Thermodynamic modelling of the warm-up of cryogenic tank at low fill levels for LH2 storage

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ICEC/ICMC

Cryogenic Applications: Hydrogen & LNG Systems

ID: 454

Introduction

Rationale: During their return voyage, LNG carriers retain a "small" quantity of liquid (heel) in one or all tanks, to mitigate tank warm-up over the duration of the voyage. This heel can be sprayed onto the tank walls prior to arrival, partially cooling the tanks and reducing excessive boil-off during loading.

Simple lumped mass models (vapour, liquid, interface) have been demonstrated to predict rate of self-pressurisation with 2 tuning parameters. However, these models are unable to directly predict vapour thermal stratification and subsequently, cumulative heat gain in the tank.

Aims:

- Develop a lumped-sum analytical model to estimate vapour stratification and tank heat gain at moderate-to-low fill levels.
- Understand the differences between heel management in existing LNG membrane-type tanks and LH2 Type-B (double walled) storage tanks.
- Investigate self-pressurisation as a method to reduce heel boil-off.

Problem Overview

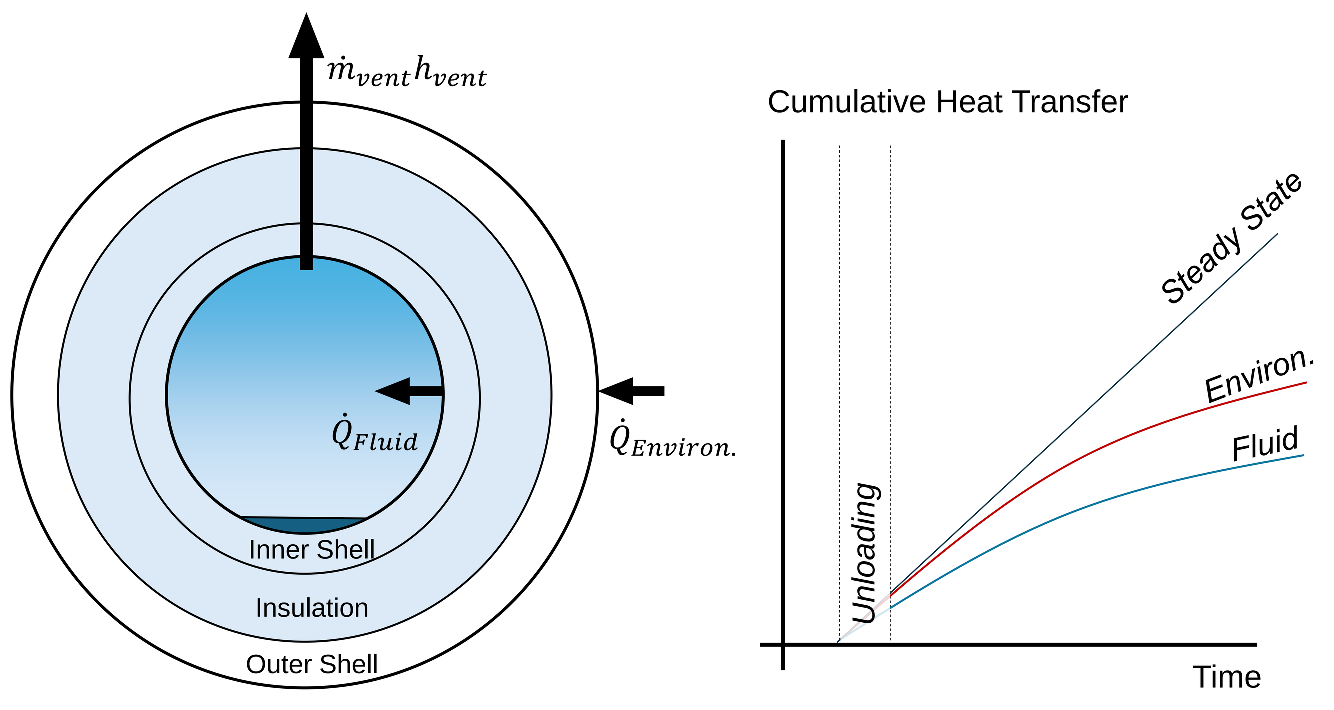

Figure 1

Considering a tank at ~100% fill, **immediately after unloading**. Prior to unloading, tank heat transfer is in a quasi-steady state.
Defining **residual heat** as:

$$U_{\text{residual}} = \int_0^t (\dot{Q}_{\text{environmental}} - \dot{Q}_{\text{fluid}})\, dt.$$

The maximum quantity of heel required under **continuous spraying** of the inner wall:

$$m_{heel,spray} = \frac{\dot{Q}_{\text{steady state}} * t_b}{h_{fg}}$$

Defining **dimensionless environmental heat gain** as:

$$\theta_1 = \frac{\int_0^t \dot{Q}_{\text{environmental}}\, dt}{\dot{Q}_{\text{steady state}} * t}$$

Defining **dimensionless environmental heat gain** as:

$$\theta_2 = \frac{U_{\text{residual}}}{\int_0^t \dot{Q}_{\text{environmental}}\, dt}$$

Methods

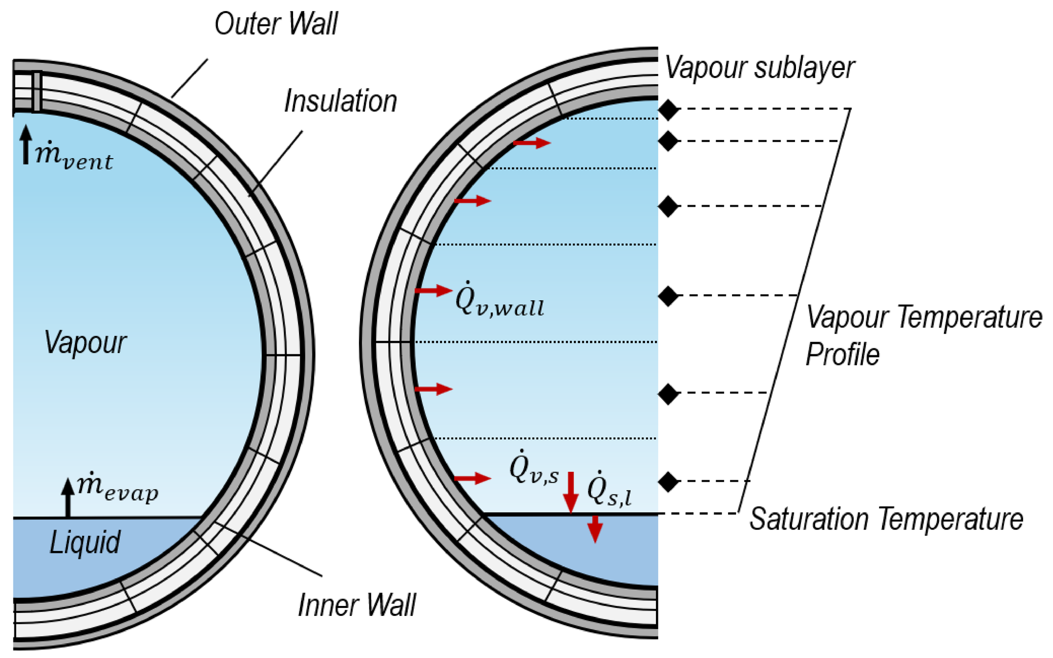

Figure 2

Assuming a linear vapour temperature profile, ullage is divided into 'n' sublayers of volume V_i^*. Thermal gradient can then be solved by minimising the mass and energy residuals:

$$\Delta m_v = m_v - \sum_{i=1}^{n} V_i^* \rho_{v,i}^* \qquad \Delta U_v = U_v - \sum_{i=1}^{n} V_i^* \rho_{v,i}^* u_{v,i}^*$$

Convergence criteria set to 0.01 for normalised residuals. Two empirical tuning parameters C_1 and C_2 are required:

$$\dot{q}_{v,s} = C_1 k_v \frac{dT}{dx} \qquad \dot{q}_{s,l} = C_2 k_l \frac{(T_{sat} - T_l)}{2\sqrt{\alpha_l t_p}} \text{ [3]}$$

Where t_p is time since pressurisation, α_l is thermal diffusivity, $\frac{dT}{dx}$ is vapour thermal gradient and k is thermal conductivity (all in SI units).

Tuning & Validation

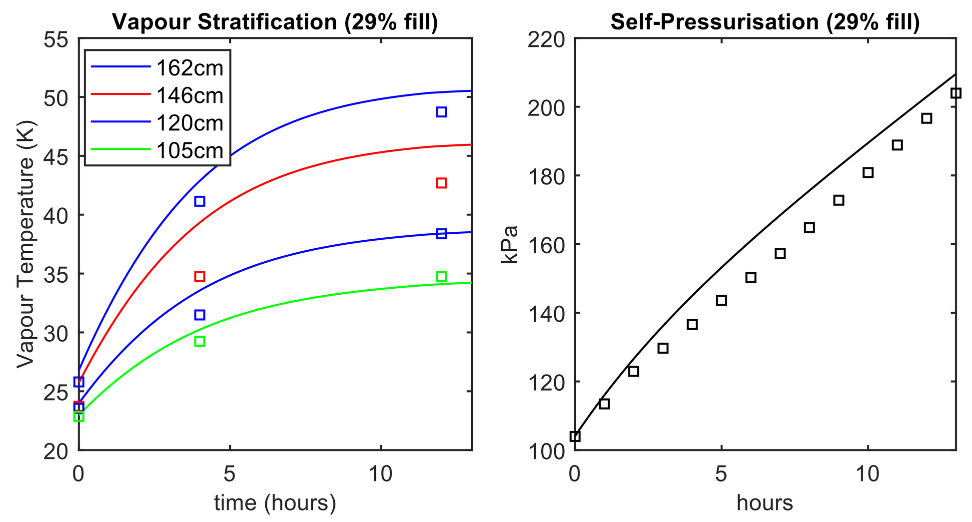

Figure 3: Temperature and pressure prediction for 29% fill.

Tuned for self-pressurisation: $C_2 = 2$, $C_1 = 25\frac{V_{vapour}}{V_{total}}$

(Fig. 3) Vapour temperatures in pressurised 4.9 m^3 spheroidal LH2 tank [1] and (Fig. 4) for unpressurised membrane-type prismatic tank for LNG [2].

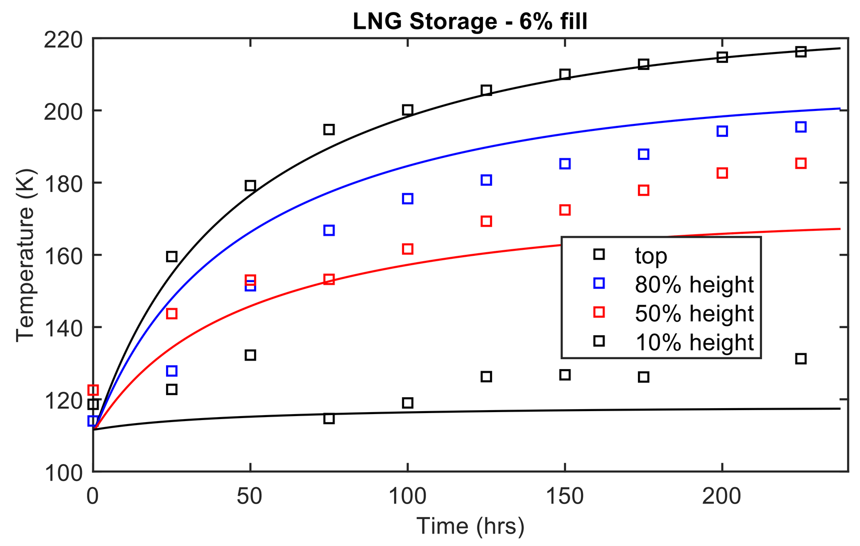

Figure 4: Temperature prediction for 6% fill in 25,000 m^3, assuming 100% methane

Results & Comparison to LNG case

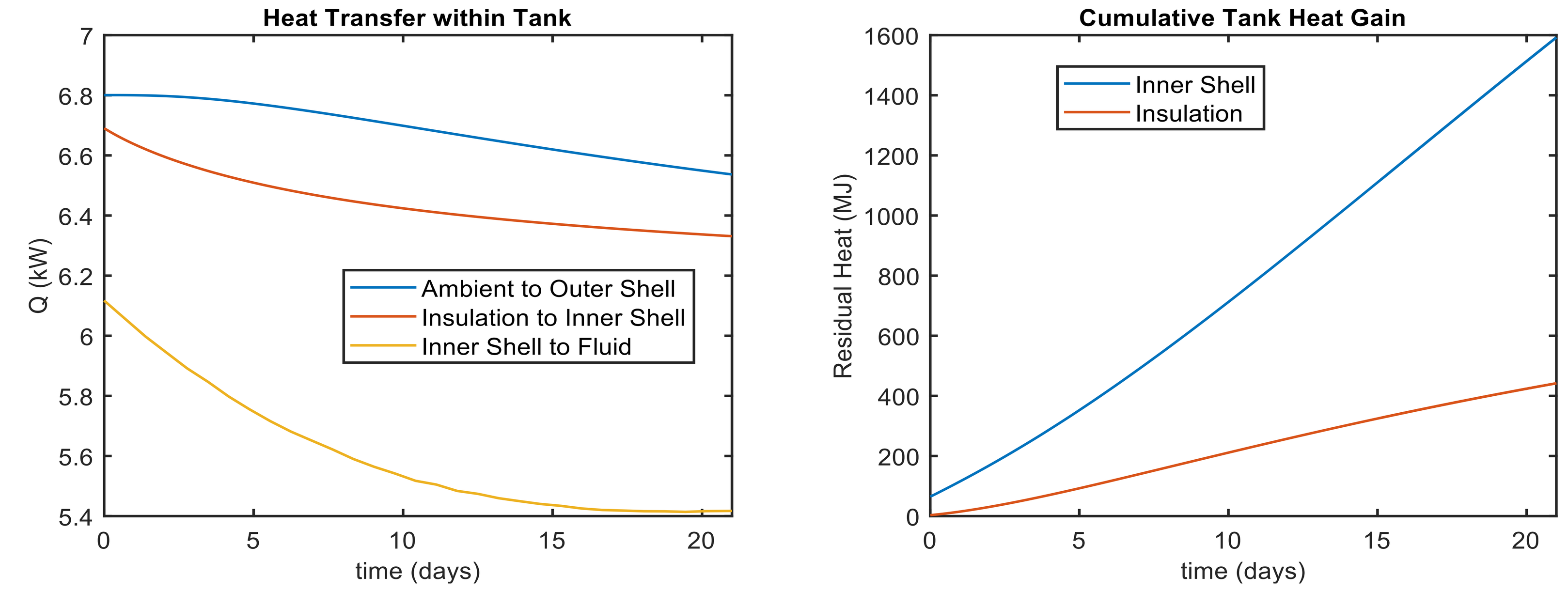

Figure 5: Heat transfer within unpressurised perlite LH2 tank

Considering 3 cases for 40,000 m^3 storage tanks at 5 % fill:

Case	Insulation Type	Insulation thickness (m)	Inner wall thickness (mm)	Inner wall material	Steady State Heat Transfer (kW)
Spherical, LH2	Perlite (100 mTorr)	0.75	65	304 Stainless Steel	6.74
Spherical, LH2	PUF (non-vacuum)	0.75	65		49.9
Prismatic membrane, LNG	PUF (non-vacuum)	0.5	1		78.7

Key Observations

- For the LH2 insulated tanks over 3 weeks, 3.6 % and 8.7 % decrease in environmental-to-outer shell for perlite and polyurethane foam (PUF) respectively.
- In comparison, estimated 30 % decrease in environmental-to-outer shell heat transfer for LNG tank over 3 weeks. Comparatively lower portion of cumulative heat transferred retained within tank for LNG tank.

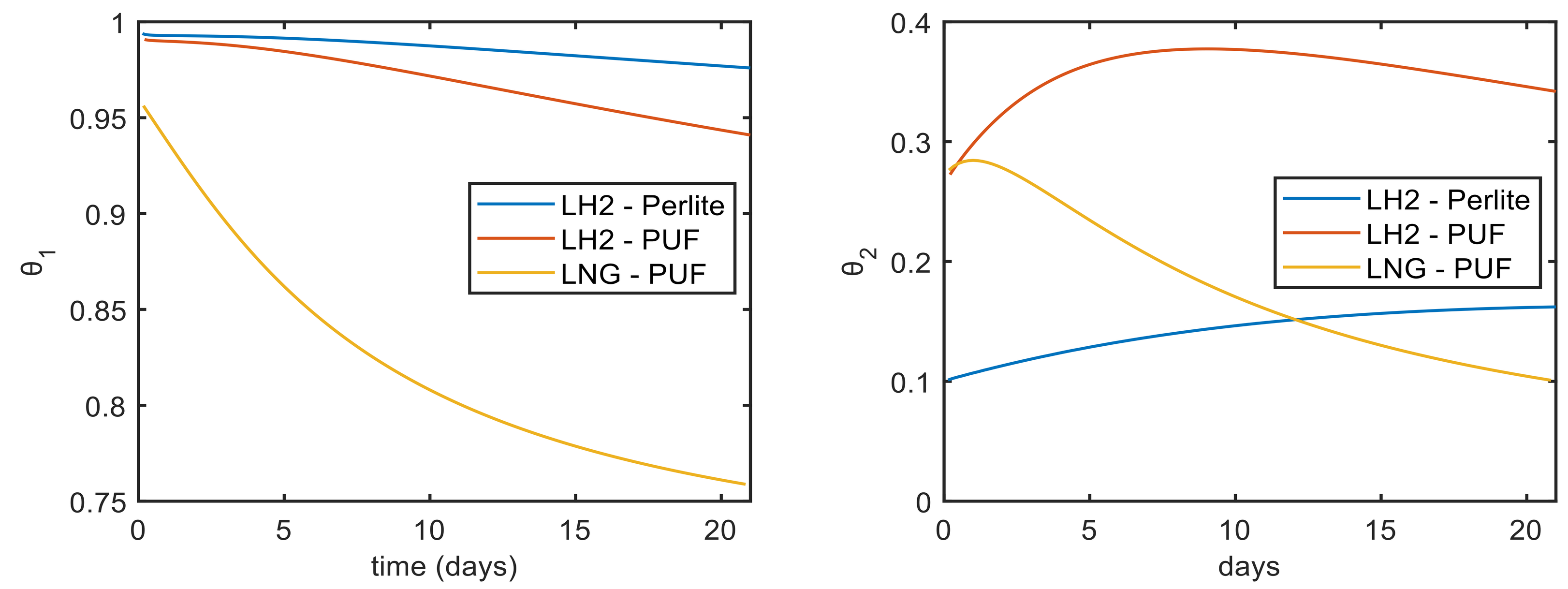

Figure 6: Dimensionless cumulative heat transfer for all tanks considered at 5% fill.

Conclusion

- New approach proposed for modelling self-pressurisation and vapour stratification using lumped mass methods, using two empirical tuning parameters.
- Self-pressurisation predicted to result in additional net heat gain. However, this may be offset by significant boil-off reductions.
- Significantly differences in heat transfer evolution between LNG and LH2 cases, primarily due to differences in thermophysical properties of steel at ~20 and ~110K and inner wall thickness.

Acknowledgements: The author acknowledges financial support from the Australian Govt and the Woodside Monash Energy Partnership in the completion of this work.

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[3] Wang, C., Y. Ju, and Y. Fu, *Dynamic modeling and analysis of LNG fuel tank pressurization under marine conditions.* Energy, 2021. **232**: p. 121029.