Modelling of Boil-Off Gas in LNG Tanks: A Case Study

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***Abstract*— This paper focuses on the effect of pressure and heat leakages on Boil-off Gas (BOG) in Liquefied Natural Gas (LNG) tanks. The Lee-Kesler-Plocker (LKP) and the Starling modified Benedict-Webb-Rubin (BWRS) empirical models were used to simulate the compressibility factor, enthalpy and hence heat leakage at various pressures to determine the factors that affect the BOG in typical LNG tanks of different capacities. Using a case study data the heat leakage of 140,000kl, 160,00kl, 180,000kl and 200,000kl LNG tanks were analyzed using the LKP and BWRS models. The heat leakage of LNG tanks depends on the structure of tanks, and the small tanks lose heat to the environment due to their large surface area to volume ratio. As the operation pressure was dropped to 200mbar, all four of the LNG tanks' BOG levels reached 0.05vol%/day. In order to satisfy the BOG design requirement, the operating pressure of the four large LNG tanks in the case study was maintained above 200mbar. Thus, the operating pressure impacts BOG on LNG tanks, but this effect is limited under the extreme high operation pressure. An attempt was made to determine the relationship between the compositions of LNG and BOG; one been combustible and the other non-combustible gases. The main component of combustible gas was methane, and nitrogen was of non-combustible gases. The relationship between BOG and methane compositions was that, as the methane fraction increases in the LNG, the BOG volume also increases. In general, results showed a direct correlation between BOG and operating pressure. The study also found that larger LNG tanks have less BOG; however as the operation pressure is increased the differences in the quantity of BOG among the four tanks decreased.**

Keywords: Boil-off Gas (BOG), Liquefied Natural Gas (LNG), Lee-Kesler-Plocker (LKP) and Starling modified Benedict-Webb-Rubin (BWRS) model.

1. INTRODUCTION

Natural gas is favored, in many countries, over other fuels such as coal because of its relatively high quality and cleaner burning character which thus reduces pollution to the environment. Liquefied natural gas (LNG) is a better form for the long distance transportation and storage of natural gas. LNG is produced by cooling natural gas with liquid nitrogen to -160^{o}C under the normal pressure. The resultant volume of the LNG will be 1/600 that of the original natural gas. Thus, LNG is the format for natural gas transportation and storage. The LNG industry and trade increased rapidly in recent years. The common characteristic of LNG Storage tanks is the ability to store LNG at the very low temperature of -160^{o}C. LNG storage tanks have double containers, where the inner contains LNG and the outer container contains insulation materials. [1, 2]
Boil-Off Gas (BOG) is the vapour phase in the LNG tanks. As the increase in BOG will leads to an increase in the pressure of the LNG tank as the volume of the gas form is much greater than the liquid form, BOG can be a big problem for LNG tanks storage.

In this study, the heat leakage of LNG tanks would be investigated, because it is the main reason for BOG of LNG tanks. As the heat leakage is determined by the structure of the tanks, the different types of LNG tank should be learned, firstly.

Some parameters also can impact BOG quantity, such as operating pressure, and compositions of LNG. Thus, the thermodynamics character of LNG needed to analysis, it is necessary to choose a suitable model to apply, and to process available computer programs, in order to compute these models. The results of each model are discussed and the general character of BOG would be obtained; thus, some useful suggestions could be given for the use of LNG tanks.

2. LNG MODELS

There are many kinds of model available for LNG modelling, which range from the simplest Gaussian model, through simplified density gas models to computational fluid dynamic codes [3]. The Gaussian model assumes dispersion is dominated by atmospheric turbulence and ignores dense gas effects thus is not considered appropriate for gas density equation. There are several current uses of CFD codes for LNG [4], as CFD directly uses the fundamental equations of fluid flow. Also local geographic feature can be included in CFD by working with a customized grid and boundary conditions. However, the disadvantage of CFD is that there are many additional modeling issues which should be addressed. Thus, CFD code has not been a routine model for LNG.

Equations of state (EOS) are commonly used to analyze the vapor-liquid phases of multi-component fluid mixtures. The Lee-Kesler-Plocker (LKP) equation draws upon the relationship of PVT (Pressure, Volume, and Temperature). It was first proposed for in use for thermodynamic properties by Ploker [5]. The LKP equation is an accurate general method for non-polar substances and mixtures, which can be used in the calculation of density and enthalpy.

In order to calculate the BOG of LNG, the density, and enthalpy are the key parameters, and virial equations are just theoretical expressions, they are developed by LKP model and BWRS model; thus, LKP and BWRS model are suitable methods to compute BOG of LNG. Furthermore, the two models are convenient for computer programming. LKP models are used for calculating the compressibility factor and deriving thermodynamic properties of normal fluids and modified LKP equations for calculation of polar fluids. An acentric factor as the fourth parameter was added to calculate vapor-phase data for each fluid. The accuracy of some equations of state for the prediction of molar volume for different hydrocarbons were reviewed by Ye *et al.* [6] and Solimando *et al.* [7], recently. Ye used the corresponding states LKP model, Peng-Robinson model, and Simonet-Behar-Rauzy equation. He concluded the LKP model to generally produce better results, especially at high pressures.

Solimando analyzed three equations (Simonet-Behar-Rauzy, Lee-Kesler-Prausnits**,** and Chain of Rotators equations), which are based on more theoretical developments. They concluded that the LKP model had more accurate densities for light hydrocarbons. Using the LKP model only the critical pressure, temperature and ancentric factor are the required input parameter needed to calculate the density and enthalpy of LNG. However, the LKP model does not consider the effect of components of LNG.

2.1 LKP model

According to Robert [6], the LKP equation is given as:

$$Z = Z^{(0)} + \frac{\omega}{\omega^{(r)}}(Z^{(r)} - Z^{(0)}) \tag{1}$$

$$\omega = -\log_{10}(\frac{p}{p_c}) - 1 \quad \text{at} \quad \frac{T}{T_c} = 0.7 \tag{2}$$

Z is compressibility factor, which is obtained using the gas law,

$$Z = \frac{PV}{nRT} \tag{3}$$

Through to improve the factor $z^{(r)}$, and $z^{(0)}$, equation (1) can be written as:

$$Z = (\frac{p_r v_r}{T_r}) = 1 + \frac{B}{v_r} + \frac{C}{v_r^2} + \frac{D}{v_r^5} + \frac{c_4}{T^3 v_r^2}(\beta + \frac{\gamma}{v_r^2})\exp(-\frac{\gamma}{v_r^2}) \tag{4}$$

Where P_r is pressure contract, T_r is temperature contract, is specific heat capacity contract. And *B*, *C*, *D*, C_4, β and γ are the parameter, which could be obtained from table [8]**.**

Assuming in the LNG tank the whole process is isothermal, and the different in enthalpy and entropy is only depended on the initial and final state. Thus, according to LKP equation, the change in enthalpy would be:

$$\frac{\Delta H}{RT_r} = (\frac{\Delta H}{RT_r})^{(0)} + \frac{\omega}{\omega^{(r)}}[(\frac{\Delta H}{RT_r}) - (\frac{\Delta H}{RT_r})^{(0)}] \tag{5}$$

Using equation (3), the density of the true liquid is obtained as:

$$\rho_t = \frac{1}{v_t} = \frac{p_t}{ZRT_t} \tag{6}$$

Thus substitute equation (6) into (4), the function of ρ_t should be:

$$\begin{aligned} f(\rho_r) = {} & T_r\{\rho_r + B\rho_r^2 + C\rho_r^3 + D\rho_r^6(\beta + \gamma\rho_r^2) \\ & \exp(-\gamma\rho_r^2)\} - p_r \end{aligned} \tag{7}$$

To derivate the function:

$$\begin{aligned} f'(\rho_r) = {} & T_r\{1 + 2B\rho_r + 3C\rho_r^2 + 6D\rho_r^5 + \\ & \frac{c_4}{T_r^3}\rho_r^2[3\beta + \gamma\rho_r^2(5 - 2\beta) - 2\gamma^2\rho_r^4\exp(-\gamma\rho_r^2)\} \end{aligned} \tag{8}$$

Thus,through the Newton-Raphson iterative formula, the data processing was computed.

2.2 BWRS model

The Benedict-Webb-Rubin equation (BWR) is an equation of state used in fluid dynamics, the original model states as [20]:

$$\begin{aligned} P = {} & \rho RT + (B_0RT - A_0 - \frac{C_0}{T^2})\rho^2 + (bRT - a)\rho^3 \\ & + \alpha a\rho^6 + \frac{c\rho^3}{T^2}(1 + \gamma\rho^2)\exp(-\gamma\rho^2) \end{aligned} \tag{9}$$

And there is a modification of BWR by Kenneth Starling [9], as:

$$\begin{aligned} P = {} & \rho RT + (B_0RT - A_0 - \frac{C_0}{T^2} + \frac{D_0}{T^3} - \frac{E_0}{T^4})\rho^2 + (bRT - a - \frac{d}{T})\rho^3 \\ & + \alpha(a + \frac{d}{T})\rho^6 + \frac{c\rho^3}{T^2}(1 + \gamma\rho^2)\exp(-\gamma\rho^2) \end{aligned} \tag{10}$$

which is BWRS model. ρ is molar density; T is the temperature; and P is the pressure.

In order to calculate [17], it is necessary to assume:

$R_1 = RT$; $R_2 = B_0RT - A_0 - \frac{C_0}{T^2} + \frac{D_0}{T^3} - \frac{E_0}{T^4}$; $R_3 = bRT - a - \frac{d}{T}$; $R_4 = \alpha(a + \frac{d}{T})$; and $R_5 = \frac{c}{T^2}$.

Thus, the BWRS equation can be written as:

$$P = R_1\rho + R_2\rho^2 + R_3\rho^3 + R_4\rho^6 + R_5\rho^3(1+\gamma\rho^2)\exp(-\gamma\rho^2) \qquad (11)$$

It also can be changed to an equivalent equation, which can be iterated.

$$\rho = \left\{\left[P - R_1\rho - R_3\rho^3 - R_4\rho^6 - R_5\rho^3\left(1+\gamma\rho^2\right)/R_2\right]\right\}^{1/2} \qquad (12)$$

This equation can be convergence to one direction, thus, to make $f(\rho) = 0$

2.3 Data of LNG Heat Leakage

The temperature of LNG is about -160°C, so heat energy is transferred through the thermal insulation layer into the LNG tanks. This heat transfer causes the LNG to evaporation. It is also the reason for the pressure change in the LNG tank. As the heat leakage is the energy exchange between the inner tank and outside environment, it can be controlled to a certain extent by the structure of LNG tank. [1,2,10,11]

Three assumptions were made for computing the heat leakage of LNG tanks which are as follows:

- All the evaporation of LNG only occurs at the surface of the liquid phase;
- During the process of evaporation, the vapour-liquid phases are equilibrium;
- The temperature and density of LNG is constant during the whole process.

The heat leakage of LNG tanks was calculated by each part: Roof, Side, and Bottom [12]. Table 1 shows the heat leakage results of four kinds of LNG tanks.[13,14]

TABLE 1:
HEAT LEAKAGE OF FOUR TANKS

	140,000 kl	**160,000 kl**	**180,000 kl**	**200,000 kl**
Roof, W	40352	37334 (without deck)	46609	45396
Side, W	51694	53935	49333	49866
Bottom, W	77872	71984	70610	68000
Total, W	169919	168243	166552	163253

2.4 Boil-off Gas of LNG Tank

LNG is stored in vessels with cryogenic tanks in the absence of any means of external refrigeration; thus, there is a little BOG, which means a little volume evaporates. The BOG of LNG has been a key issue for economic and technical reasons. BOG causes the pressure to increase inside the inner LNG tank, which also produces a safety risk. The assessment of the BOG quantity and thermodynamic properties during storage in the tank is of key importance to the whole LNG transport system. The heat leakage leads to the BOG of the tank. [15, 16]

The boil of gas (BOG) is computed using equation

$$BOG = \frac{m \times 3600 \times 24}{V\rho} \qquad (13)$$

The rate of gas evaporation could be obtained as:

$$m = \frac{\phi}{\Delta h} \qquad (14)$$

Figure1 and Figure 2 show the results of LKP model and BWRS models.

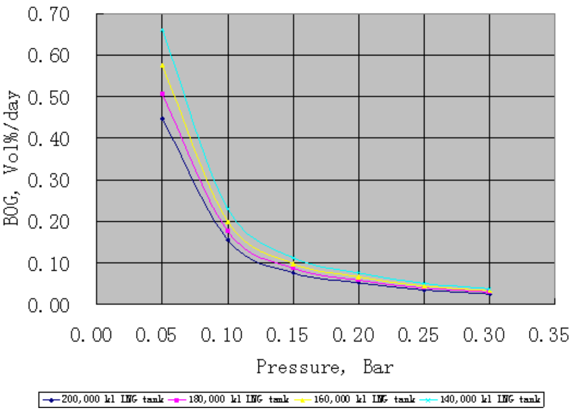

Fig.1: The relationship between operating pressure and BOG

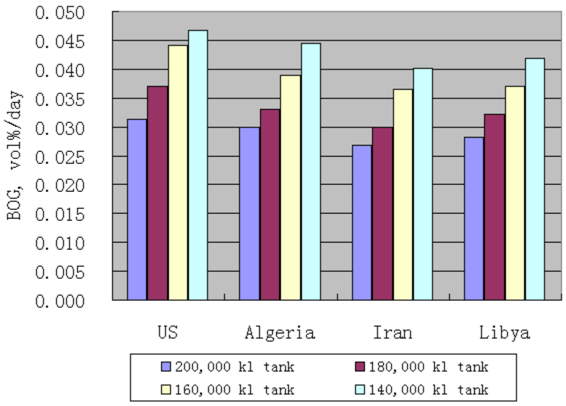

Fig.2: BOG of different sources of LNG [18]

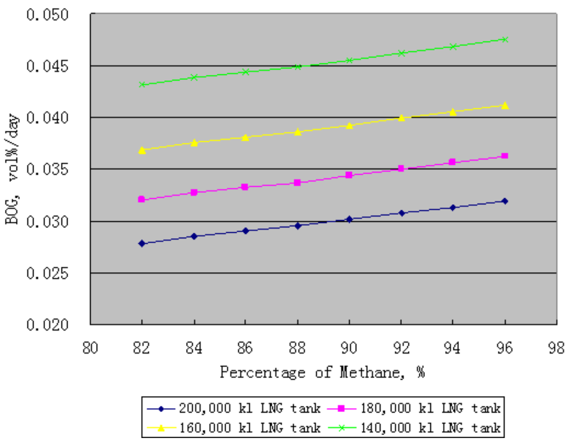

Fig.3: Relationship between BOG and percentage of Methane

The heat leakage of LNG tanks depends on the structure of tanks, and the small tanks lose heat to the environment due to their large surface area to volume ratio.

There are several types of LNG tanks that have the different insulation systems; as such the thermal conductivity of LNG tanks is dependent on the insulation system of the tank in addition to its size. Using case study data the heat leakage of 140,000 kl, 160,000 kl, 180,000 kl and 200,000 kl LNG tanks were calculated to be 169,919 W, 168,243 W, 166,552 W and 163,253 W, respectively.

According to Prasad *et al.* [11], the BOG of normal large LNG tank is about 0.03~0.08 vol%/day, thus, there could be about 60~160 kl of liquid gas evaporating every day from a 200,000 kl LNG tank. The vapour can lead to the pressure of LNG tank increasing; on the other hand, it is useful to know the BOG volume of LNG tank through pressure monitoring.

In the case study, the design pressure of large LNG tanks are between 50~350 mbar [13], and the design BOG is 0.05 vol%/day. However, results using LKP model showed that the BOG levels increase as the operation pressure decreases (Fig.1). When the operation pressure was dropped to 200mbar, all four of the LNG tanks' BOG levels reached 0.05 vol %/day. So, in order to satisfy the BOG design requirement, the operating pressure of the four large LNG tanks in the case study must be maintained above 200 mbar.

3. CONCLUSION

The heat leakage should be the key requirement for BOG in LNG tank; and the size can impact the thermal conductivity of the LNG tank, except the insulation system. The heat leakage of a tank during storage has been analyzed. For different types of tanks, heat transmission through tank roof, sides and bottom has been defined and described in general formula.

The operating pressure and compositions of LNG can impact BOG during storage. As the temperature and volume of LNG tank are constant, the operating pressure can be a monitor for BOG. It analyzed the results from LKP model, the relationship between operating pressure and BOG can be obtained, as Fig.1 shown. These curves can be the reference for LNG tank operating to control the BOG. In addition, the different source of LNG also should be considered during the storage, the results from BWRS model gave the reference for the relationship between compositions of LNG and BOG.

It is necessary to simulate the whole process of the BOG in LNG tanks. The simulation needs be consider the dynamic process of vapour space of the LNG tanks. There are also some other parameters, which can impact BOG, needed to add into the simulation; such as, the changing of environment temperature, and the time for LNG storage.

It is better to find a suitable method to deal with the BOG. There are several ways to manage the BOG, such as re-liquefaction, or torching the BOG [19]. Torching is a easy way to deal with BOG, but it would waste LNG; re-liquefaction can recycle the BOG as LNG, however, the operating costs of re-liquefaction system is expansive. Thus, it is necessary to built a model for choosing the method to manage the BOG of LNG tanks.

NOMENCALTURE

A: Area (m^2)
B, C, D: Parameters of equation of state
Δh: Enthalpy difference (kJ/kg)
h: Heat transfer coefficient(W/(m^2/K))
m: the quantity rate for boil-off gas of tank (kg/s)
n: Number of moles of a substance
P: Pressure (bar)
R: Universal gas constant
r: Thermal resistant(W/(m·K))
T: Temperature (K)
V: Volume (kl)
X: Angle factor between the roof and suspended deck (degree)
Y: Each component of LNG (%)
Z: Compressibility factor
Greek symbols
ρ : Density (kg/m^3)
ω: Acentric facto (Dimensionless)
Φ : Heat leakage of tank (W)
δ : Thickness of insulation layer (mm)
λ : Thermal conductivity of insulation layer (W/(m K))
ε : Emissivity (Dimensionless)
σ : Blackbody radiation constant (W/m^2K^4)

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