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# Dynamic modelling and optimization of an LNG storage tank in a regasification terminal with semi-analytical solutions for $N_2$-free LNG

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ABSTRACT

A comprehensive dynamic model for an LNG storage tank in a typical regasification terminal, operating in holding mode, is presented. The model incorporates LNG recirculation for cooling the transfer lines for loading/unloading. It assumes a hypothetical thin vapour interface in equilibrium with the liquid to compute LNG evaporation, which allows the boil-off gas to be hotter than the tank LNG, as observed in practice. A numerical procedure based on the secant method is implemented in MATLAB for solving the governing ordinary differential equations. For the special case of $N_2$-free LNG, a semi-analytical solution is proposed to solve the dynamic model for this relatively complex system and compute the amount of boil-off gas (BOG). The semi-analytical solution is subsequently used to optimize the LNG storage tank and recirculation loop designs.



## 1. Introduction

Stringent environmental regulations, the desire for enhanced energy security, and global competition escalate the demand for natural gas (NG). Where transport via pipelines is not a viable option, NG is liquefied to reduce its volume by a factor of 600 and transported as LNG (Liquefied Natural Gas). NG liquefaction is energy-intensive, and losses through boil-off during transport and storage due to the continuous heat leak from the surroundings are undesirable. Minimizing the boil-off gas (BOG) losses in a regasification terminal is a challenge, as such a terminal must maintain large LNG inventory to ensure an uninterrupted supply of NG to the end users. In this study, we present a comprehensive mathematical model and its solution for a generic cryogenic LNG storage tank in a regasification terminal. We consider a regasification terminal operating in the holding mode, i.e. no LNG transfer occurs between the storage tank and an LNG carrier, but LNG is withdrawn from the tank at a fixed rate. A part of this LNG is recirculated through the loading/unloading transfer lines to cool them, and the rest is sent for regasification. A schematic of the tank and recirculation is shown in Fig. 1. The heat leak into the tank and recirculation line generates BOG, which must be removed to maintain tank pressure. The main modelling complexity arises due to the fact that the amount of heat ingress into the vapour- and liquid-phases of the tank varies with their exposed areas and temperatures.

BOG generation impacts the operating cost of a regasification terminal significantly. This has provided the impetus for numerous studies on utilization and processing of BOG (Zongming et al., 2015; Moon et al., 2007), BOG management/operation (Park et al., 2010; Querol et al., 2010), and BOG re-condensation (Li et al., 2012). The majority of these studies concern BOG generation and LNG weathering in marine transports. Such studies invariably assume some boil-off rate (BOR), which is appropriate for marine transport, wherein approximate vapour-liquid thermal equilibrium is maintained by occasional spraying/splashing of LNG on the inner wall of the tank. Dimopoulos and Frangopoulos (2008) developed a dynamic BOG model that accounts for the variations in BOG mass flow, fluid composition, and fluid properties during a voyage. Their model assumes ideal behaviours for both vapour and liquid phases, employs non-linear VLE (Vapour-Liquid Equilibrium) equations, and uses an average heat-transfer coefficient matched against typical BORs for LNG vessels. Miana et al. (2010) proposed and validated two models for LNG ageing during marine transportation. The former is derived from first principles, and assumes a constant BOR, while the latter is an empirical neural-network model trained against a database of several hundred recorded journeys.

A storage tank in a regasification terminal differs from a marine cargo tank in three ways. One, the liquid level changes substantially between loadings. Two, there is no mechanism for maintaining vapour-liquid thermal equilibrium. Three, most regasification

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## Nomenclature

*Greek Symbols*

| | |
|---|---|
| $\Delta$ | Difference |
| $\eta$ | Efficiency |
| $\lambda$ | Latent heat of vaporization ($J \cdot mol^{-1}$) |
| $\rho$ | Density ($kg \cdot m^3$) |
| $\theta$ | Delay ($s$) |
| $\theta_1 \ldots \theta_7$ | Intermediate groups |
| $\varphi$ | Total viscous dissipation |
| $\varphi_f$ | Fanning friction factor |

*Alphanumeric Symbols*

| | |
|---|---|
| $C_p$ | Heat capacity ($J \cdot Kg^{-1}K^{-1}$) |
| $D$ | Diameter ($m$) |
| $E$ | Error |
| $e$ | Roughness ($m$) |
| $f$ | Generic function, or fraction, as per context |
| $H$ | Height ($m$) |
| $K$ | K-factor |
| $M$ | Time domain partition number |
| $MW$ | Molar mass ($Kg \cdot mol^{-1}$) |
| $m$ | Mass ($Kg$) |
| $N$ | Taylor truncation number |
| $P$ | Pressure ($Pa$) |
| $Q$ | Heat ($J$) |
| $R$ | Universal gas constant ($J \cdot mol^{-1}K^{-1}$) |
| $T$ | Temperature ($K$) |
| $t$ | Time, or thickness, as per context ($s$ or $m$) |
| $U$ | Overall heat-transfer coefficient ($W \cdot m^{-2}K^{-1}$) |
| $X$ | Liquid-phase mass fraction; unless otherwise stated, refers to liquid subsystem |
| $Y$ | Vapour-phase mass fraction; unless otherwise stated, refers to vapour subsystem |
| $z$ | Length ($m$) |

*Subscripts*

| | |
|---|---|
| 0 | Initial |
| *amb* | Ambient |
| *B* | Boil-off stream |
| *By* | Bypass stream |
| *bottom* | Tank bottom |
| *E* | Evaporation |
| *end* | End |
| *F* | Flash subsystem |
| *I* | Insulator |
| *i* | Component "i" |
| *j* | Data point "j" |
| *k* | Time step "k" |
| *L* | Liquid subsystem |
| *l* | Iteration "l" |
| *loop* | Recirculation loop subsystem |
| *NN* | Neural network |
| *P* | Pump-out, or partition, as per context |
| *pump* | Recirculation loop pump |
| *R* | Return stream |
| *side* | Tank shell |
| *top* | Tank roof |
| *T* | Tank |
| *V* | Vapour subsystem |
| *valve* | Valve |
| $\rightarrow$ | Vector |
| $*$ | Vapour subsystem-liquid subsystem interface |
| $-$ | On mass basis |
| $\cdot$ | Flow rate, or tagged, as per context |
| $\sim$ | Point approximation |
| $\hat{}$ | Per unit volume |

terminals have a recirculated stream of LNG which cools the loading/unloading transfer lines. The first two differences invalidate the assumption of constant BOR. It is noted, however, that several studies have made this (or equivalent) assumption for modelling of above-ground storage tanks in regasification terminals. For example, Jourda and Probert (1991) investigated steady-state heat ingress via conduction, convection, and radiative heat transfers from the top, shell and bottom sides of the tank. Their model assumes some constant heat ingress, which results in some constant BOR. Pellegrini et al. (Pellegrini et al., 2014) removed the assumption of constant BOR, and validated their weathering prediction model against experimental data, but retained the assumption of vapour-liquid thermal equilibrium. Migliore et al. (2015) studied LNG weathering in a containment-type storage tank in a regasification terminal. They constructed a rigorous thermodynamic model with corrected LNG density to predict dynamic BOG generation as a function of initial LNG composition, liquid level, feed composition and ambient temperature. In their model, the heat ingress through the tank walls varies with the ambient temperature and liquid level in the tanks, but those through the tank roof and bottom are constant. While Pellegrini et al. (2014) and Migliore et al. (2015) have at least in part considered the effect of changing liquid height, they did not consider the send-out and recirculation of LNG common in regasification terminals.

Wordu and Peterside (2013) estimated heat leaks from various elements in a regasification terminal such as the storage tank, recirculation/jetty cooling lines, loading pumps, vapour displacement, and flashing of recirculated LNG into the storage tank. They found that the vapour displacement and the shaft work by the loading pumps contributed significantly to BOG generation. Despite the broad view taken by the authors, the model does not possess any dynamics, and assumes vapour-liquid thermal equilibrium. Nevertheless, it provides a useful qualitative view of the system under consideration.

We can conclude from the above discussion that a comprehensive dynamic model of LNG tank operation in a regasification terminal including continuous send-out and cooling of jetty lines via LNG recirculation is not available. Depending on the demand, the tank may experience significant changes in its liquid level, making the constant liquid-phase heat ingress assumption invalid. Another important limitation is the assumption of complete thermal and mass equilibrium between liquid- and vapour-phases.

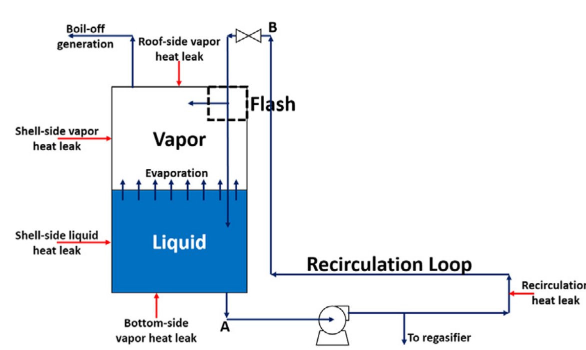


**Fig. 1.** Schematic of an LNG storage tank operating in holding mode with its vapour, liquid, recirculation loop and flash subsystems. Points A and B are locations of interest along the recirculation line (see Section 3.2).