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Optimization methods for the real-time inverse problem posed by modelling of liquefied natural gas storage

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ABSTRACT

If two liquefied natural gases (LNG) obtained from two different sources are inappropriately fed into a storage tank, lighter LNG may lie over heavier LNG forming a stratification, which could eventually lead to a rollover. Few models available in the literature predict time to rollover in LNG storage tanks. These are semi-empirical in nature as they are based upon empirical correlations to estimate heat and mass transfer coefficients across the stratified layers. We present a lumped parameter model in order to predict time to rollover and to investigate its sensitivity to variation of heat and mass transfer coefficients. The novelty of the present work is its ability to estimate heat and mass transfer coefficients from the real time data using an inverse methodology. We assimilate the real time LNG level–temperature–density (LTD) data from LNG storage tank in order to estimate heat and mass transfer coefficients from the densities of the stratified layers. The optimized heat and mass transfer coefficients are then used to predict time to rollover. We present a sequence of LTD profiles obtained from real time LNG terminal and which are leading to rollover in one case study (Section 4.1). The time to rollover predicted using this inverse methodology is compared with the LTD profiles obtained from real LNG tank and also with time to rollover obtained using empirical correlations. Heat transfer coefficients estimated using empirical correlations are found to be over-estimated for some case studies, which under predict time to rollover. For the real time case study, time to rollover predicted using empirical correlations is under predicted by about 84%, where as that using the inverse methodology is under predicted by about 20%.

1. Introduction

In today's globalised market of the liquefied natural gas (LNG) industry, LNG bought from different sources has potentially different density due to different composition. Although composition of LNG varies depending on its source, it is mainly comprised methane, ethane, propane, butane and traces of nitrogen. When fresh LNG is fed into a tank, the composition and temperature of LNG already in the tank could be different to the fresh LNG. This could result in stratification of the tank; commonly known as fill induced stratification, due to inappropriate filling of the tank with LNG of different densities. This stratification could eventually lead to a phenomenon called rollover. If the stratification is significant, then the LNG in the lower layer of the stratified tank can become superheated, as it receives heat from the sidewalls and the bottom of the tank, which cannot escape to the vapour phase due to a cover formed by LNG in the upper layer. The schematic of an LNG storage tank and the processes involved is shown in Fig. 1. The densities of the two layers eventually equalize due to heat and mass transfer between the stratified layers and boil-off from the top surface. The hotter LNG in the lower layer comes to the top releasing all the heat it contained during incubation. This phenomenon is called "rollover" and could be potentially dangerous due to the possibility of a higher boil-off rate at the time of rollover increasing the vapour pressure in the tank. The severity of the rollover event depends upon the state of stratification and temperature gradient between the stratified layers and is addressed in detail in this article.

Natural gas is normally stored in a liquefied state, as the natural gas is compressed by as much as 600 times when liquefied and is stored at just above atmospheric pressure and at a temperature of around −160 °C. As liquefied natural gas (LNG) is stored at such a low temperature, there is a significant heat leakage from the surroundings into the tank varying the temperature inside the tank. The composition of LNG in the stratified layers may also vary due to evaporation (boil-off) at the surface and mass transfer between the stratified layers. This requires continuous monitoring of the tank particularly for temperature and density. In this article, we

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Nomenclature

A	cross-sectional area of the tank, m^2
A^A, B^A *and* C^A	constants used in Antoine equation
C_K	correction factor used in Klosek–McKinley density correlation
C_l	molar concentration of LNG in lower layer, kg mol/m^3
C_u	molar concentration of LNG in upper layer, kg mol/m^3
$C_{L,l}$	molar heat capacity of LNG in lower layer, J/kg mol/K
$C_{L,u}$	molar heat capacity of LNG in upper layer, J/kg mol/K
D	diameter of the tank, m
f_Q	fraction of total heat transfer rate to the vapour space which is returned to LNG
h	heat transfer coefficient, W/m^2/K
$\overline{H_B}$	enthalpy of bulk liquid, J/kg mol
$\overline{H_V}$	enthalpy of vapour evolving from the upper layer, J/kg mol
$\overline{H_S}$	enthalpy of liquid at the top surface of upper layer, J/kg mol
k	thermal conductivity of LNG, W/m/K
L	height of the tank, m
MW_l	average molecular weight of LNG in lower layer, kg/kg mol
MW_u	average molecular weight of LNG in upper layer, kg/kg mol
$\dot{M}_{in}$	total molar flow rate in to the tank, kg mol/s
$\dot{M}_{out}$	total molar flow rate out of the tank, kg mol/s
$\dot{M}_l$	molar flow rate from cargo to lower layer, kg mol/s
$\dot{M}_R$	molar recirculation flow rate between two layers, kg mol/m^2/s
$\dot{M}_u$	molar flow rate from cargo to upper layer, kg mol/s
$\dot{M}_V$	molar vapourization rate from upper layer (boiloff rate), kg mol/m^2/s
P	total pressure in the tank, bar a
P_i^{sat}	saturation pressure of species *i*, bar a
q_b	heat flux from the bottom of the tank, W/m^2
q_t	heat flux from the top of the tank, W/m^2
q_{LL}	heat flux from the sidewall of the tank to the lower layer, W/m^2
q_{UL}	heat flux from the sidewall of the tank to the upper layer, W/m^2
q_V	heat flux from the sidewall of the tank to the vapour space, W/m^2
Q	total heat transfer to vapour space from surroundings, W
q_R	heat flux returned from the vapour space to the liquid, W/m^2
T_l	temperature of LNG in lower layer, K
T_u	temperature of LNG in upper layer, K
V_i	molar volume of species *i*, m^3/kg mol
V_m	molar volume of methane, m^3/kg mol
$x_l(i)$	mole fraction of species *i* in the bulk liquid phase in lower layer
$x_f(i)$	mole fraction of species *i* in the film region
$x_u(i)$	mole fraction of species *i* in the bulk liquid phase in upper layer
$y(i)$	mole fraction of species *i* in the bulk vapour phase

Greek letters

α	thermal diffusivity, m^2/s
β	thermal expansion coefficient
δ_l	layer thickness of lower layer, m
δ_u	layer thickness of upper layer, m
δ_{VS}	layer thickness of vapour space, m
κ	turbulent mass transfer coefficient, kg mol/m^2/s
υ	kinematic viscosity, m^2/s
ρ_l	average density of LNG in lower layer, kg/m^3
ρ_u	average density of LNG in upper layer, kg/m^3
$\overline{\rho}$	average of density of lower and upper layers, kg/m^3
$\Delta\rho$	difference in density of lower and upper layers, kg/m^3
$\overline{\rho}^R$	average of density of lower and upper layers for Rayleigh circulation, kg/m^3
$\Delta\rho^R$	difference in density of lower and upper layers for Rayleigh circulation, kg/m^3

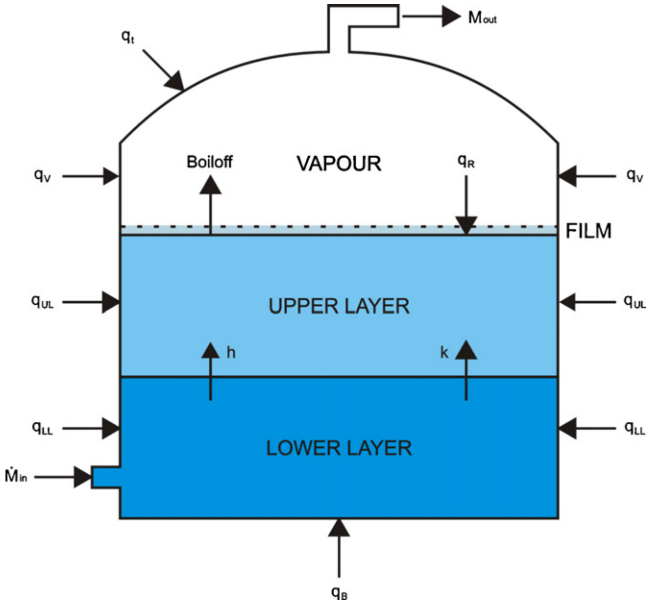

Fig. 1. Schematic of LNG storage tank.

describe a lumped parameter model, which is developed to predict the behaviour of LNG inside a storage tank leading to rollover from the fundamental principles of material and energy balance equations and thermodynamic principles.

In the literature, there are only a couple of well-documented experimental evidences of LNG stratification resulting into rollover [1,2]. However, there are quite a few theoretical models available in the literature (Chaterjee and Geist [3,4]; Germeles [5]; Heestand et al. [6]; and Bates and Morrison [7]). Chaterjee and Geist [3] considered only two chemical species: methane and non-volatile heavy hydrocarbon and the rollover criterion considered in their approach was equal temperature and composition of the stratified layers. Germeles [5] reported that equal density should be the rollover criterion instead of equal temperature and composition, as there would be no change in vapour pressure and boil-off rate, if the latter is considered. Heestand et al. [6] considered the five most common constituents of LNG namely methane, ethane, propane, n butane and nitrogen. Heestand et al. [6] argued about the use of thermohaline heat and mass correlations of Turner [8] in the previous models, as those correlations were provided for salt–water experiments