Thermal analysis of repurposing liquified natural gas (LNG) tanks for liquid hydrogen (LH2) storage

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1. Introduction

With the Net Zero Emission Scenario (NZS) predicted by the International Energy Agency (IEA) for the world by 2040, many global LNG terminals (Figure 1) with liquefaction and regasification facilities will be outmoded in the coming decades. Since the LNG storages at these facilities account for more than half of the capital cost of the terminals and are equipped to operate at cryogenic temperatures of -162 ^{0}C, repurposing them as Liquid Hydrogen (LH2) storages has emerged as a feasible notion that needs to be evaluated.

Figure 1 - LNG Terminal with Storage Tank and Vessel (Hodge, 2016)

Current Status of LNG Trade (GIIGNL,2023)

LNG Trade 2022	**389.2 MT** **0.9 x 10^{9} m^{3}**
Global Liquefaction Capacity	**476 MTPA***
Global number of liquefaction storage tanks	**134**
Global nominal regasification terminal capacity	**1068 MTPA**
Global number of regasification terminal storage tanks	**742**
LNG shipping fleet	**734 vessels**

*MTPA is Million Tons Per Annum

1.1 Challenges of repurposing

- Reduced temperature of the storage liquid -161.5 ^{0}C ➔ -252.58 ^{0}C
- The requirement of high insulation to minimize the boil-off
- Modified carrying capacity over the density variation Spec. Density LNG – 0.5 and LH2 0.07
- Requirement of enhanced safety features due to the high flammability range of hydrogen (4% - 75%)
- The durability of the inner tank against cryogenic conditions at -252.58 ^{0}C
- Changes in the required minimum allowance for joints, welds, pores, or any discontinuation in the containment chamber
- Change in provision for the venting/increased venting
- High permeability of hydrogen compared to LNG
- The tank requires high fatigue resistance due to constant storage and cycling capabilities.
- Possibility of hydrogen embrittlement in internal storage tank

2. Methodology

- **This simulation only assesses the performance of the shell of the LNG tank.**
- Heat transfer through the shell side of the tank was simulated using the finite element analysis considering conduction, convection and radiation. A cross-sectional homogeneous sample of 1/19780th of the total area LNG tank shell was modeled during the simulation.
- Thermal conductivity coefficients were input as either a function of pressure or temperature or both. Convective heat transfer coefficients were calculated using the Nusselt number, Grashof number, and Prandtl number. Solar radiation was modeled as a heat flux into the system.

2.1 Tank Specifications

Tank type and volume	**Full containment tank 200,000 m^{3}**
Internal tank diameter	**84 m**
9% Nickel Steel thickness (internal tank)	**33 mm**
Insulation layer 1 thickness (Glass fiber)	**432.9 mm**
Insulation layer 2 thickness (Perlite)	**655.6 mm**
Insulation layer 3 thickness (PU)	**111.5 mm**
Reinforced concrete thickness	**750 mm**
Design pressure	**29 kPa**

2.2 Boil-Off Calculation

$$\text{Daily volumetric boil-off \% (VB)} = \frac{Q_{shell} \times 24 \times 3600}{\rho \times V_{tank} \times \Delta H} \times 100\%$$

Analysis of volumetric boil-off % of LNG and LH2

$$\frac{VB_{LH2}}{VB_{LNG}} = I_Q \times I_\rho \times I_{\Delta H}$$

Q_{shell} – Heat transfer from the shell, ρ – density (428.38 kg/m^{3} for LNG and 69.80 kg/m^{3}),
ΔH – Latent heat of vapourization (508.82 kJ/kg for LNG and 441.49 kJ/kg), V_{tank} - Volume of the tank
I_Q – Ratio of heat transfer, I_ρ – Ratio of density, $I_{\Delta H}$- Ratio of Latent Heat of vapourization

3. Results

3.1 Performance of the existing insulation system with LH2

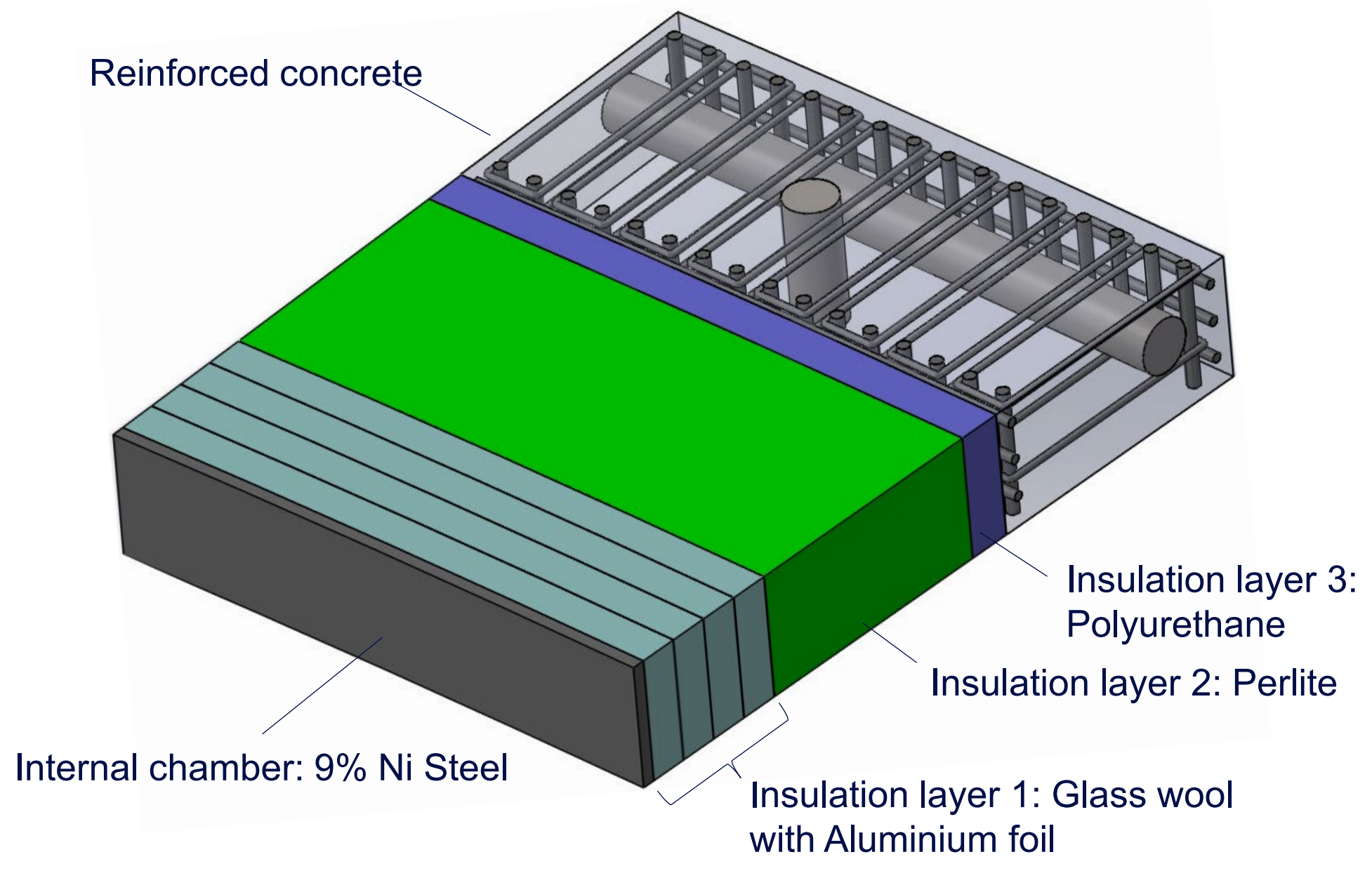


Figure 2 - Cross Section of LNG Tank

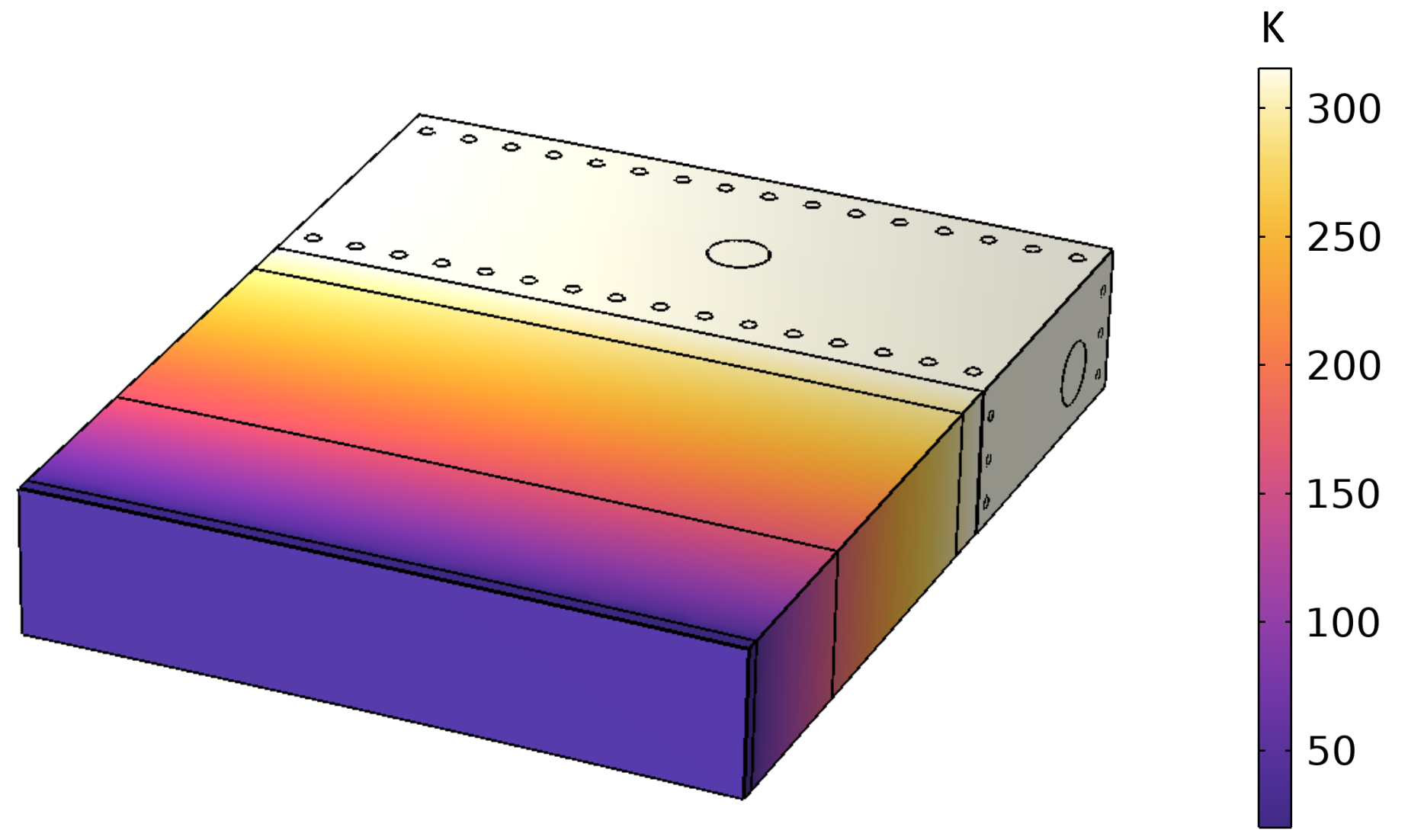
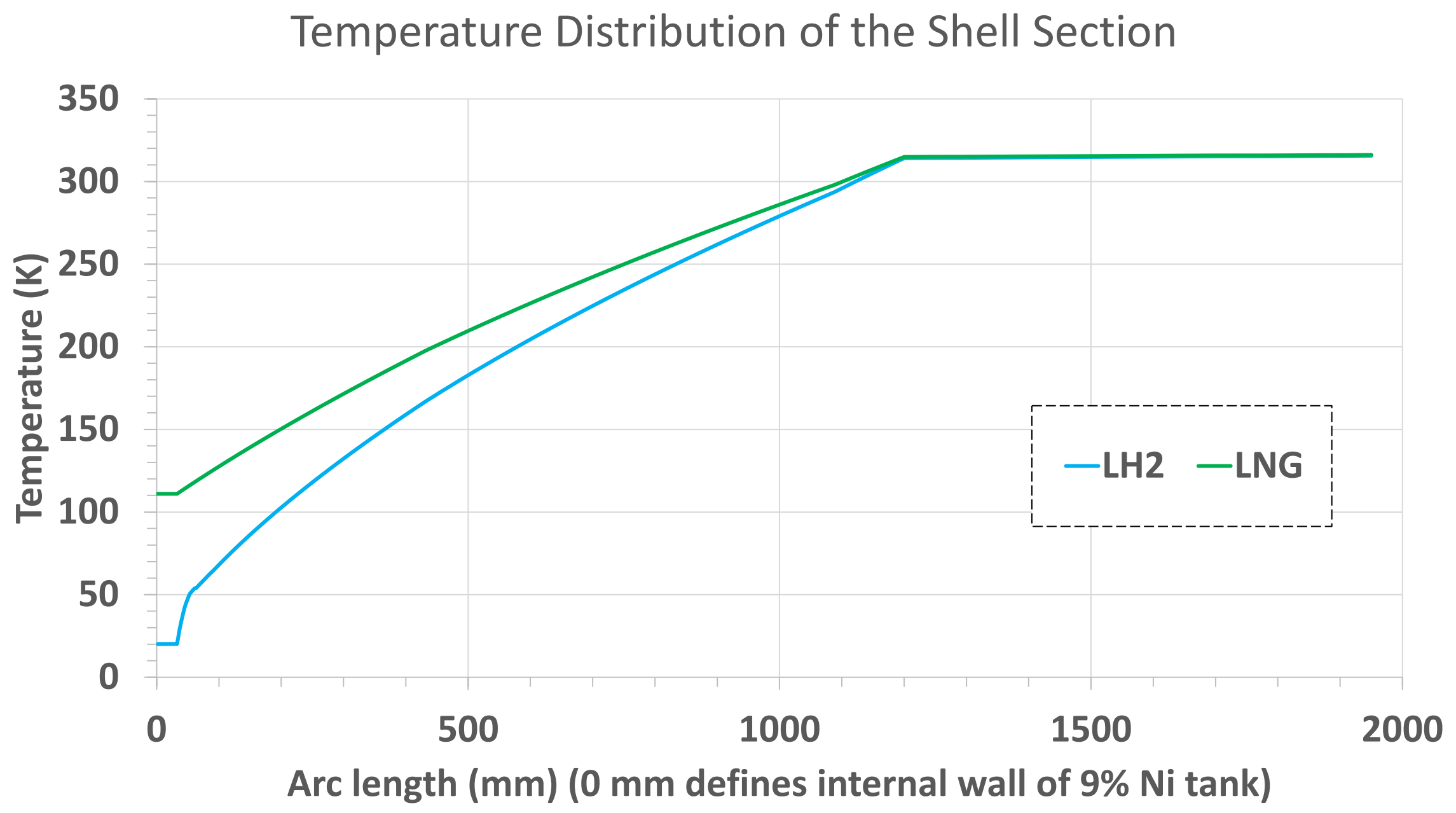
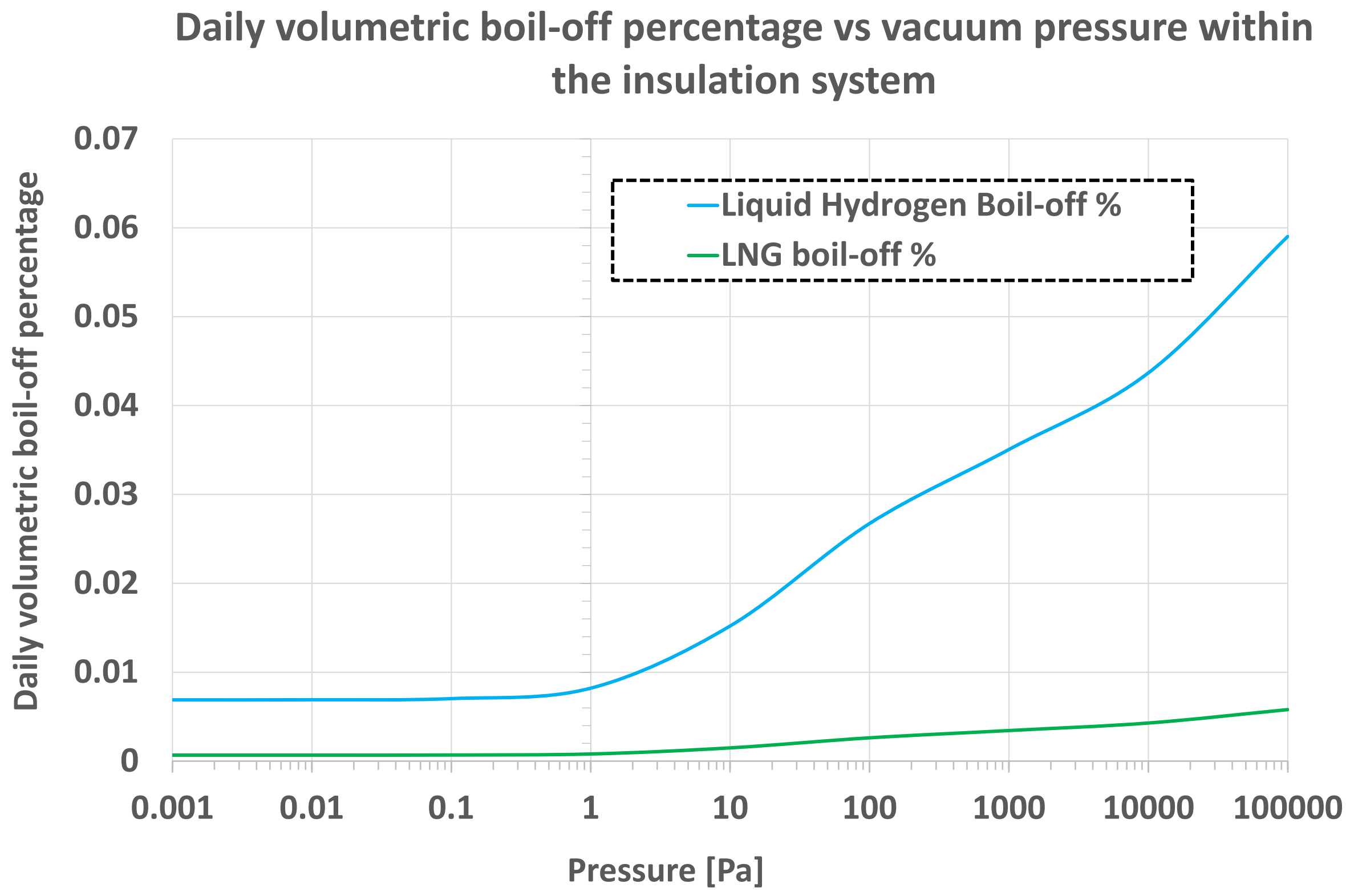


Figure 3 - Temperature distribution of the shell



3.2 Impact of Vacuum Insulation



Pressure (Pa)	Heat flux in LH2 (W)	
0.001	4,920	Heat flux in LNG at 1 bar = 29,236 W
0.01	4,929	
0.1	5,020	
1	5,858	
10	10,847	Daily volumetric boil-off of LNG at 1 bar = 0.006%
100	19,068	
1000	25,008	
10000	31,152	
100000	42,101	

3.3 Impact of Alternative Insulation Materials

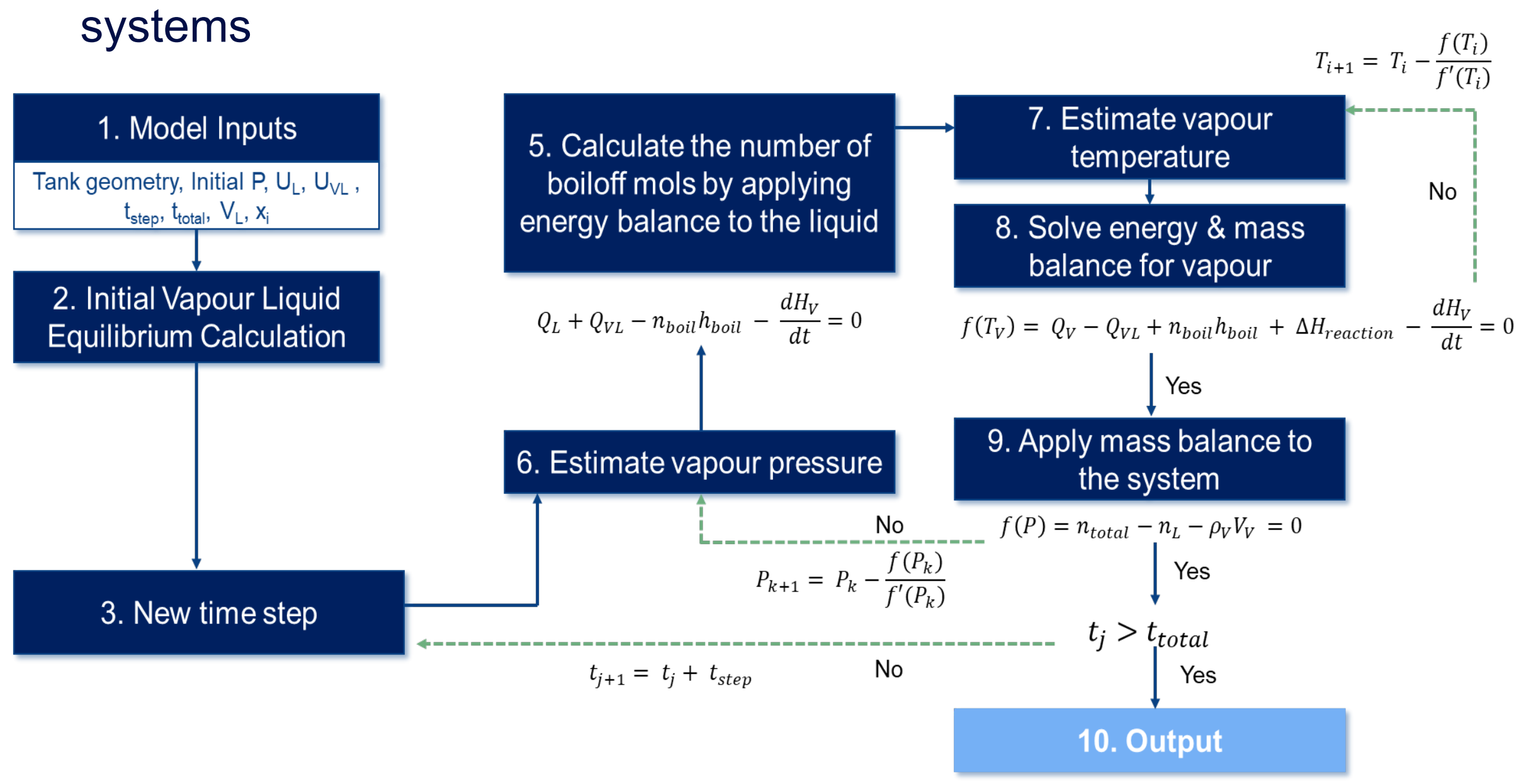
Materials considered	Perlite, Polyurethane, Aerogel, Glass microspheres
Insulation pressure	1 bar
Daily volumetric boil-off % of LH2	0.04 % - 0.09%
Best performing insulation	i. Aerogel, ii. Glass microspheres

4. Conclusion

- Storing LH2 using the existing shell insulation structure will experience 1.2 – 1.5 times heat flux compared to LNG. However, the density difference between LH2 and LNG contributes to the biggest difference of the daily volumetric boil-off rate calculations.
- Application of vacuum insulation to existing insulation at least up to 1 Pa can significantly reduce LH2 boiloff, thus providing competitive boil-off rates with LNG
- Replacing the existing insulation system with alternative insulation materials can reduce the volumetric boiloff rate up to 0.04% at 1 bar pressure.
- Concrete section is not exposed to considerable heat flux even storing LH2, thus the impact on reinforcements is minimal

5. Future Work

- Conduct thermal simulations covering all three components of the tank; roof, shell, and bottom including support systems
- Assess the boil-off performance of the tank using the following dynamic boil-off model for new active and passive insulation systems



1. Model Inputs
Tank geometry, Initial P, U_L, U_{VL} , t_{step}, t_{total}, V_L, x_i
2. Initial Vapour Liquid Equilibrium Calculation
3. New time step
5. Calculate the number of boiloff mols by applying energy balance to the liquid
$Q_L + Q_{VL} - n_{boil}h_{boil} - \frac{dH_V}{dt} = 0$
6. Estimate vapour pressure
7. Estimate vapour temperature
$T_{i+1} = T_i - \frac{f(T_i)}{f'(T_i)}$
8. Solve energy & mass balance for vapour
$f(T_V) = Q_V - Q_{VL} + n_{boil}h_{boil} + \Delta H_{reaction} - \frac{dH_V}{dt} = 0$
9. Apply mass balance to the system
$f(P) = n_{total} - n_L - \rho_V V_V = 0$
$P_{k+1} = P_k - \frac{f(P_k)}{f'(P_k)}$
$t_j > t_{total}$
$t_{j+1} = t_j + t_{step}$
10. Output

- Assess the structural and safety performance of the tank including response to earthquakes and resistance to impact and explosion

References

- GIIGNL (2023). GIIGNL Annual Report 2023. [online] GIIGNL releases 2023 Annual Report. Available at: https://giignl.org/giignl-releases-2023-annual-report/
- Hodge, K. (2016). Darwin LNG Gas Plant Burn off in April 2016. Available at: https://www.flickr.com/photos/40132991@N07/25734427783.