indicator of Nigeria's position as one of the fastest-growing LPG markets in the world. While the growing LPG adoption rate undoubtedly holds huge promise for Nigeria's clean energy agenda (due to LPG's low carbon intensity) Nigeria does not appear to be ready for large-scale LPG adoption in its domestic market. This un-readiness is due to a number of bottlenecks including a low level of regulation of the LPG retail market, shortage of LPG facilities, an unresolved tank crisis in the country, and BOG generation in the LPG storage tank [26].

LPG retail market in Nigeria's largely unregulated. This is primarily because during the enactment of the 1969 Petroleum Act, Nigeria's primary oil and gas regulatory law, gas resources were not paid sufficient attention and, consequently, the Petroleum Act has been largely oil-focused [27]. The government is attempting to rectify this issue with the Petroleum Industry Bill, which has been in the legislative pipeline for over a decade, and was just passed by the Senate last week. The absence of adequate regulation has resulted in the widespread presence of unregistered and illegal LPG operators, with dire consequences. For instance, although LPG decanting has been shown to increase the risk of explosions, the practice of LPG decanting continues to be widespread, with unregistered roadside gas refilling shops littered all over the country decanting LPG to consumers. The prevalence of illegal LPG operators has not only culminated in immense losses for gas investors; it has also endangered the lives of Nigerians. A case in point is the infamous 2014 Ondo gas explosion, which occurred due to the operations of an unregistered gas refilling plant. The explosion led to the destruction of over 42 shops and houses, and over eight people were critically injured. As the LPG market continues to grow, illegal operators will continue to act, posing an increasing risk to public safety. The Nigerian government urgently needs to intensify efforts towards clamping down on illegal LPG operators. Such efforts could include the adoption of a whistle-blowing channel for communities to report suspected illegal LPG operators. These whistle-blowing channels could be made effective by the adequate sensitization of community members to the dangers of illegal LPG operations.

4. AVAILABILITY OF LPG FACILITIES

Nigeria has a dearth of LPG facilities. The LPG transportation network is weak, with the absence of a rail or pipeline distribution network. This is coupled with the problem of inadequate storage facilities and bottling plants. Nigeria's current LPG storage capacity stands at 69,968 metric tonnes, a figure far below South Africa's capacity of over 200,000 metric tonnes [1]. Similarly, there are only about 200 registered LPG bottling plants across Nigeria, the majority of which are situated in urban and semi-urban areas. To put these figures into context, Nigeria essentially has only one registered LPG bottling plant for every one million Nigerians. This is in sharp contrast with South Africa, which currently has 4,452 refilling plants with a population of approximately 58.5 million people, as opposed to Nigeria's 200 million.

Evidently, Nigeria's LPG sector has an infrastructure problem. In order to resolve this challenge, Nigeria needs to drive more investment towards LPG. While recent investments like the Ajaokuta-Kaduna-Kano gas pipeline project are undoubtedly notable, they are insufficient to solve Nigeria's shortage of facilities in the retail market. As such, Nigeria needs to intensify efforts directed at encouraging private sector investment in the downstream gas sector through the creation of a comprehensive investment scheme tailored to the expansion of LPG access [28]. Such an investment scheme would involve the disbursement of funds for the construction of storage and bottling facilities, as well as the provision of funding to prospective downstream LPG investors.

Nigeria's LPG cylinder value chain has been largely disorganized, and this has posed a major threat to safety and quality compliance. Nigeria currently operates a customer-controlled cylinder distribution model, which involves the full purchase and ownership of cylinders by consumers. Under this model, consumers only have to buy cylinders and refill them at intervals. However, the operation of this distribution model has been severely hampered by the lack of adequate monitoring of the quality of the cylinders circulating the Nigerian market [27]. Nigerian consumers often purchase unbranded and sub-standard LPG cylinders from roadside sellers, a culture which has led to the widespread infiltration of sub-standard gas cylinders in the domestic market. The infiltration of these sub-standard cylinders is so prevalent that about 90 per cent of all the LPG cylinders currently in circulation are expired. These expired cylinders are imported into the country, and often evade quality checks by the Standards Organization of Nigeria (SON) [29].

The overwhelming prevalence of sub-standard LPG cylinders has had fatal effects, as cylinder explosions have rocked several Nigerian households. Realizing the severity of the situation, in January 2020, the Nigerian government announced the transition of the domestic LPG market from a customer-controlled distribution model to a marketer-controlled model. This marketer-controlled model involves a system where marketers retain ownership of the cylinders and assume full responsibility for cylinder testing. Essentially, under this distribution model, consumers will have to make a deposit in order to obtain branded cylinders from marketers. When such cylinders are empty, they are returned to the marketer, in exchange for a filled cylinder. During this process, the marketer retains ownership at all times. The consumer only obtains a filled cylinder, makes use of it, and exchanges the empty cylinder for a filled one. Cylinders can only be returned to the same marketer; as such cylinders are often branded. Responsibilities of testing and quality assurance are solely on the marketer.

However, the transition plan has had little impact. The operation of a marketer-controlled distribution model is barely feasible in Nigeria, primarily because the implementation of this model is highly capital-intensive. In addition, as previously mentioned, Nigeria does not have enough large-scale refilling plants located in close proximity to consumers to cater for the domestic demands of Nigeria's large population. Instead of a marketer-controlled distribution model, Nigeria needs a model that takes the peculiarity of the Nigerian LPG market into consideration [33]. An option could be maintaining the current customer-controlled model, but with the provision of LPG testing facilities across all the states in the federation, under this system, consumers would be encouraged to regularly take their cylinders to testing centers for the verification of the cylinders' standards. Through this model, the government would be able to exercise considerable control over quality compliance, while also ridding the market of sub-standard cylinders.

The major concern with the adoption of this strategy is the continued indifference of market participants to periodically testing their cylinders. To ensure that consumers comply with the proposed model, the government has to embark on rigorous sensitization about the need for LPG testing. Subsequently, the government may provide incentives such as discounts on new cylinders to consumers who have sub-standard cylinders. The funding of these discounts can be covered through a partnership between the government and local cylinder manufacturing companies. Australia has adopted a similar strategy by providing a host of accredited LPG testing centers for LPG consumers in its domestic market [32].

Coupled with this, efforts could also be intensified to reduce the importation of LPG cylinders by encouraging investment in domestic cylinder manufacturing plants. Fiscal policies such as tax holidays will help to incentivize such investment [34]. Consequently, the government will have a significant share of the domestic LPG market, and would be able to ensure standardization along the cylinder value chain.

5. LPG TANK CAPACITIES AND LAYOUT

LPG (Liquefied Petroleum Gas) storage tanks are containers designed to store large quantities of propane or butane, which are commonly used as a source of fuel for heating and cooking in both residential and industrial applications [31]. These tanks are typically made of steel or

Another durable material that can withstand the high pressure and low temperatures required to store LPG in its liquid form [30]. LPG storage tanks come in various sizes, from small cylinders used for portable stoves and heaters to large tanks used for industrial purposes, such as powering forklifts and other heavy equipment. The capacity of LPG storage tanks can range from a few hundred liters to several thousand liters, depending on the specific application and the amount of LPG needed.

LPG storage tanks must be designed and installed in compliance with strict safety regulations to prevent accidents and leaks. This includes regular inspection and maintenance to ensure that the tank is in good working condition and that any potential issues are addressed promptly.

Figure 1: LPG Storage Tank [30]

There are several types of LPG storage tanks, each designed for specific applications and with varying capacities. Some of the most common types of LPG storage tanks include:

- Aboveground LPG storage tanks: These are large tanks that are installed above the ground and are typically used for storing LPG in bulk for commercial and industrial applications.
- Underground LPG storage tanks: These tanks are installed underground and are commonly used for storing LPG in residential areas where space is limited.
- Horizontal LPG storage tanks: These tanks are designed to be installed horizontally and are commonly used for storing LPG in industrial settings.
- Vertical LPG storage tanks: These tanks are designed to be installed vertically and are commonly used for storing LPG in residential areas and small commercial settings.
- Mounded LPG storage tanks: These tanks are installed on a concrete platform or mound and are commonly used for storing LPG in industrial settings.
- Propane cylinders: These are small portable tanks used for storing LPG for outdoor cooking and camping.
- Cylindrical Storage Tanks
- Spherical Storage Tanks

Each type of LPG storage tank has its own advantages and disadvantages, and the choice of the tank will depend on the specific application and the amount of LPG Spherical or horizontal cylindrical type (bullet type) storage tanks are generally used to store LPG. The horizontal cylindrical types are usually used for small-capacity or underground installations and Spherical ones are used for higher capacities. The design of high-pressure LPG storage tanks is critical. Many parameters need to be considered during design.

6. LPG TANK APPURTENANCES

The tank shell attachments are designed in conformance with API Standard 650 [35] as followings:

- Manhole: One roof manhole of diameter 600 mm, should be provided for tanks 20m diameter or less and two for tanks over 20 m diameter.

- Vents and relief valves: The number and size of vents provided shall be based on the venting capacity obtained from the API 2000 and should be sufficient to prevent any increasing of pressure or vacuum (including that arising from inert gas blanketing) exceeding the design conditions specified for and approved by the Company. For fixed roof low pressure tanks (20mbar and/or 2kPa) containing low flash point material a pressure and vacuum type breather valve should be designed and provided upon the approval of the Company. These valves should be fitted with a screen of appropriate mesh. Pressure and vacuum relieving devices shall be designed in accordance with provisions of API Standard 620 and requirements above. For fixed roof non-pressure tanks containing high flash point material, which is never heated above the flash point, free vents of the Company approved design should be provided. These free vents should be fitted with screens of appropriate mesh.
- Control instrumentation: Temperature sensor alarm is required at sensing points.

7. CONCLUSIONS

Significant numbers of research had been conducted recently in analyzing temperature and pressure changes, heat leakage and boil-off rate in LPG storage tanks using thermodynamic and heat transfer methods and the analyses showed direct correlations between boil off gas and operating pressure. As temperature and pressure changes is one of the crucial factors in the generation of BOG which causes evaporation losses and safety concern around the tank.

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