A realistic vapour phase heat transfer model for the weathering of LNG stored in large tanks

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Introduction

Liquefied natural gas (LNG) storage tanks are subject to heat ingress from the surroundings. The heat ingress leads to the preferential evaporation of LNG with the most volatile components, methane and nitrogen, predominantly ending in the vapour phase. In large tanks, the vapour produced is typically removed to keep the tank pressure constant and is denominated as boil-off gas (BOG). The heat ingress and BOG removal produce weathering of the remaining LNG, as the concentration of the heavier components increases over time. Weathering has major industrial implications, as it can induce safety hazards such as rollover and it limits the LNG marketability. In this work a new non-equilibrium weathering model applicable to the storage of LNG in large tanks under constant pressure has been developed.

Objectives

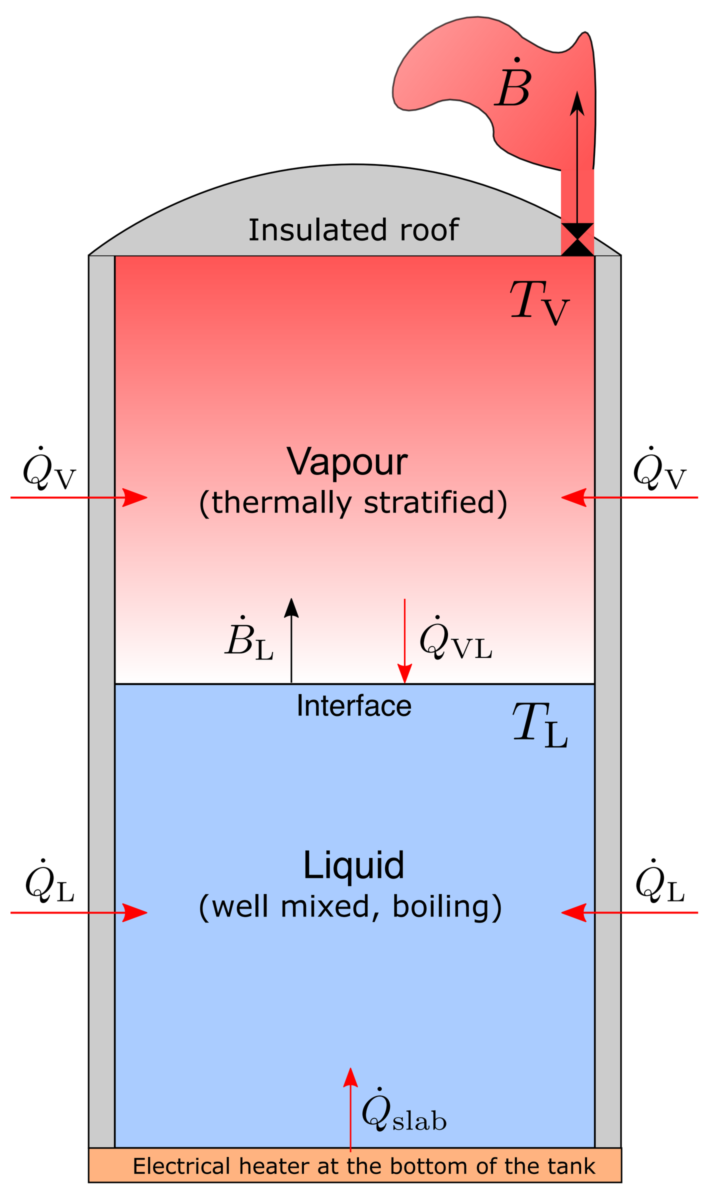
- Develop a realistic heat transfer model for the vapour phase in LNG weathering to predict accurately the vapour temperatures, and the contribution of the vapour heat transfer to BOG rates.
- Produce a weathering model easy to interpret and use for industrial applications by simplifying the hydrodynamics in both liquid and vapour phases, while retaining the dominant weathering mechanisms.

Model development

The full weathering model is a combination of a mass and energy balance model, a thermodynamic model and a heat transfer model. The LNG and its vapour were assumed to be divided by a smooth vapour-liquid interface and each phase is considered a subsystem.

It was assumed that the liquid was at physicochemical equilibrium with the vapour interface. The thermodynamic properties were evaluated using the Peng-Robinson equation of state.

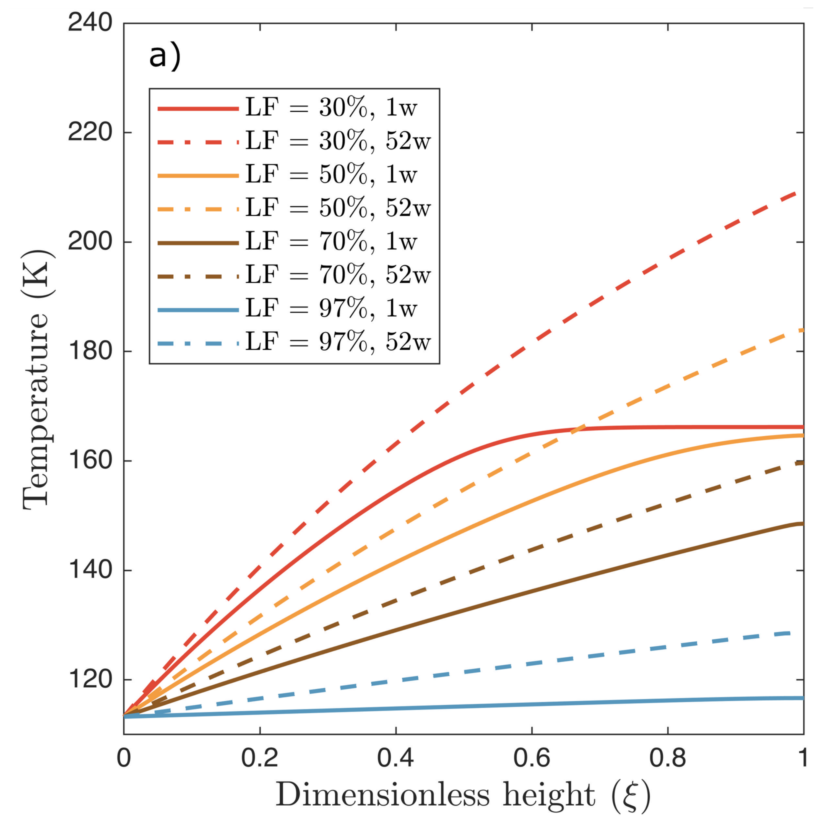
The vapour temperature was modelled using the unsteady advection-diffusion equation with a source term. An average vertical advective velocity was assumed. The vapour wall heating was modelled as a volumetric source term.



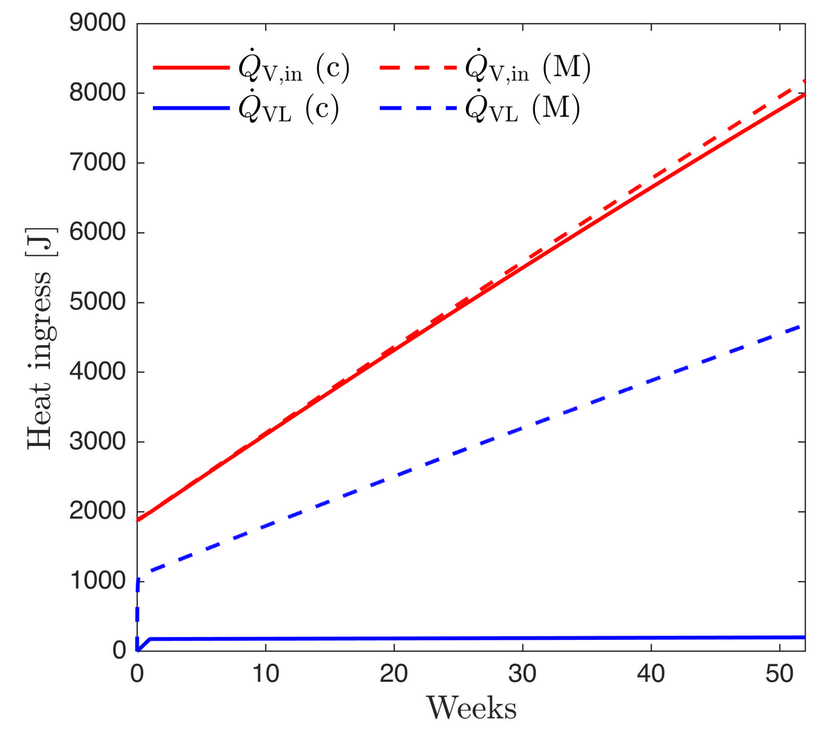
Evaporation rate	$-\dot{B}_L = \frac{d}{dt}(\rho_L V_L)$
BOG rate	$-\dot{B} = \frac{d}{dt}(\rho_L V_L + \bar{\rho}_V V_V) = -\dot{B}_L + \frac{d}{dt}(\bar{\rho}_V V_V)$
Liquid phase energy balance	$\dot{Q}_L + \dot{Q}_{slab} + \dot{Q}_{VL} - \dot{B}_L h_V(T_L) = \frac{d}{dt}(\rho_L V_L h_L)$
Phase equilibrium	$y_i = \frac{\phi_i^L}{\phi_i^V} x_i = K x_i$
Advection-Diffusion equation	$\frac{\partial T_V}{\partial t} = \bar{\alpha}\frac{\partial^2 T_V}{\partial z^2} - \bar{v}_z \frac{\partial T_V}{\partial z} + \frac{\bar{\alpha}}{k}\dot{S}_{wall}$
Advective velocity	$\bar{v}_z = \frac{4\dot{B}_L}{\pi d_i^2 \bar{\rho}_V}$
Vapour heating source term	$\dot{S}_{wall} = \frac{4 U_V d_o}{d_i^2}(T_{air} - T_V)$
Vapour to liquid heat transfer rate	$\dot{Q}_{VL} = -\frac{\pi d_i^2}{4}\left(k_V \frac{\partial T_V}{\partial z}\right)\Big\vert_{z=0}$

Results

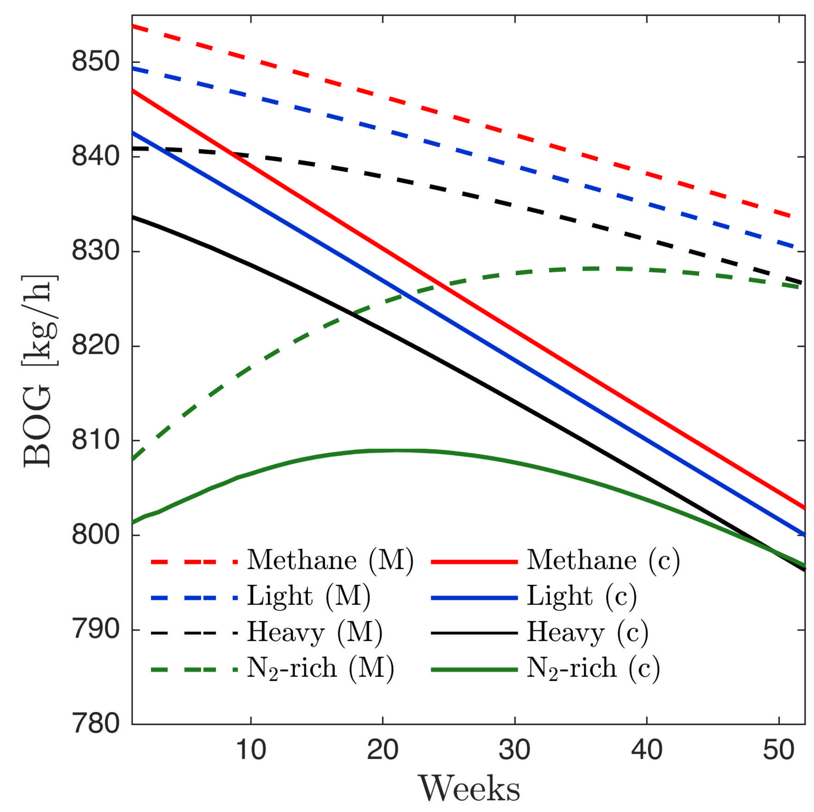
- The vapour temperature increases monotonically with decreasing liquid filling (LF).
- The system reaches a quasi-steady state after a transient period.
- Heat transfer by the advective flow dominates the energy transfer within the vapour.



- The vapour heat ingress and vapour to liquid heat ingress predicted by our model (c) were lower than the results of Migliore et al [1] (M).
- The vapour to liquid heat transfer was small, in line with recent experimental findings, and is estimated to contribute less than 0.3% to BOG rates.



- All BOG rates predicted by the new model (c) are lower than the ones from [1] (M) because of lower vapour to liquid heat ingresses.
- The nitrogen content of the LNG mixture has a pronounced effect on BOG rates.



Conclusions

- Following an initial, transient period, the vapour temperature achieves a pseudo-steady state profile, displaying a monotonic increase as a function of the height of the vapour space.
- The initial liquid filling has a pronounced effect on all the relevant variables, leading to a decrease in vapour temperature and in BOG temperature and an increase in BOG rates.
- BOG decreases as a function of weathering duration for non-nitrogen containing LNG. The presence of nitrogen leads to a maximum in BOG, that is a result of the interplay between the decreasing heat ingress into the liquid and decreasing enthalpy of vaporization.
- During the transient period we observed an interesting array of behaviour with steep changes in vapour temperature and density, vapour to liquid heat transfer and BOG rates.

References

[1] Migliore C, Salehi A, Vesovic V. A non-equilibrium approach to modelling the weathering of stored Liquefied Natural Gas (LNG). Energy 2017;124:684-92.

Acknowledgements

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