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Weathering prediction model for stored liquefied natural gas (LNG)

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ABSTRACT

A model is proposed to predict the weathering of LNG stored in containment tanks, typically used in regasification terminals, due to the effects of heat ingress and Boil-off-Gas (BOG) release. The model integrates a rigorous thermodynamic model of LNG vapour–liquid equilibrium and a realistic heat transfer model. It provides a number of advances on previously developed models, in so far as: (i) heat ingress is calculated based on the outside temperature and LNG composition, that allows for daily or seasonal variation; (ii) Boil-off-Ratio is not an input parameter, but is calculated as part of the simulations and (iii) the LNG density is estimated using an accurate experimentally based correlation.

The model was validated using real industry data and the agreement obtained in predicting the overall composition of weathered LNG, its density and the amount vaporized was within current industry requirements. The model was run in the predictive mode to explore the sensitivity of BOG to different scenarios. In the initial stages of weathering the nitrogen content of LNG will have a marked effect on BOG generation. Even the presence of 0.5% of nitrogen will lead to nearly a 7% decrease in BOG, making the initial BOG unmarketable. The high sensitivity is a result of preferential evaporation of nitrogen and increase in the direct differential molar latent heat. In the final stages of weathering the heavier hydrocarbons govern the dynamics of BOG which becomes a strong function of the initial composition and the level of LNG remaining in the storage tank.

The change in ambient temperature of 1 °C will lead to a change in BOG of 0.2%, irrespective of the size of the tank and initial LNG composition.

1. Introduction

As a society, we face a number of challenges due to the high demand for energy. It is recognized that these have to be balanced against the need to mitigate ever increasing carbon dioxide emissions, without compromising the longer term energy security. In this context natural gas is seen by many as an optimal vehicle to ensure an orderly transition from the fossil-fuel driven economy to one driven by renewable energy (World Energy Outlook, 2011). Currently the share of natural gas in the global energy mix is around 20%, with forecasts indicating that the demand for natural gas by 2035 is expected to be 50% higher than today (World Energy Outlook, 2011). The increase in demand translates to increasing trade in natural gas, with some forecasts indicating doubling of the current trade.

Natural gas is either transported through pipelines, as gas at high pressure, or it is liquefied and transported as liquefied natural gas (LNG). The choice depends primarily on the distance, but also on the location of the gas field and issues concerning the security of supply. The fact that natural gas can be liquefied in commercial quantities has made the development of the LNG chain possible, thus increasing the availability and versatility of natural gas. The LNG is transported by special marine carriers from the production facilities to regasification terminals, where it is stored in highly insulated storage tanks at pressures slightly above atmospheric and temperatures corresponding to its bubble point. Due to the heat inleak into the storage tank some of the LNG will vaporize, resulting in an increase in overall pressure. In order to avoid overpressurization of the tank, the boil-off gas (BOG) is continuously removed by BOG compressors at the rate at which the LNG vaporizes, thus maintaining the constant pressure in the tank. As LNG vaporizes, the more volatile components (methane and nitrogen) will vaporize preferentially and the remaining LNG will get richer in the heavier components (ethane, propane, etc.). Over time the composition of LNG will change and that will influence not only its

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thermodynamic properties, in particular the boiling temperature and latent heat, but also its heating value. The process of preferential vaporization is known in the LNG industry as weathering and can be summarized as progressive alteration of thermophysical properties of stored LNG through vaporization, due to the heat ingress from the surroundings.

Weathering prediction of stored LNG is of particular significance to the LNG industry, especially in LNG shipping and in the operation of regasification facilities. In LNG shipping, it helps to anticipate the allocation of LNG cargoes and to set up in advance the operation of the receiving terminal. In the regasification terminal an accurate estimation of the weathering effect on the received LNG allows to plan operating procedures in advance in order to ensure the suitability of the delivered natural gas in terms of its properties and heating value. In regasification facilities, weathering has been traditionally a minor problem in base load[1] terminals, compared to peak-shaving[2] installations; however, today's combined effect of sudden fluctuations in the regional gas price and seasonality is producing an increase in the storage time, hence the accurate prediction of weathering becomes important in evaluating the compatibility of the stored LNG with the supplied gas system and final users. Furthermore, if LNG has undergone a substantial weathering in a storage tank its boiling temperature and density will increase as a consequence of it being richer in heavier components. If a new batch of LNG is introduced, that will by necessity be lighter and cooler, a number of undesirable events, involving stratification, sudden vapour release and a possible roll-over, can take place that can endanger normal operations.

For stored LNG, the amount and quality of produced BOG depends on the initial composition, the insulation of the LNG tank and primarily on the time elapsed since the tank was filled. In LNG shipping, the liquid stock in an LNG carrier remains almost constant during the trip from the production facility to the receiving terminal. The longest trips are of the order of 20 days during which 2–3% of the total volume of the transported LNG evaporates. The usual approach, to predict LNG weathering during marine transport, is to assume the constant boil-off rate (BOR), where the BOR is defined as the ratio of volume, in liquid terms, of LNG that has evaporated in one day, relative to the initial LNG volume in the tank. The BOR figure used in industry for LNG carriers depends on carrier size. For smaller and older ships a BOR of 0.15% tends to be used (Colson et al., 2012), while for the latest LNG tankers with an average capacity of 170,000 m^3 the BOR is nearer to 0.1%. To predict the weathering in above ground LNG storage tanks, typically used in regasification terminals, the situation is somewhat different. A constant BOR tends to be assumed based on the value adopted during the design stage when a maximum BOR value is specified, usually around 0.05% (Yang et al., 2006), and the tank insulation is designed accordingly.

BOR was initially studied in the early stages of the LNG industry by a number of workers (Churchill, 1962; Neill et al., 1968) who focused on the influence of insulation and radiative cooling of the vapour exposed section of the wall on BOR, assuming steady-state and without taking compositional variation of LNG into account. In 1999 the Institute of Gas Technology (IGT) (Kountz, 1999) conducted an experimental test program to measure LNG weathering in on-board storage tanks. The experimental set up measured the evolution of composition, mass and temperature of stored LNG in a pressurized container under controlled constant heat inflow, utilizing different LNG compositions. Recently Dimopoulos and Frangopolous (Dimopoulos and Frangopoulos, 2008) and Miana and co-workers (Miana et al., 2010) independently studied LNG weathering during marine transport. The former developed a rigorous model, based on treating LNG as an ideal mixture and constant heat ingress into the stored LNG, while Miana et al. (Miana et al., 2010) developed two models (physical model and i-model) with the aim of predicting the LNG composition and properties at the receiving terminal.

A number of researchers (Chen et al., 2004; Adom et al., 2010; Pellegrini et al., 2014) have recently investigated boil-off from LNG storage tanks. Of special interest to this study is the work of Pellegrini et al. (Pellegrini et al., 2014) who have developed a weathering model for LNG stored in above-ground tanks based on mass and energy balance, but without the assumption of constant BOR. The model assumes thermodynamic equilibrium for the stored LNG, ideal mixture for enthalpy of vapour and liquid and uses the SRK equation of state (EOS) for phase equlibria and density calculation, with the Penéloux correction for liquid density. The assumption of constant heat ingress limits the model in terms of its applicability to conditions where both the outside temperature and the LNG boiling temperature do not show large temporal variation.

In this work we present a new model aiming to predict the vaporization rate and the compositional variation of LNG stored in a full containment above-ground tank, due to the effects of heat ingress and BOG vapour release. The model is developed by integrating: (i) a rigorous LNG vapor–liquid equilibrium (VLE) model and (ii) a realistic heat transfer model, into an integrated model to predict the compositional variation of the stored LNG. The model builds on the previously published work, but removes a number of constraints that exist in the reported models (Kountz, 1999; Dimopoulos and Frangopoulos, 2008; Miana et al., 2010; Chen et al., 2004; Adom et al., 2010; Pellegrini et al., 2014; Shah and Aarts, 1974; Aspelund et al., 2007), namely: (i) heat ingress is calculated based on the outside temperature and LNG composition, that allows for daily or seasonal variation; (ii) BOR is not an input parameter, but is calculated as part of the simulations and (iii) the LNG density is estimated using an accurate experimentally based correlation, thus replacing the need for an estimate based on EOS that for two parameter cubic EOS requires an empirical correction.

2. Model development

Here we consider the development of the model for the LNG weathering in a typical above-ground storage tank, schematically shown in Fig. 1, used in industry to store received LNG.

As the heat ingresses into the stored LNG it causes the preferential vaporization of the lighter components, with the produced vapour (BOG) being removed to control the tank pressure. The energy balance over the storage tank links the amount of heat entering the tank per unit time, Q, to the rate of vapour removal, $\dot{B}$ and can be simply expressed as,

$$Q = \frac{dH_\mathrm{V}}{dt} + \frac{dH_\mathrm{L}}{dt} + \dot{B}h_\mathrm{V} \tag{1}$$

where H and h are the enthalpy and molar enthalpy, respectively, while subscripts V and L indicate vapour and liquid, respectively. The rate of vapour removal can be obtained from the mass balance,

$$-\dot{B} \equiv -\frac{dB}{dt} = \frac{d(\rho_\mathrm{L}V_\mathrm{L})}{dt} + \frac{d(\rho_\mathrm{V}V_\mathrm{V})}{dt} \tag{2}$$

where ρ is the molar density and V is the volume of the storage tank occupied by both the liquid, V_L, and vapour, V_V. Taking into account

[1] Base load is the rate of production below which demand is not expected to fall during a given period.

[2] A peak-shaving installation is a facility used to store surplus natural gas to meet demand requirements during peak consumption periods (typically in winter).