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CFD model of pressure and temperature dynamics in LH2 storage tank due to heat ingress

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Introduction 1/2

Background

- Self pressurisation in closed LH2 storage, driven by boil-off depends upon
    - Heat transfer (magnitude, mode, location of heat ingress)
    - Flow conditions (laminar or turbulent mixing)
    - Storage fill level
    - Initial conditions

- Existing CFD models' limitations
    - Boundary conditions restricted to constant and/or uniform heat flux
    - Not accounted tank material properties dependence on temperature
    - Use of ideal gas EoS for GH2 and Boussinesq approximation for LH2
    - Use of laminar or RANS models to simulated transitional and weakly turbulent flows

- J. C. Aydelott, 'Normal Gravity Self-Pressurization of 9-Inch- /23 Cm/ Diameter Spherical Liquid Hydrogen Tankage', Report Number: NASA-TN-D-4171, Oct. 1967.
- M. M. Hasan, C. S. Lin, and N. T. Vandresar, 'Self-pressurization of a flightweight liquid hydrogen storage tank subjected to low heat flux', presented at the 1991 ASME/AIChE National Heat Transfer Conference, Minneapolis, MN, Jan. 1991.
- M. Kassemi and O. Kartuzova, 'Effect of interfacial turbulence and accommodation coefficient on CFD predictions of pressurization and pressure control in cryogenic storage tank', Cryogenics, vol. 74, pp. 138–153, Mar. 2016
- I. C. Tolias et al., 'Best practice guidelines in numerical simulations and CFD benchmarking for hydrogen safety applications', Int. J. Hydrogen Energy, vol. 44, no. 17, pp. 9050–9062, Apr. 2019.

Introduction 2/2

Relevance

- Safety implications
  - Pressure relief valve or boil off valve malfunction
  - Blockage of vent tube
- Practical application
  - Modelling LH2 to GH2 conversion in fuel cell systems
  - LH2 storage design with reduced boil-off

Scope of study

- Modelling heat transfer to closed LH2 storage accounting temperature dependent radiative and thermophysical material properties for both tank material and fluid (particularly important for non-uniform and transient heat flux distribution simulation)
- Using NIST EoS for accurate representation of both phases
- Using LES turbulent model to simulate complex transitional and weakly turbulent flow

Validation experiment NASA (TN D-4171) 1/2

Experimental setup

- Experimental vessel
  - Inner shell – ∅ 9” spherical LH2 tank (thickness – 0.254 mm)
  - Middle shell – radiant heaters (hemispherical top and bottom), T=273 K
  - Outer shell – cold guard and vacuum jacket
- Vacuum: below 10^{-5} Pa(a)
- Test 4 (out of 21): 50% fill, “uniform heating”
- Experiment duration: 400 s
- Pressure growth: 0.1 - 0.743 MPa(a)
- Experimental data available:
  - Pressure dynamics
  - Temperature transients in multiple locations

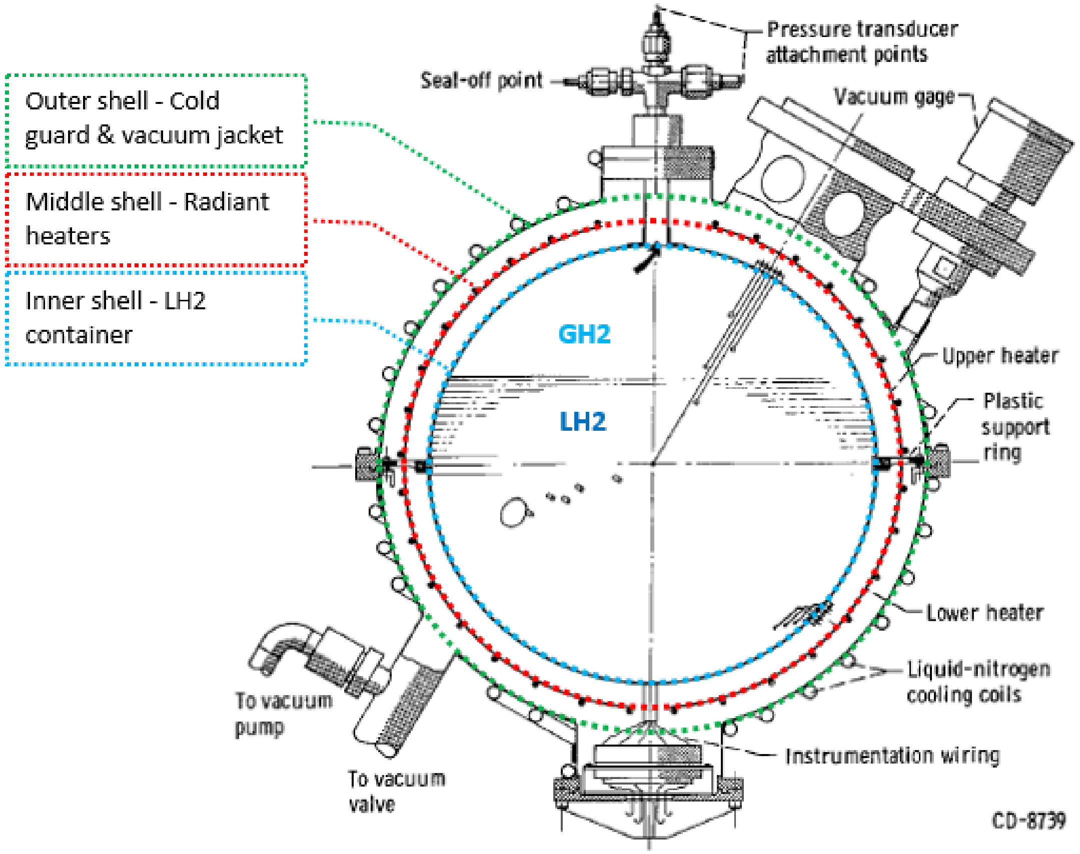


Image adapted from: J.C.Aydelott “Normal Gravity Self- Pressurization of 9-inch diameter spherical liquid hydrogen tankage” NASA TN D-4171, 1967

Validation experiment NASA (TN D-4171) 2/2

Key considerations

- Radiation dominates heat transfer
- Stratified temperature inside the tank

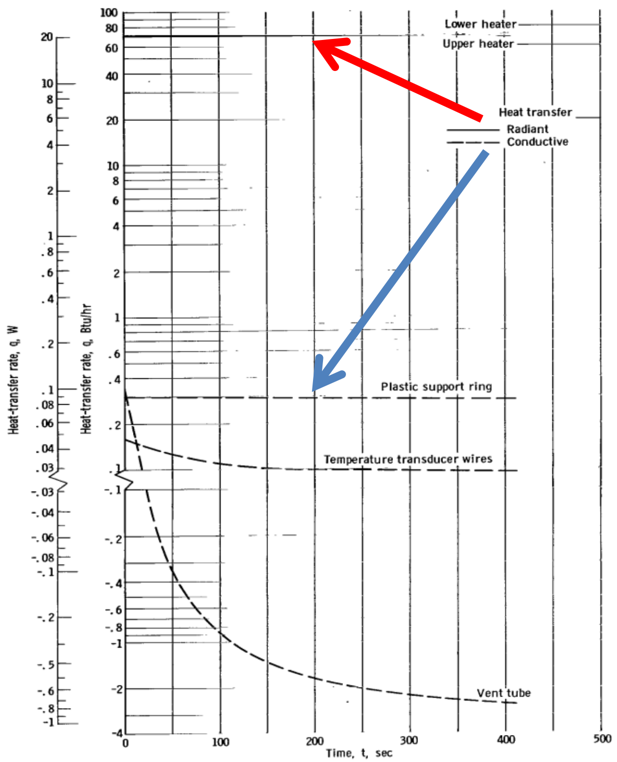


Figure 12. - Rate of heat input as function of time for each heat source for typical quiescent test.

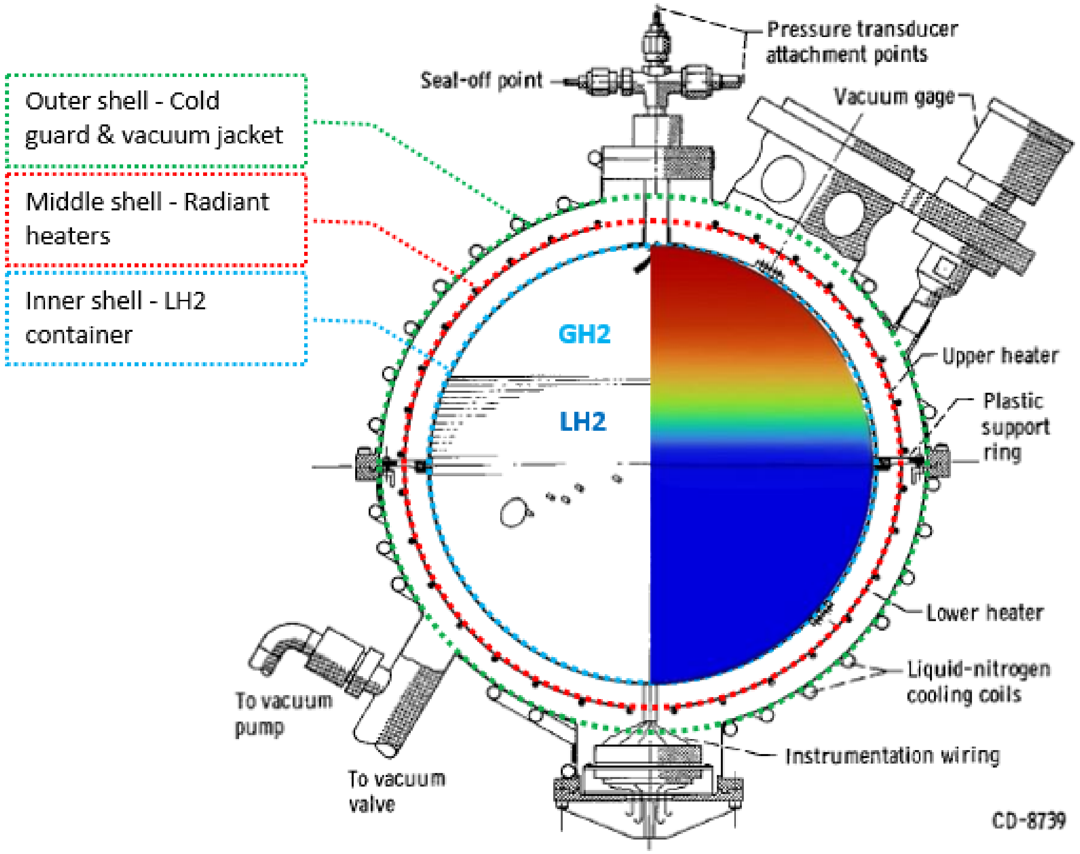
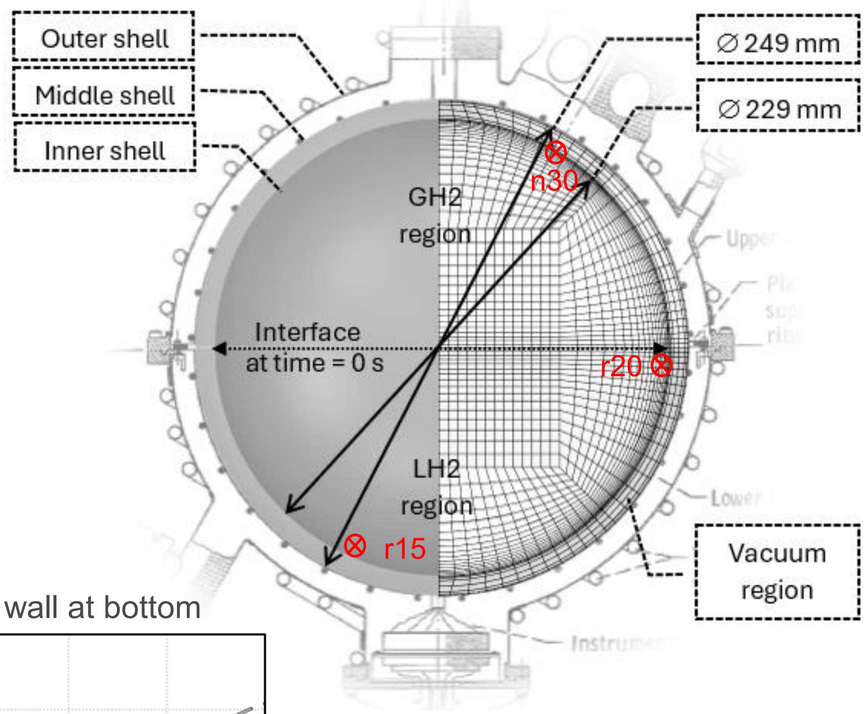


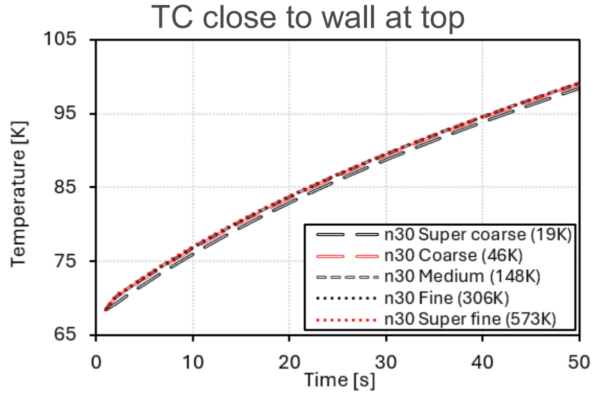
Image adapted from: J.C.Aydelott "Normal Gravity Self- Pressurization of 9-inch diameter spherical liquid hydrogen tankage" NASA TN D-4171, 1967

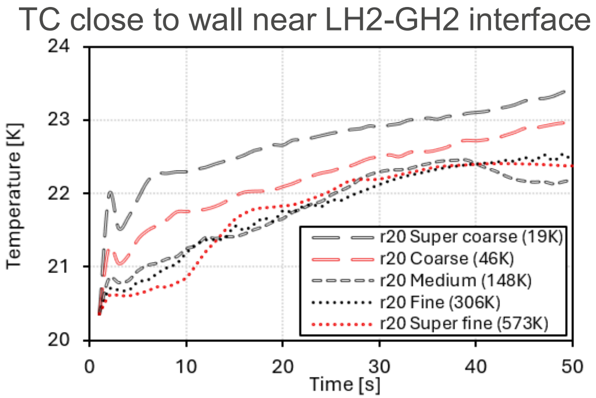
CFD model 1/3

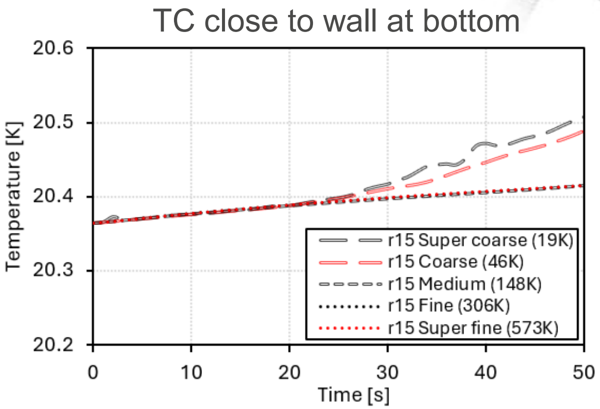
Calculation domain and numerical mesh

- Calculation domain includes
  - Radiating middle shell ∅ 249 mm with
    - Upper non heating orifice, 1190 mm^2
    - Lower non heating orifice, 100 mm^2
  - Inner shell ∅ 229 mm
    - Thickness 0.254 mm
- Numerical mesh:
  - 148,360 hexahedral CVs
  - Average orthogonal quality 0.96





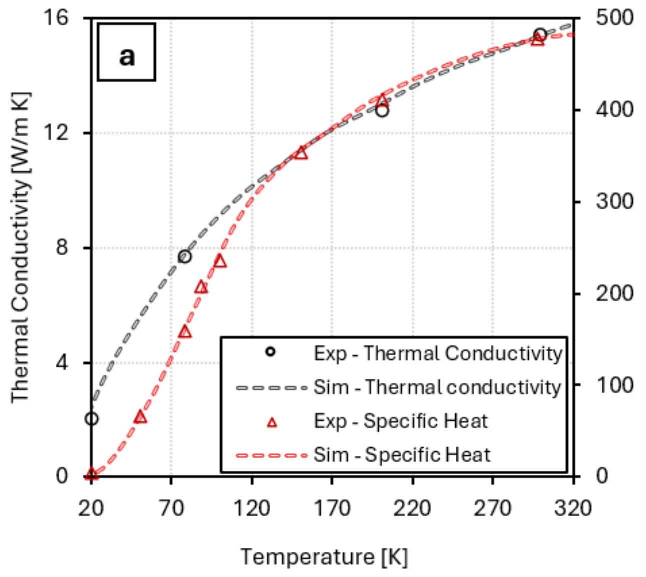


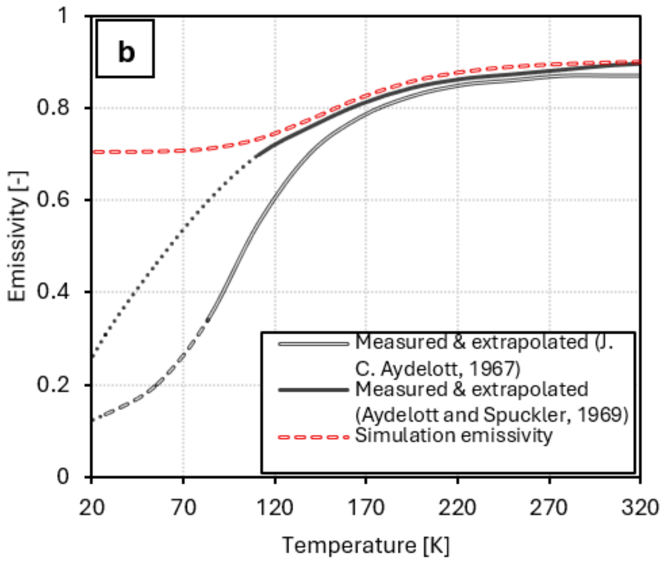


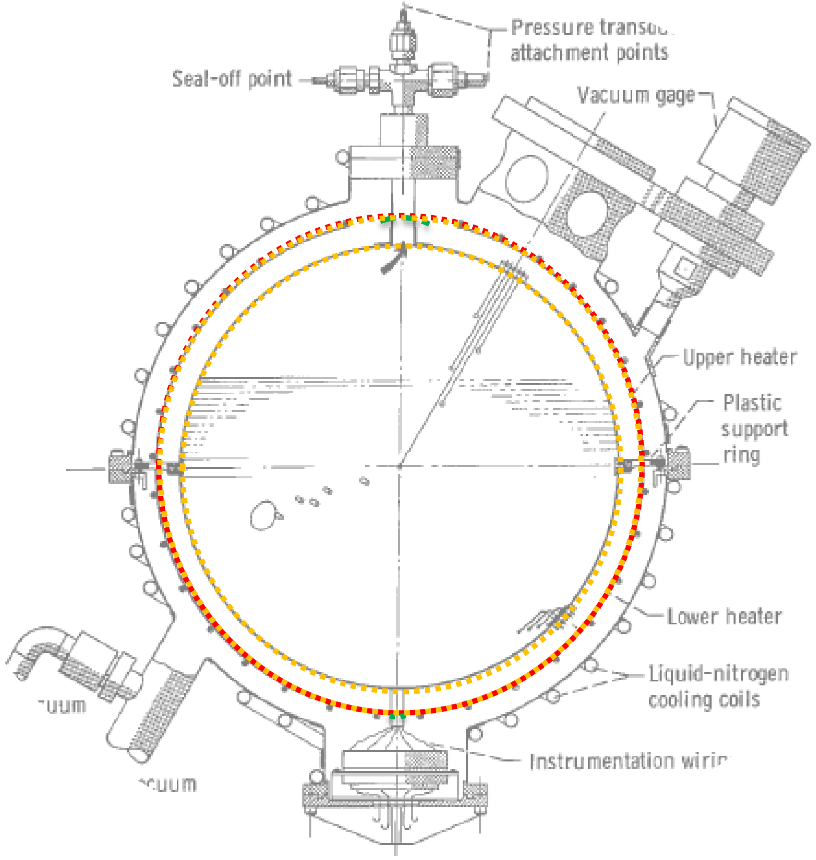
CFD model 2/3

Boundary conditions

▪ Heater temperature	293 K
▪ Temperature elsewhere	72 K to 86 K
▪ Radiative and thermophysical shell properties	
○ Black-painted surfaces emissivity	0.7 – 0.9
○ Emissivity elsewhere	0.1



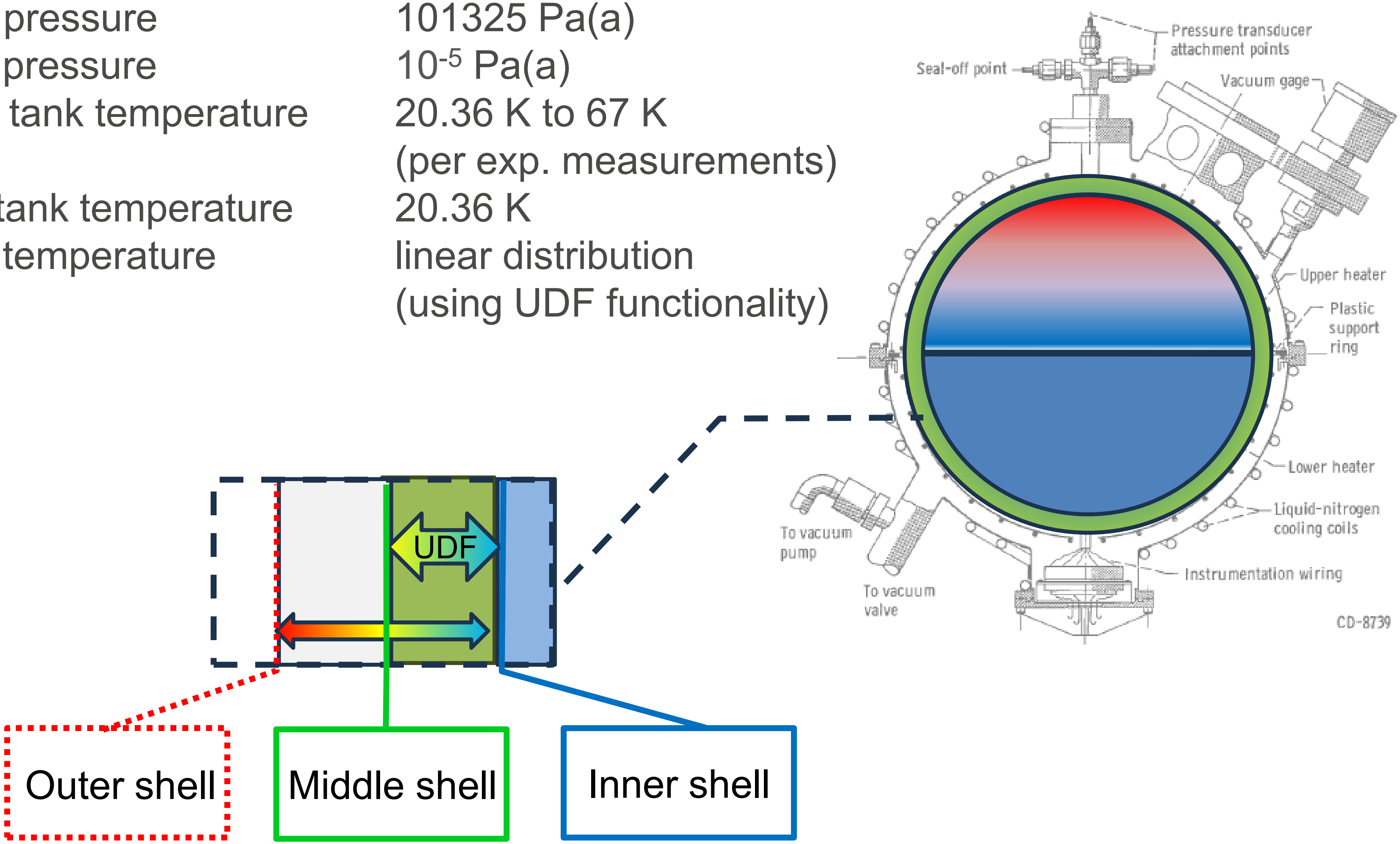




CFD model 3/3

Initial conditions

▪ Hydrogen tank pressure	101325 Pa(a)
▪ Vacuum jacket pressure	10^{-5} Pa(a)
▪ GH_2 and upper tank temperature	20.36 K to 67 K (per exp. measurements)
▪ LH_2 and lower tank temperature	20.36 K
▪ Vacuum jacket temperature	linear distribution (using UDF functionality)

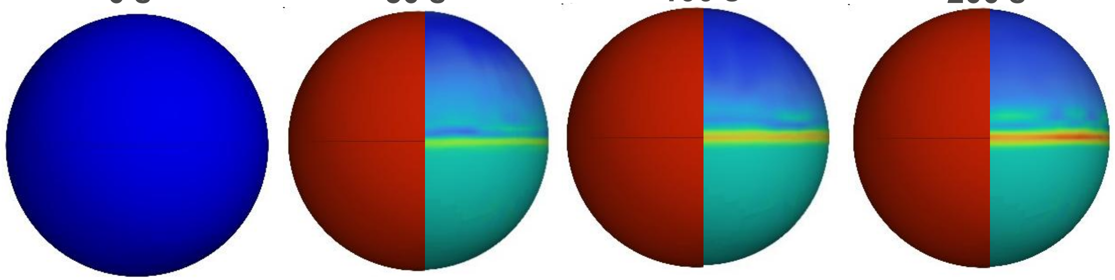


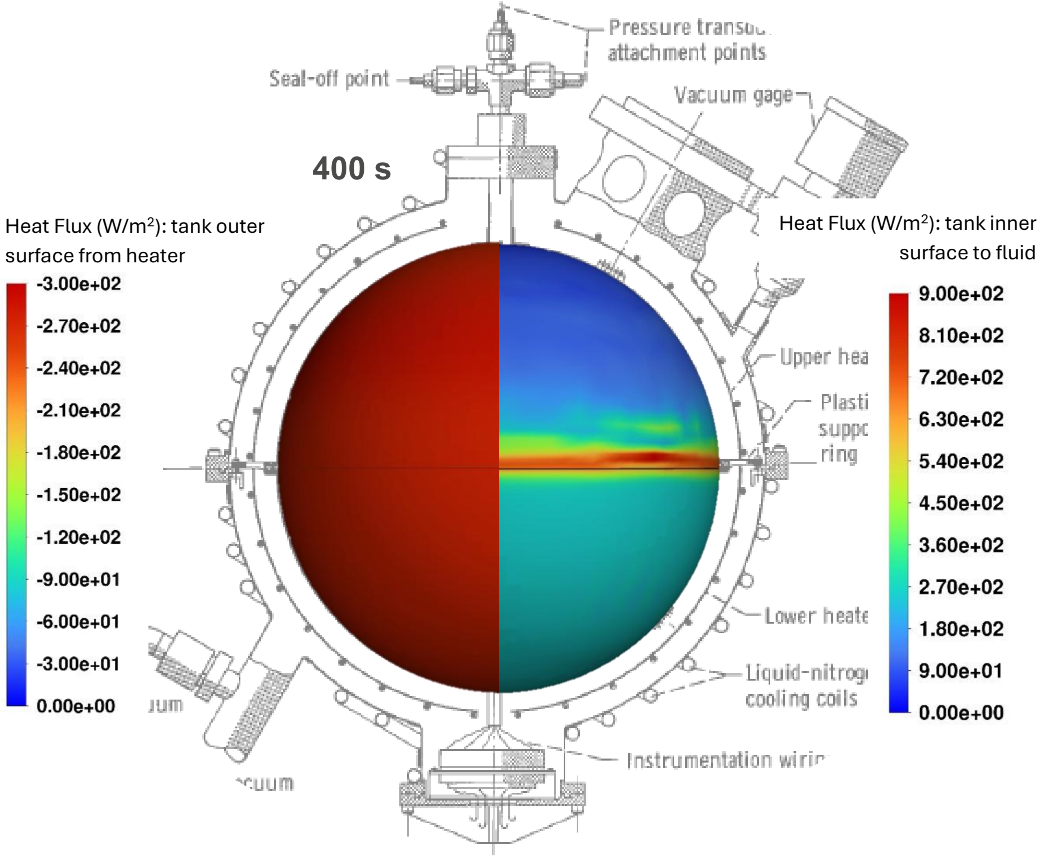
Simulation results 1/4

Heat and mass transfer 1/2

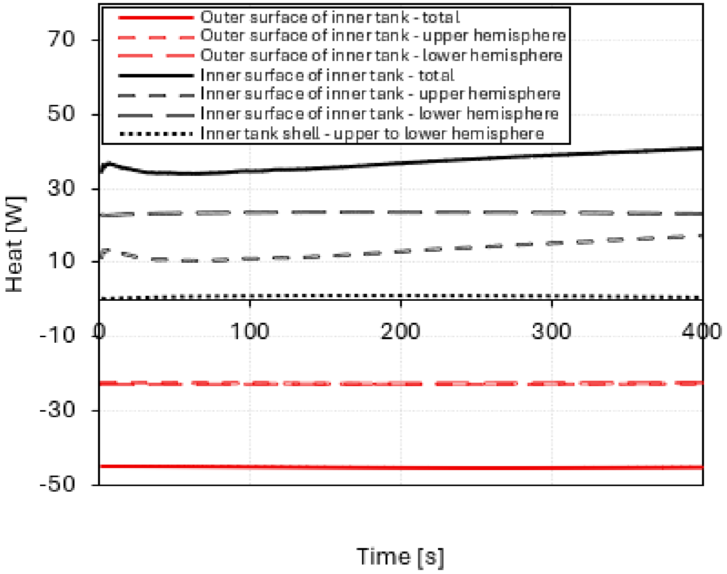
- Radiator at *T*=293 K results in non-uniform, time-dependant heat flux to fluid
- Heat flux to fluid is largest at LH2-GH2 interface
- Heat flux distribution is affected by temperature dependent radiative and thermal properties of tank and fluid

Heat flux distribution





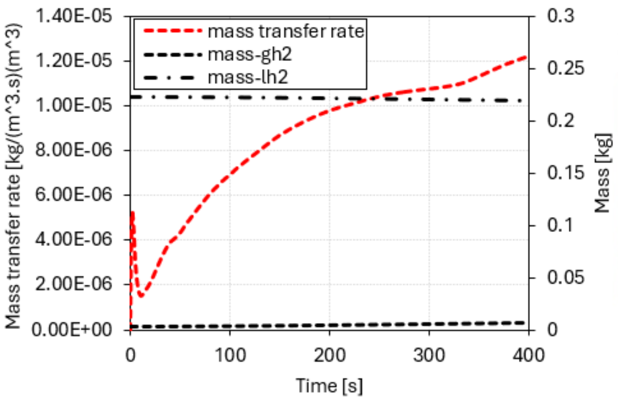
Outer tank surface Inner tank surface

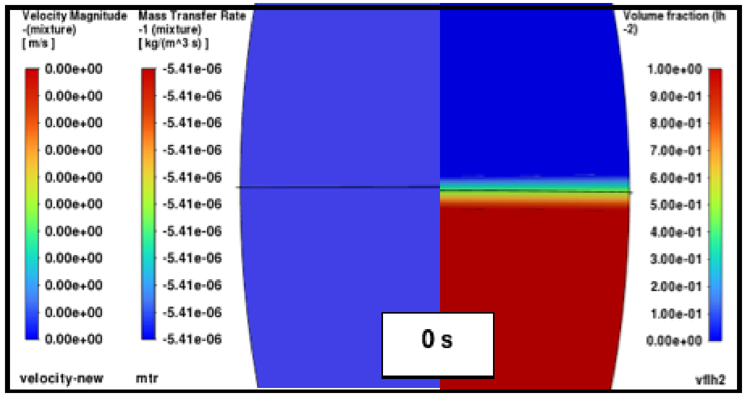


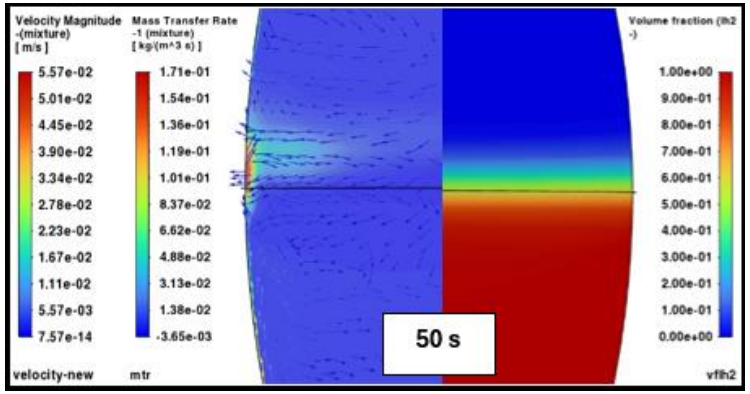
Simulation results 2/4

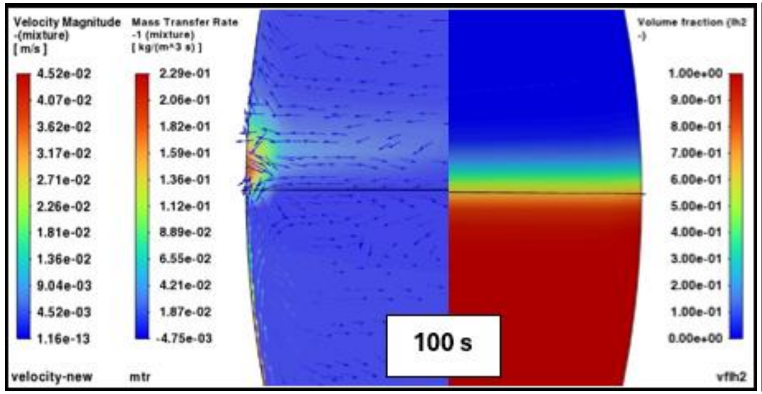
Heat and mass transfer 2/2

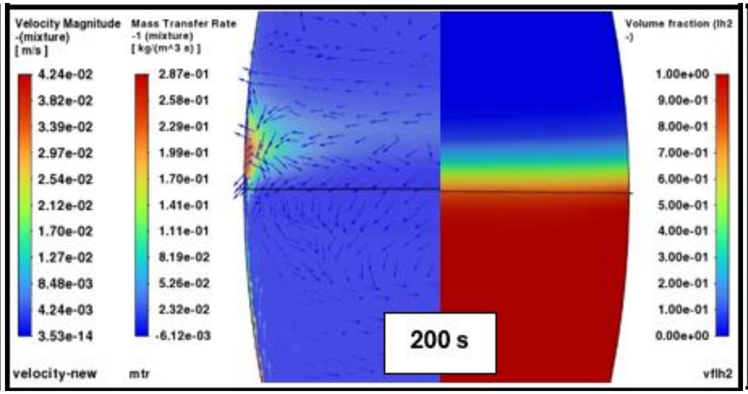
- LH2 at rest at initial moment promotes its local warming up and mass transfer rate
- LH2 convection development reduces the mass transfer rate
- LH2 natural convection is significant only close to wall (velocity ~0.05 m/s)
- Evaporation – only at LH2-GH2 interface and is amplified close the wall

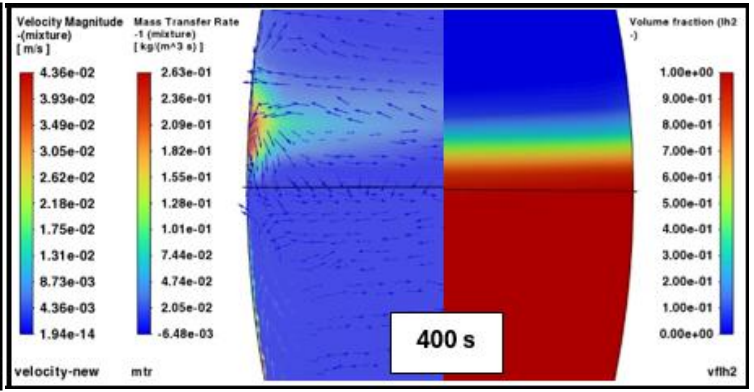










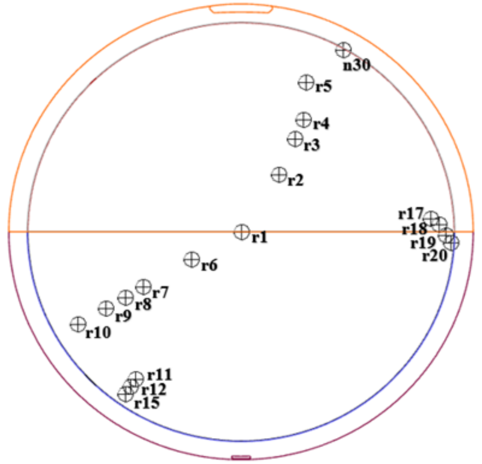


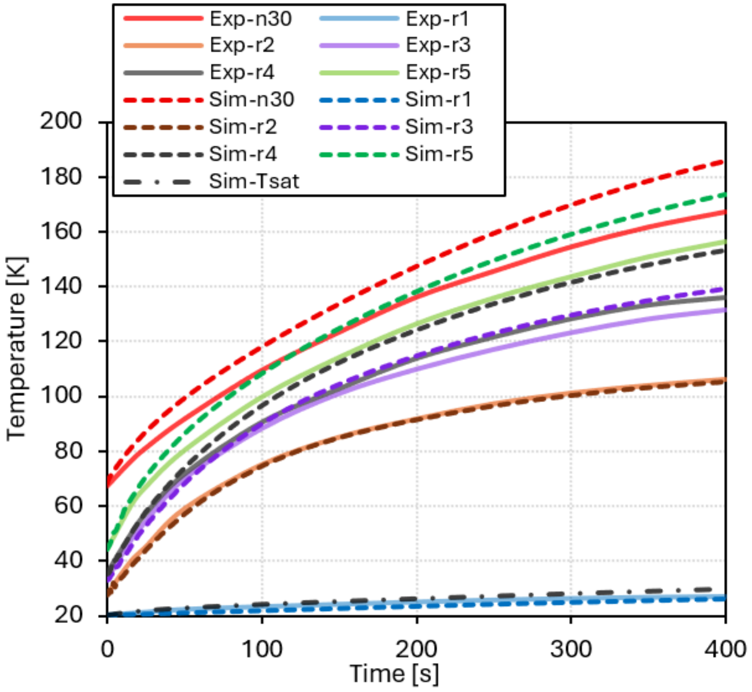
Cross-section contour view

Simulation results 3/4

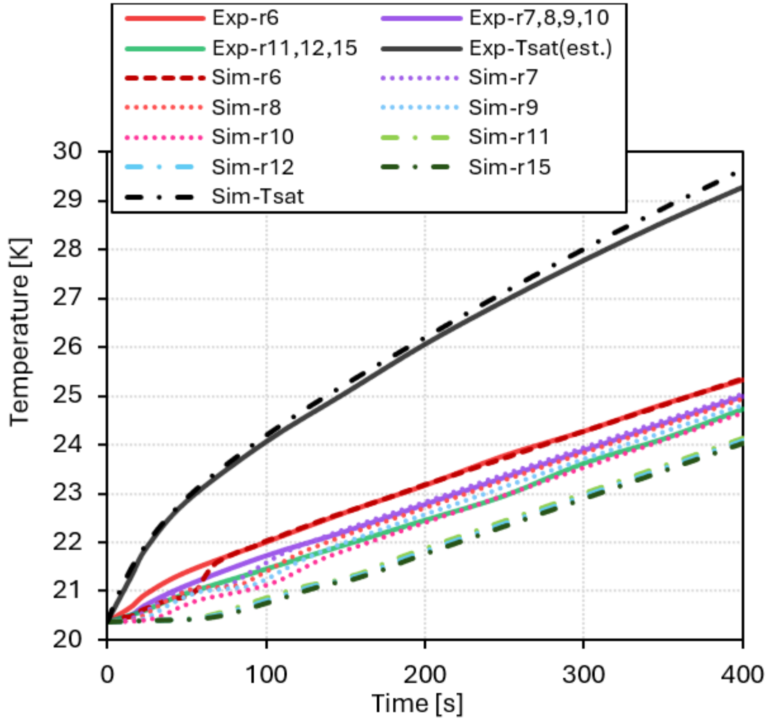
Temperature transients

- Temperature transients follow the experiment
- Maximum deviation is 12.5%
- Stratification is observed in GH2 and LH2 phases

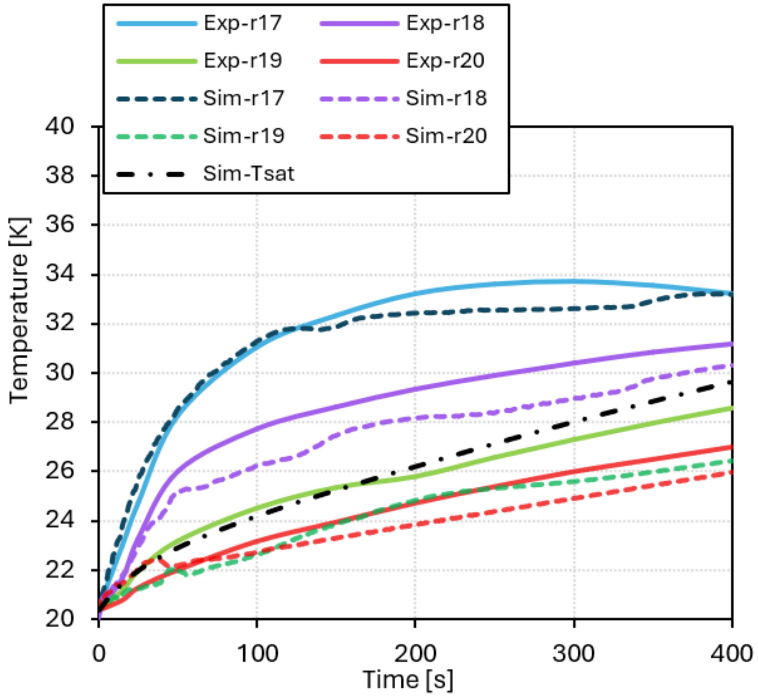




TCs at/above interface
(r1 - r5, n30)



TCs below interface
(r6 - r15)

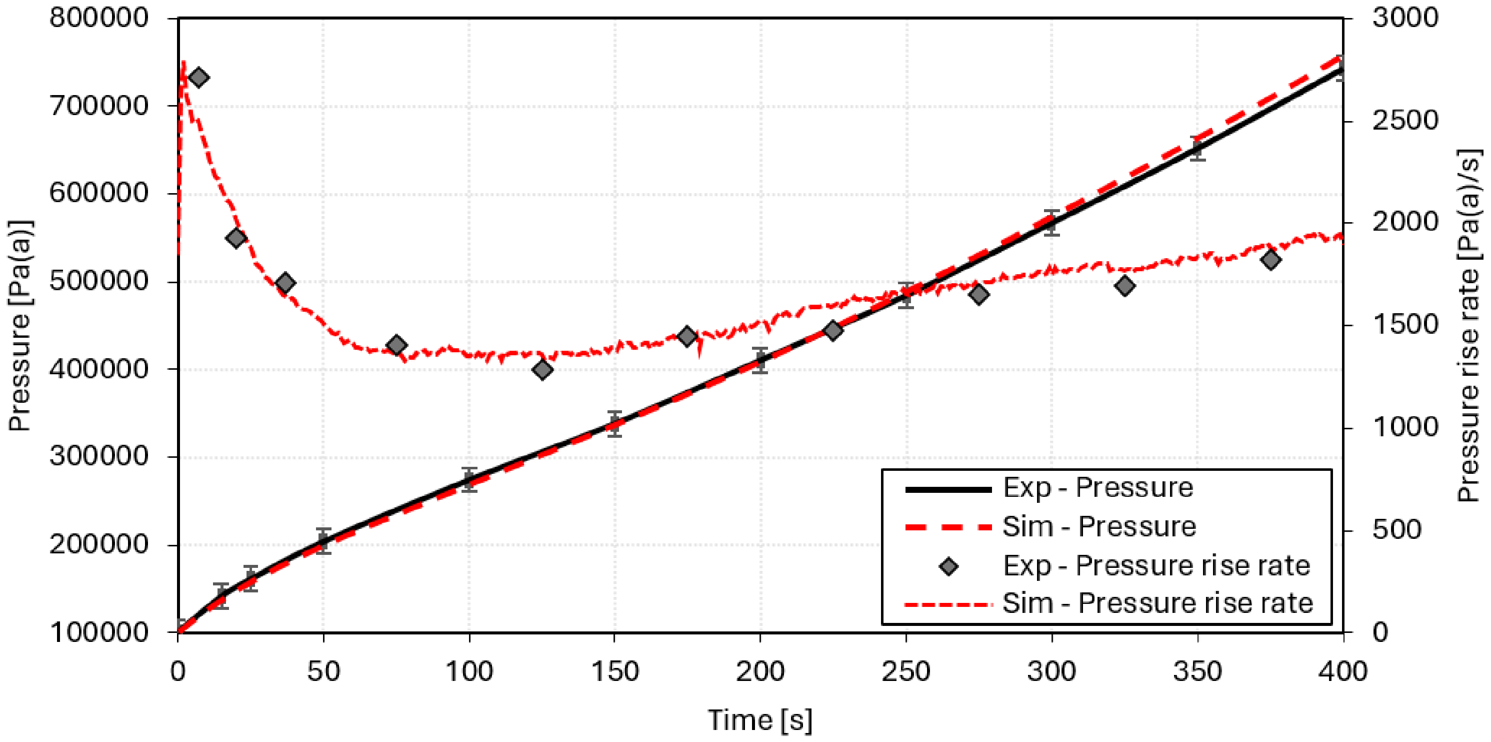


TCs in proximity to interface
and tank wall (r17 – r20)

Simulation results 4/4

Pressure dynamics

- Maximum deviation is 2.02%
- Wires, support structure and vent act as heat conductor
- Pressure underprediction/overprediction could be caused by initial net conductive heat transfer to the tank and out of the tank at later stage



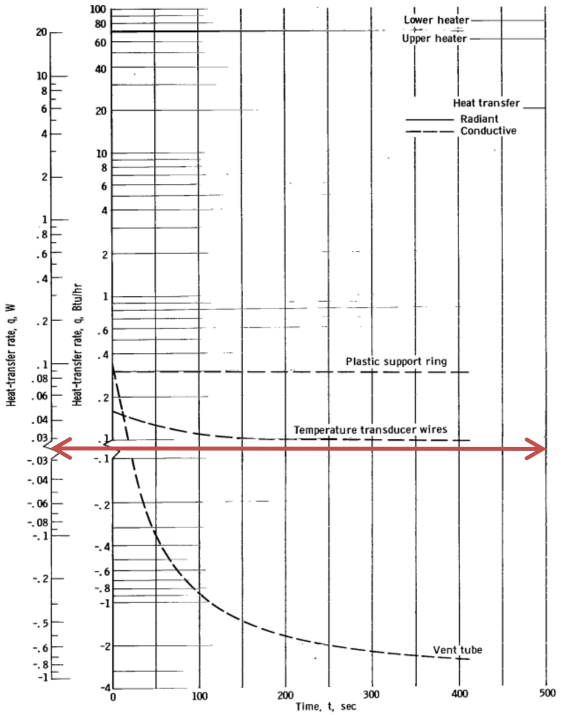


Figure 12. - Rate of heat input as function of time for each heat source for typical quiescent test.

Conclusions

- CFD model, based on LES and NIST hydrogen properties, provided good agreement with experimental pressure and temperature dynamics
- Despite constant temperature radiation heaters, distribution of the heat flux to fluid is highly non-uniform
- Accounting for temperature dependent tank material properties was crucial for correct prediction of LH2/GH2 phase transfer
- Evaporation was localised around the liquid-vapour interface and particularly intensive close to the vessel wall
- Temperature stratification was observed in both LH2 and GH2 phases
- Initially higher pressure rise rate was observed in both experiment and simulation
- Model is planned to be extended to account for convective heat transfer (when data are available for loss of vacuum condition)

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Thank You