



Self-pressurisation in a vacuum-insulated LH2 storage tank

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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

Introduction 2/2

Relevance

- Safety implications
 - Pressure relief valve or boil off valve malfunction / Blockage of vent tube
 - Incident scenarios like loss of vacuum.
- Practical application
 - Modelling boil-off systems - 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 – $\varnothing$ 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, “constant radiator temperature”
- Experiment duration: 400 s
- Pressure growth: 0.1 - 0.743 MPa(a)
- Experimental data available:
 - Pressure dynamics
 - Temperature transients in multiple locations

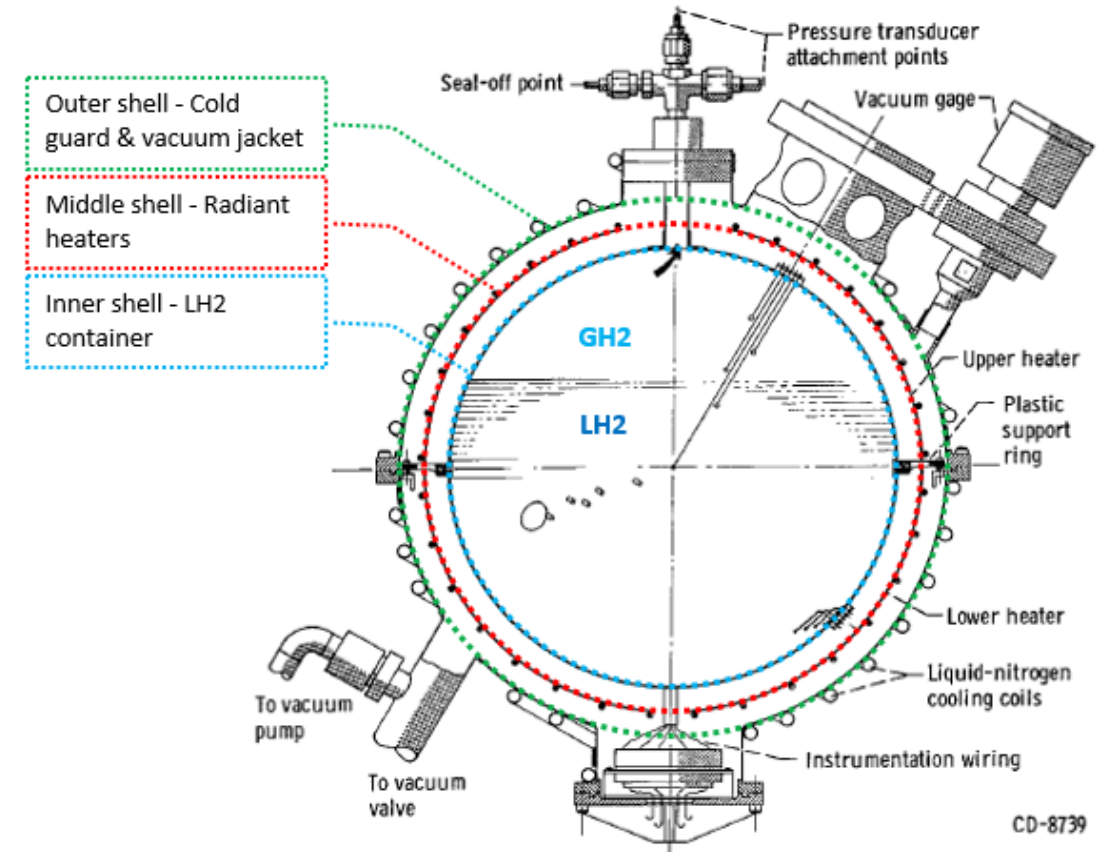


Image adapted from: J.C.Aydelott “Normal Gravity Self- Pressurization of 9-inch diameter spherical liquid hydrogen tankage” NASA TN D-4171, 1967

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

Key considerations

- Radiation dominates heat transfer
- Stratified temperature inside the tank

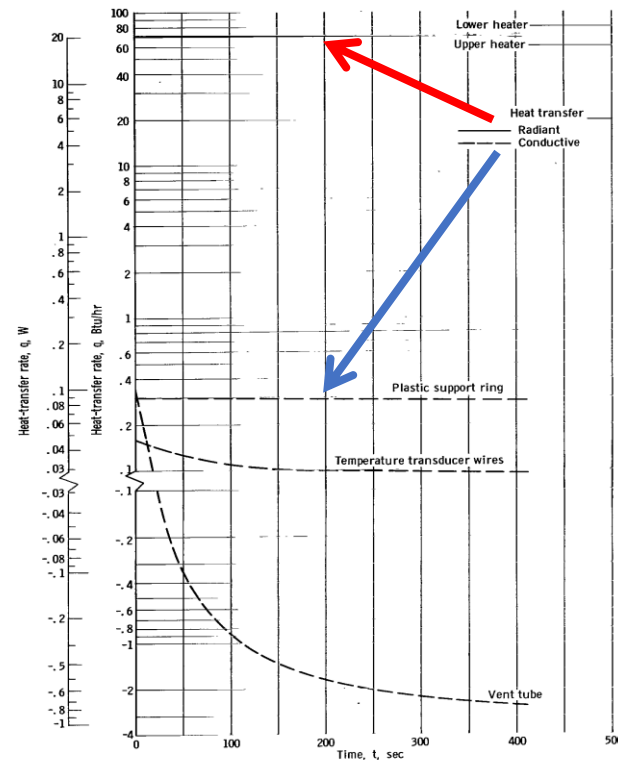


Figure 12. - Rate of heat input as function of time for each heat source for typical quiescent test.

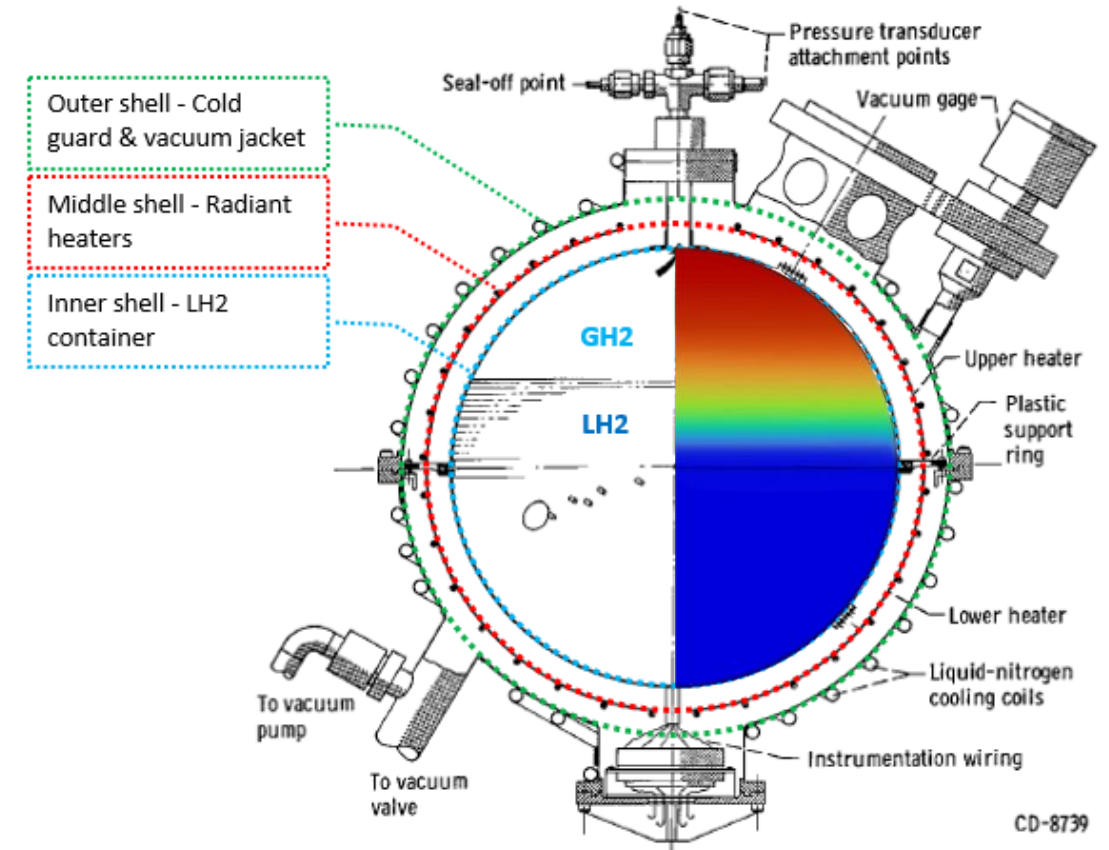
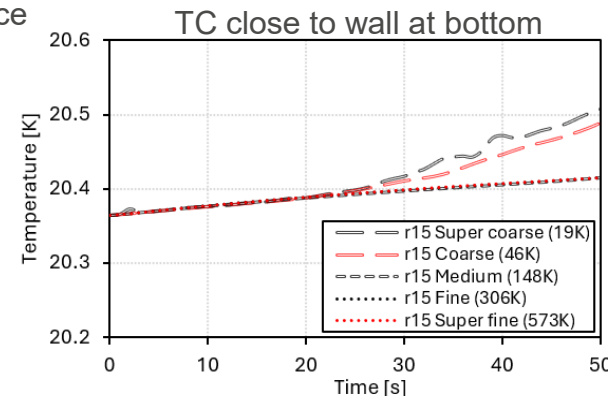
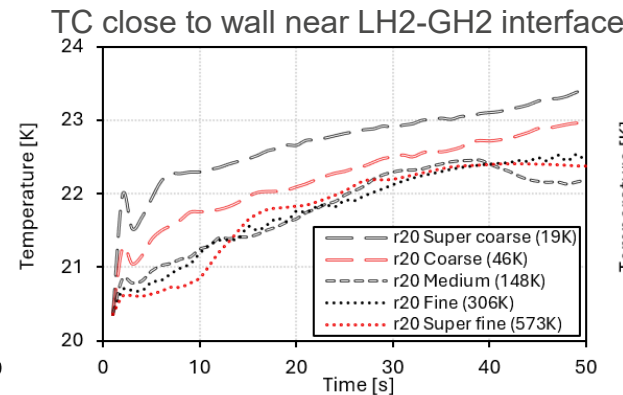
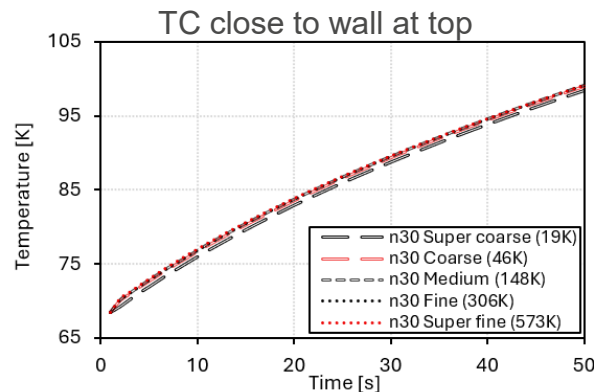
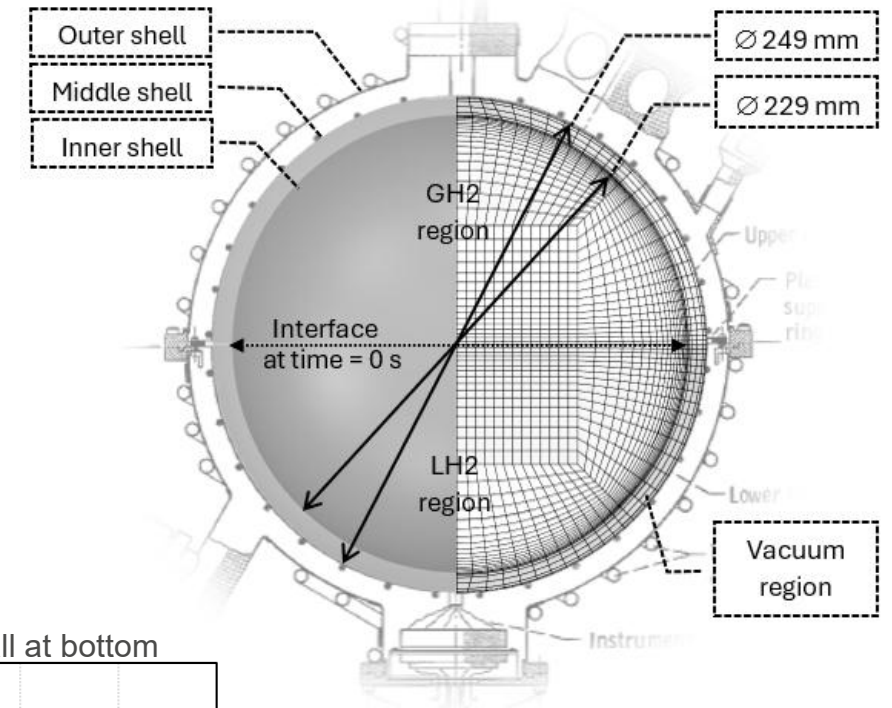


Image adapted from: J.C.Aydelott "Normal Gravity Self- Pressurization of 9-inch diameter spherical liquid hydrogen tankage" NASA TN D-4171, 1967

CFD model 1/3

Calculation domain and numerical mesh

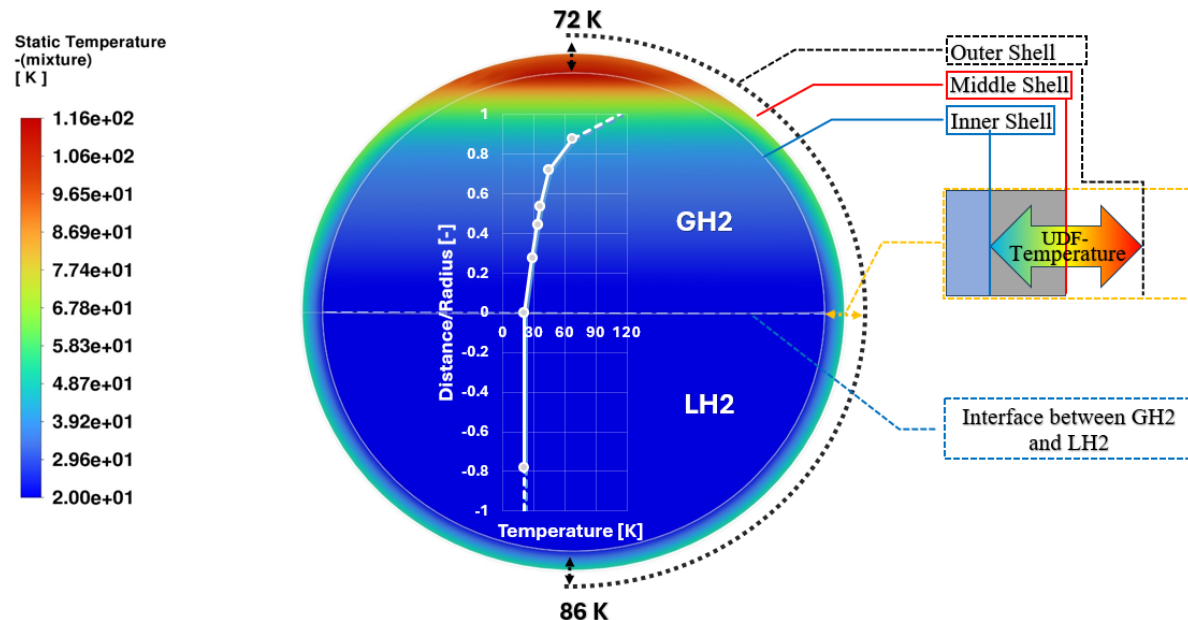
- Calculation domain includes:
 - Radiating middle shell $\varnothing$ 249 mm with
 - Upper non heating orifice, 1190 mm²
 - Lower non heating orifice, 100 mm²
 - Inner shell $\varnothing$ 229 mm
 - Thickness 0.254 mm
- Numerical mesh: 148,360 hexahedral CVs, average orthogonal quality 0.96



CFD model 2/3

Initial and boundary conditions

- Hydrogen tank pressure 101325 Pa(a)
- Vacuum jacket pressure 10^{-5} Pa(a)
- GH2 and upper tank temperature 20.36 K to 67 K
- LH2 and lower tank temperature 20.36 K
- Vacuum jacket temperature linear distribution
- Heater temperature 274 K



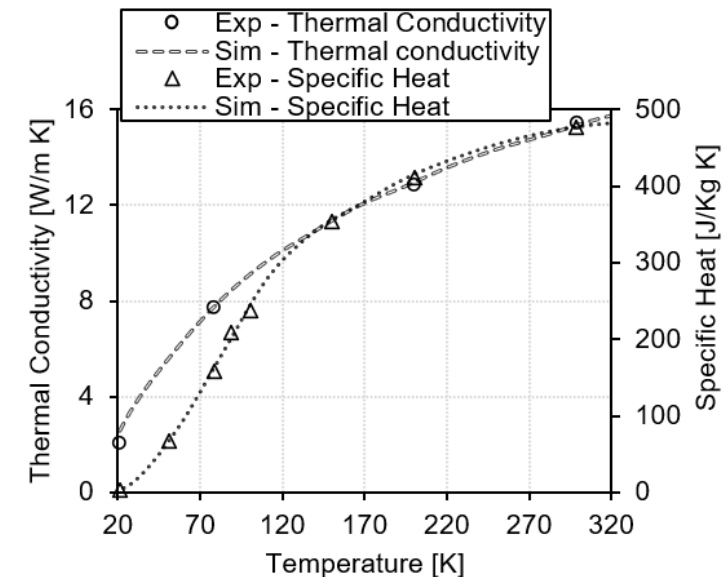
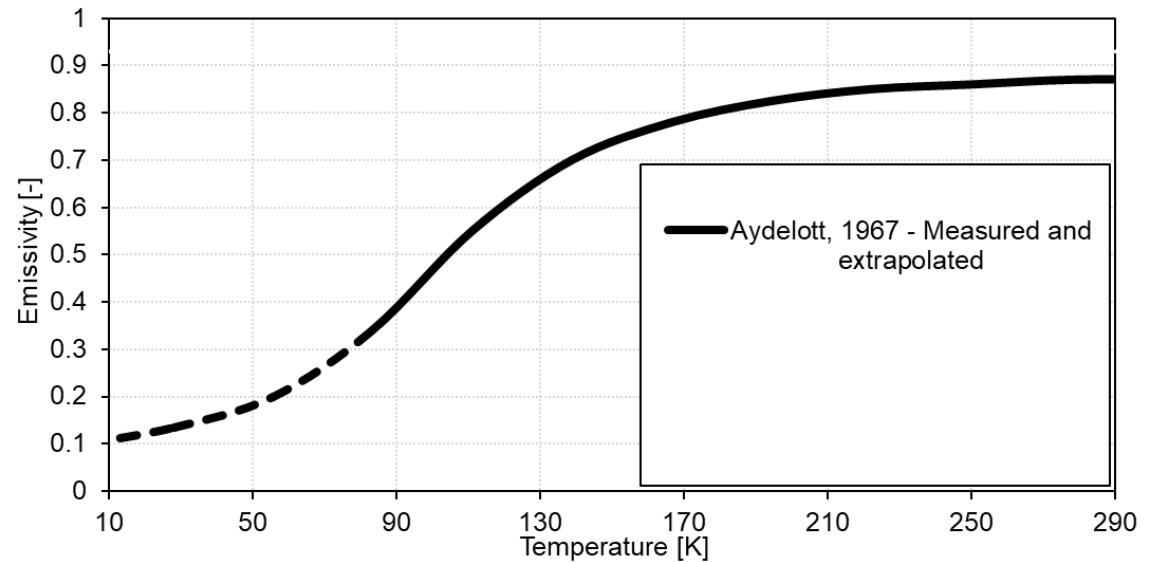
CFD model 3/3

Initial and boundary conditions

- Radiative and thermophysical shell properties

Governing equations & Models

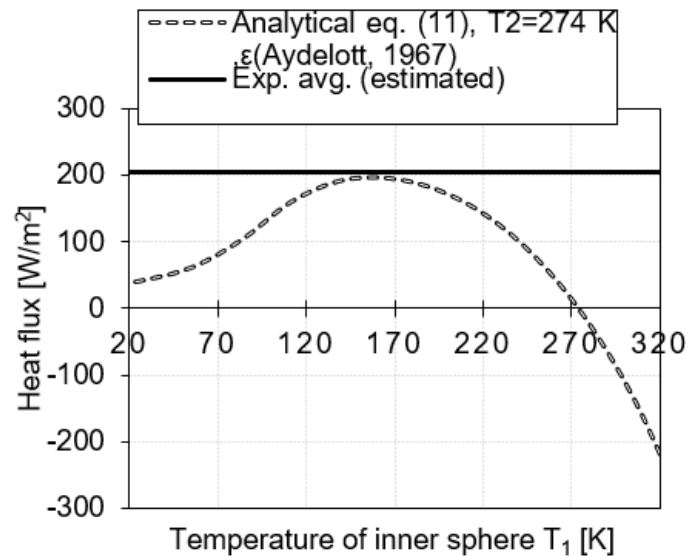
- Transient mass, momentum, energy conservation equations
- Multiphase: Volume of Fluid (VOF) method
- Mass transfer: Lee model
- Turbulence: Large eddy simulation (LES), dynamic Smagorinsky-Lilly model
- Radiation: Discrete Ordinate (DO) model



CFD 1/7: Experimentally reported emissivity

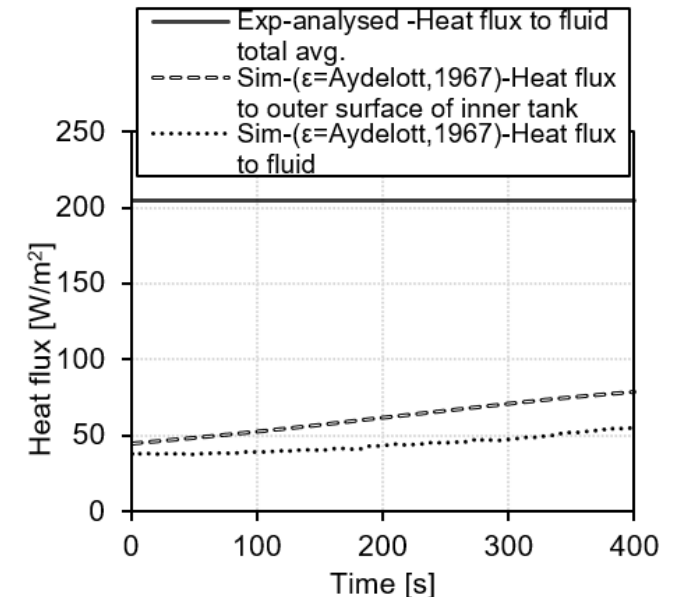
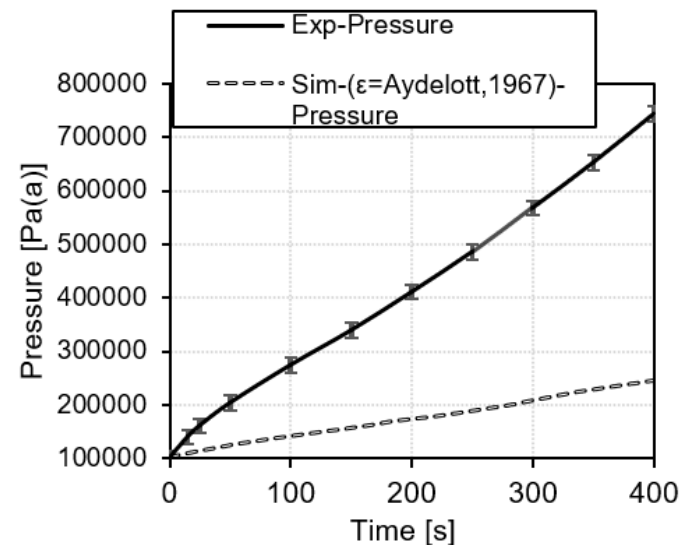
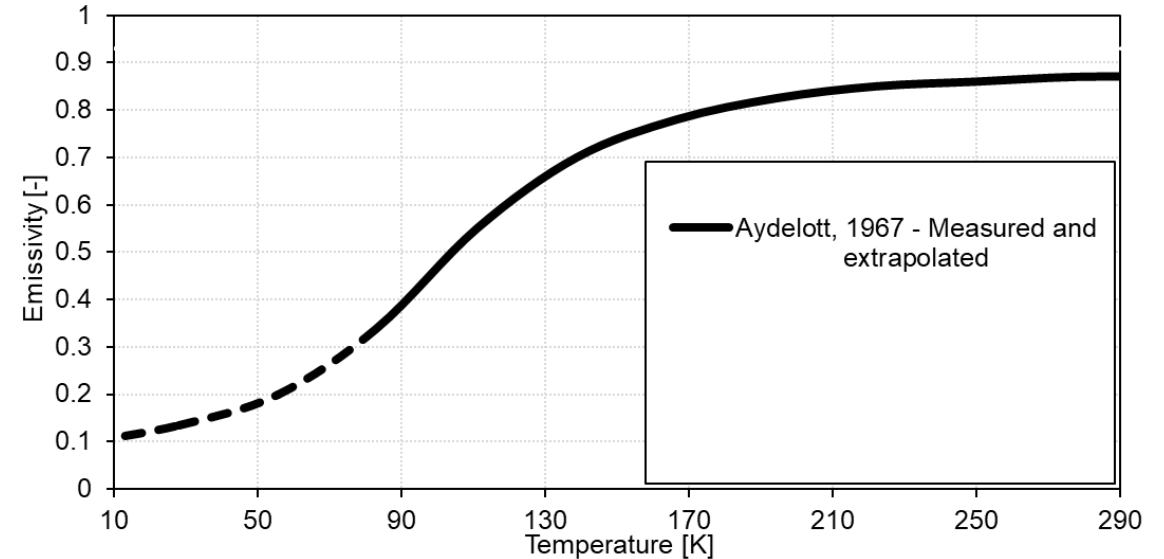
Case 1

- Radiator temperature = 274 K
- Emissivity = Aydelott, 1967



$$Q_{12} = -Q_{21} = \frac{A_1 \sigma (T_1^4 - T_2^4)}{\frac{1}{\varepsilon_1} + \left(\frac{A_1}{A_2}\right) \left(\frac{1}{\varepsilon_2} - 1\right)}$$

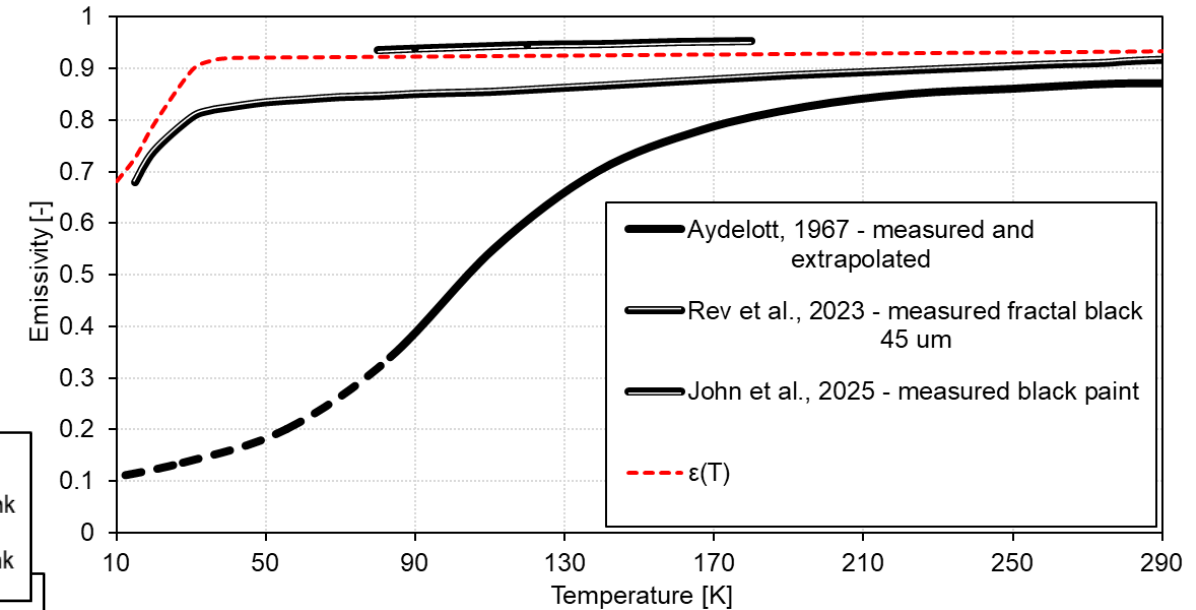
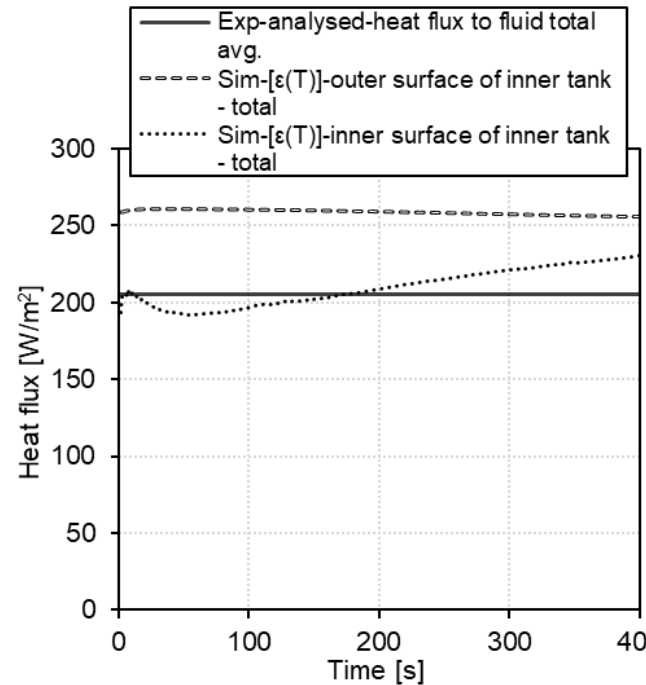
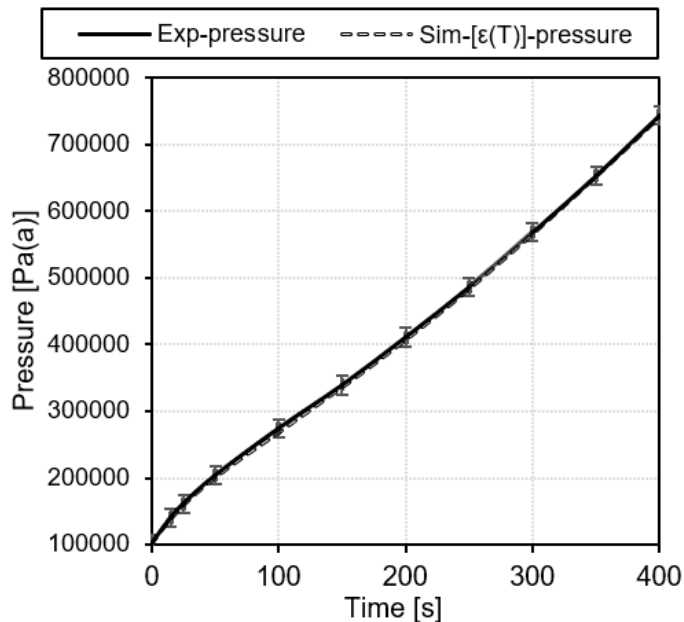
Benjamin G., 1971; Kern D.Q., 1988; Howell J. R., 2010



CFD 2/7: Adopted emissivity

Case 2

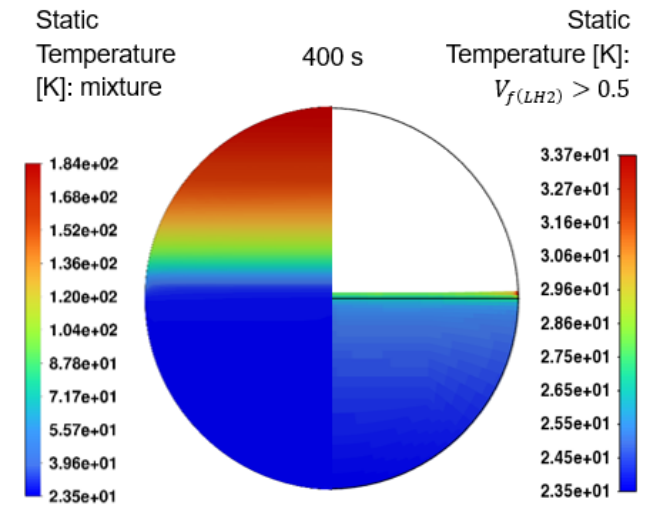
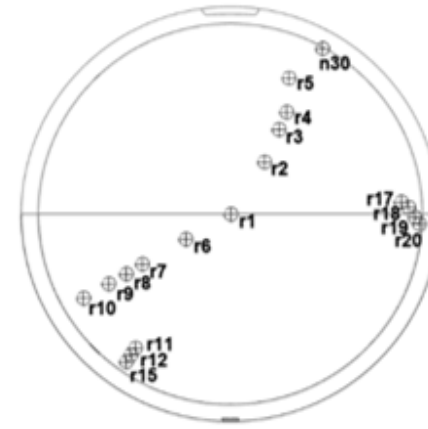
- Radiator temperature = 274 K
- Emissivity = $\epsilon(T)$



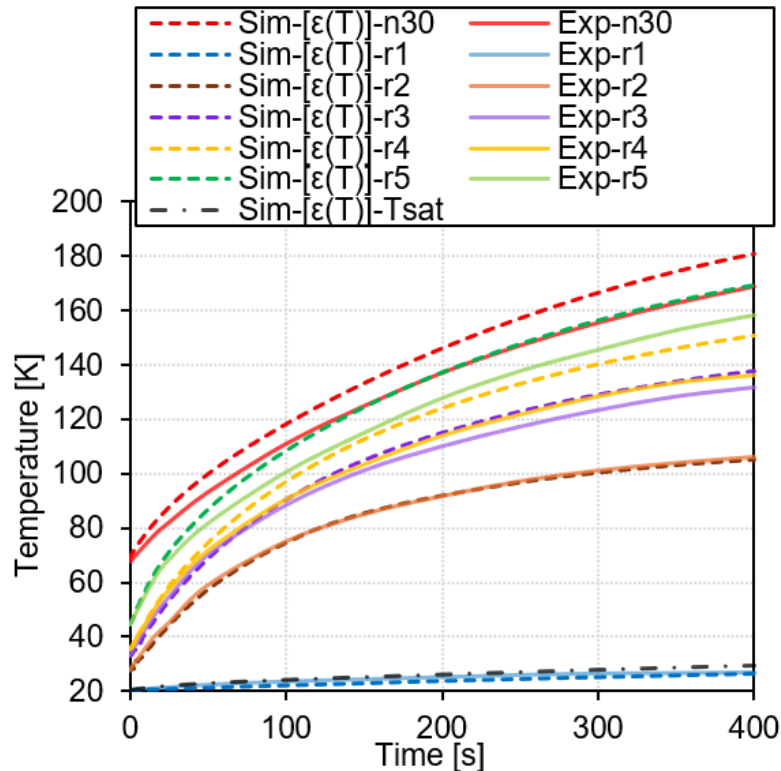
CFD 3/7: Dynamics $T(t)$

Case 2

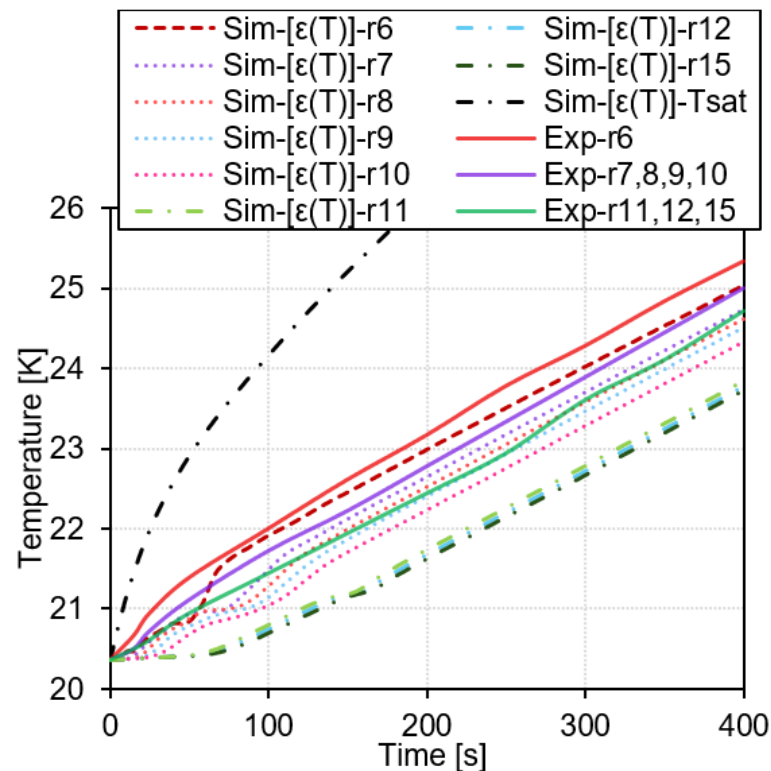
- Radiator temperature = 274 K
- Emissivity = $\varepsilon(T)$



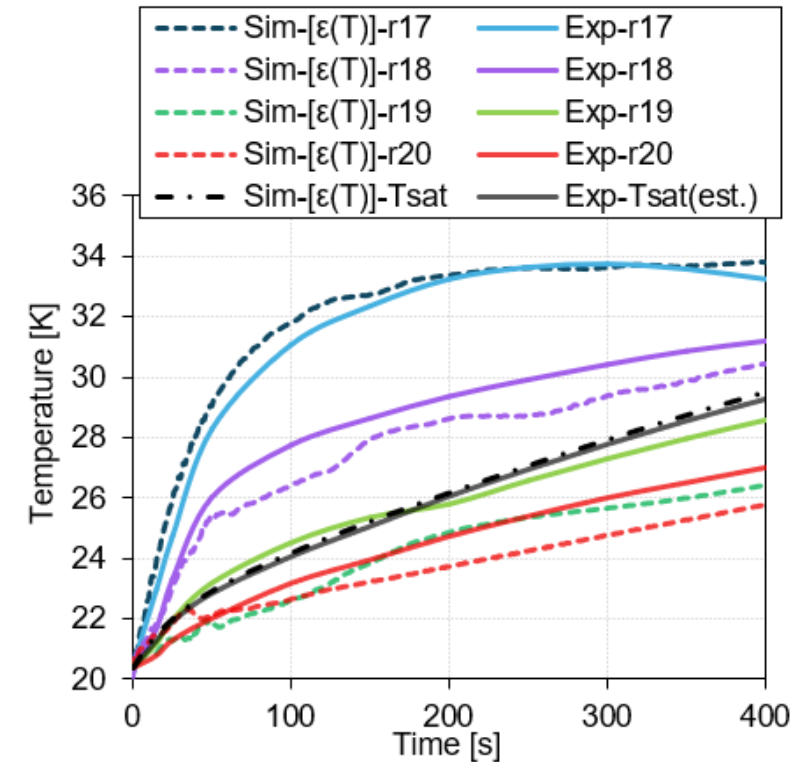
TC in upper hemisphere



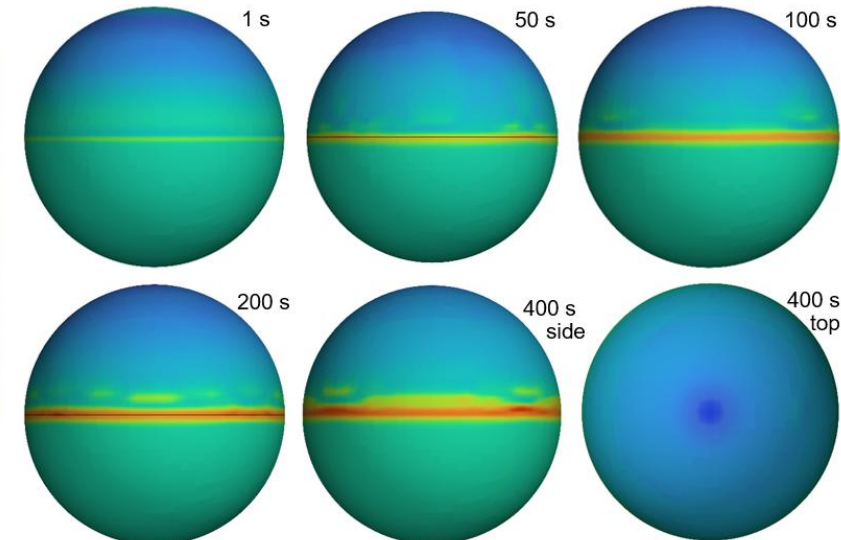
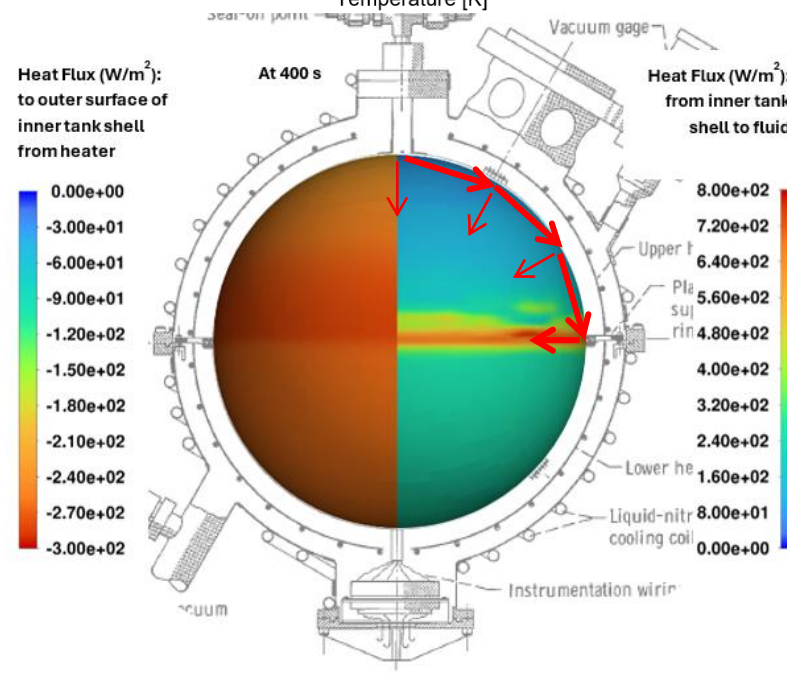
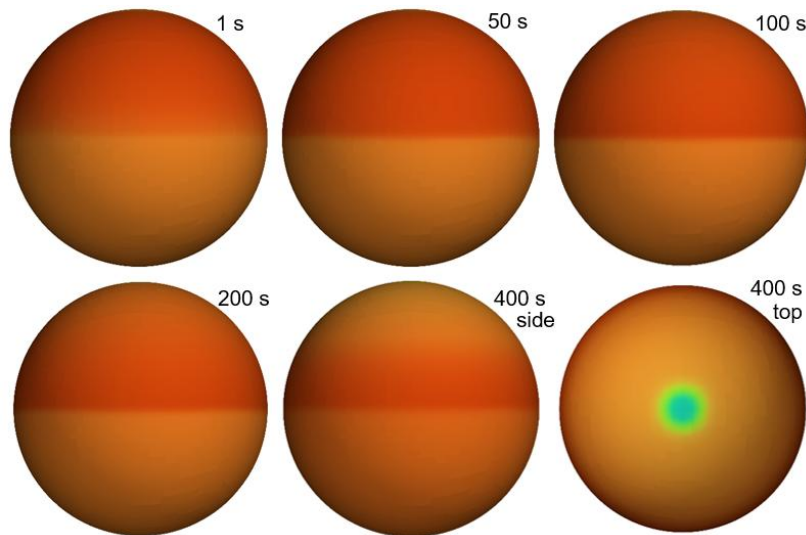
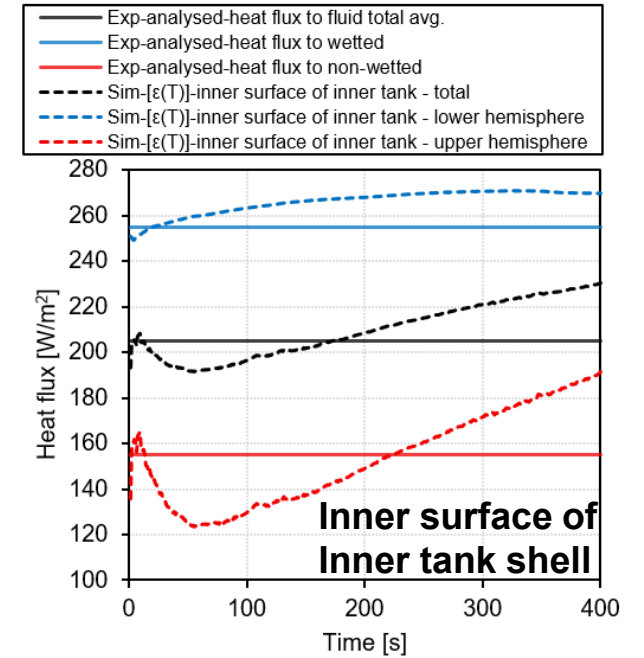
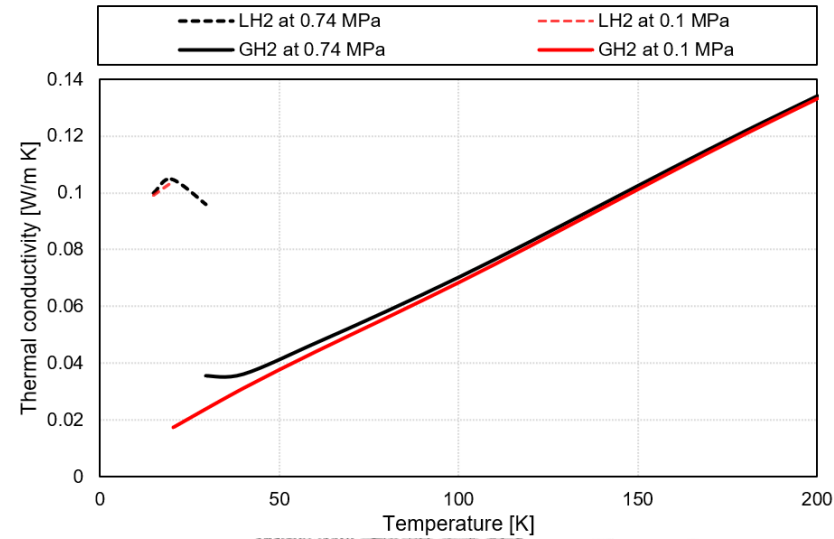
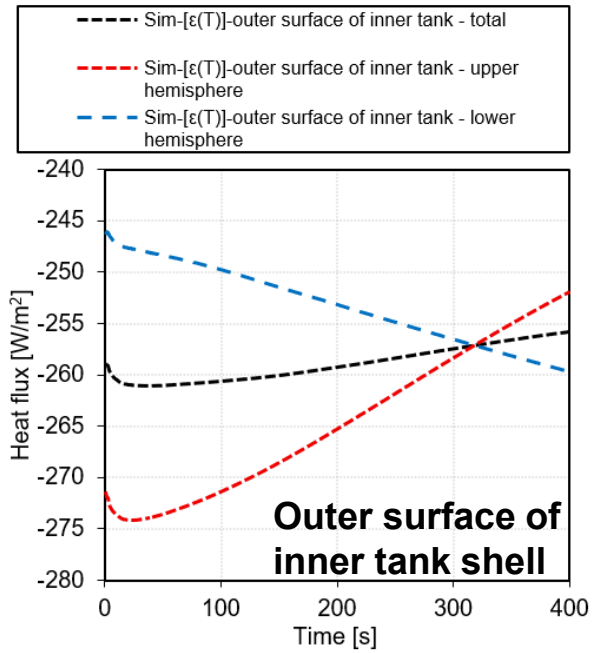
TC in lower hemisphere



TC close to intersection of interface and wall



CFD 4/7: Heat flux dynamics

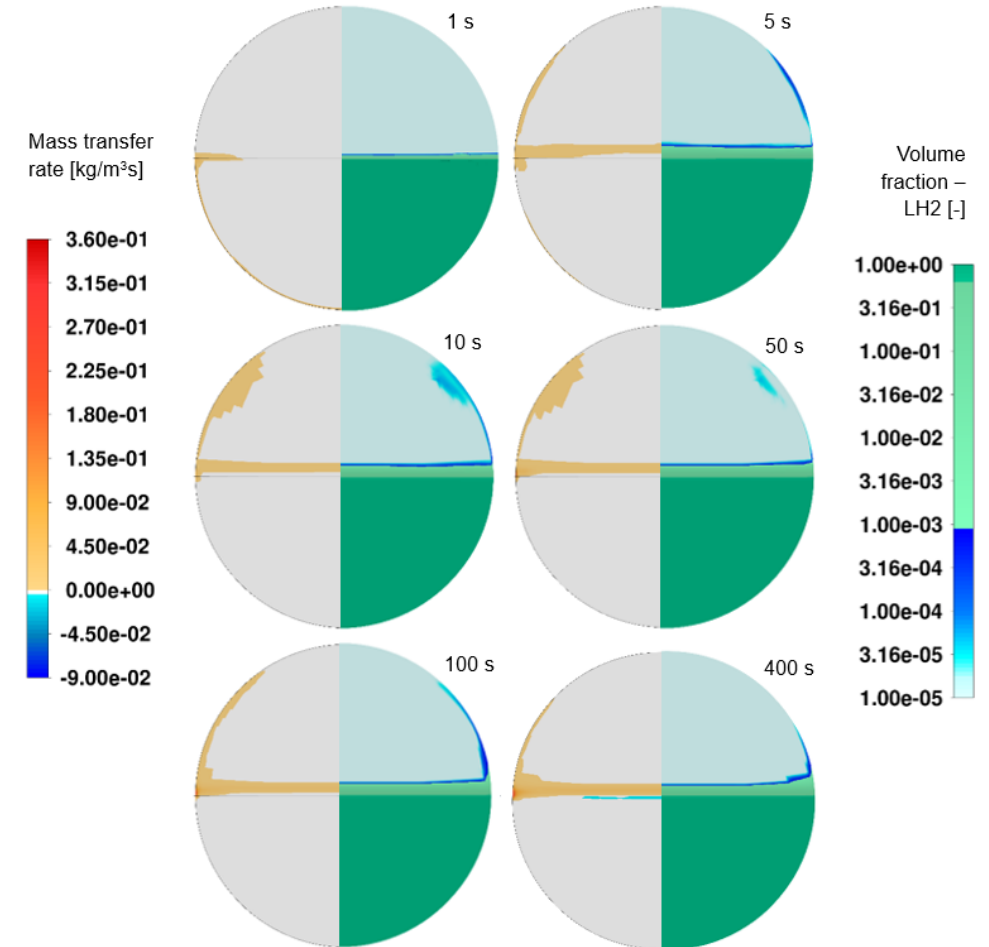
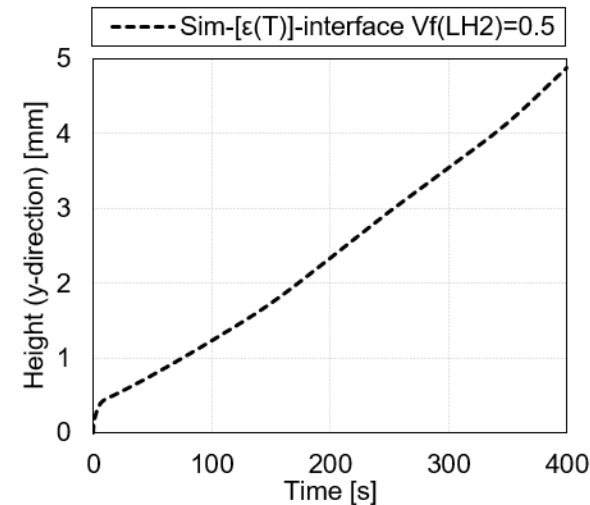
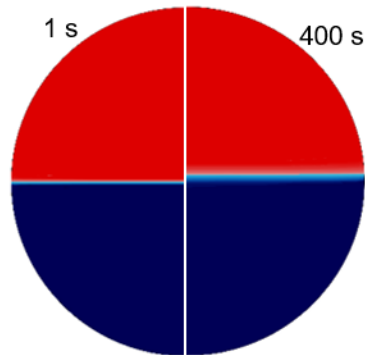
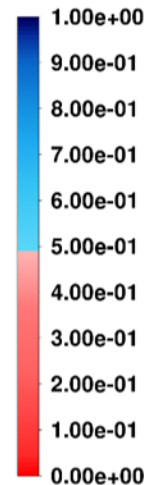


CFD 5/7: Liquid level and phase transfer

Case 2

- Radiator temperature = 274 K
- Emissivity = $\epsilon(T)$

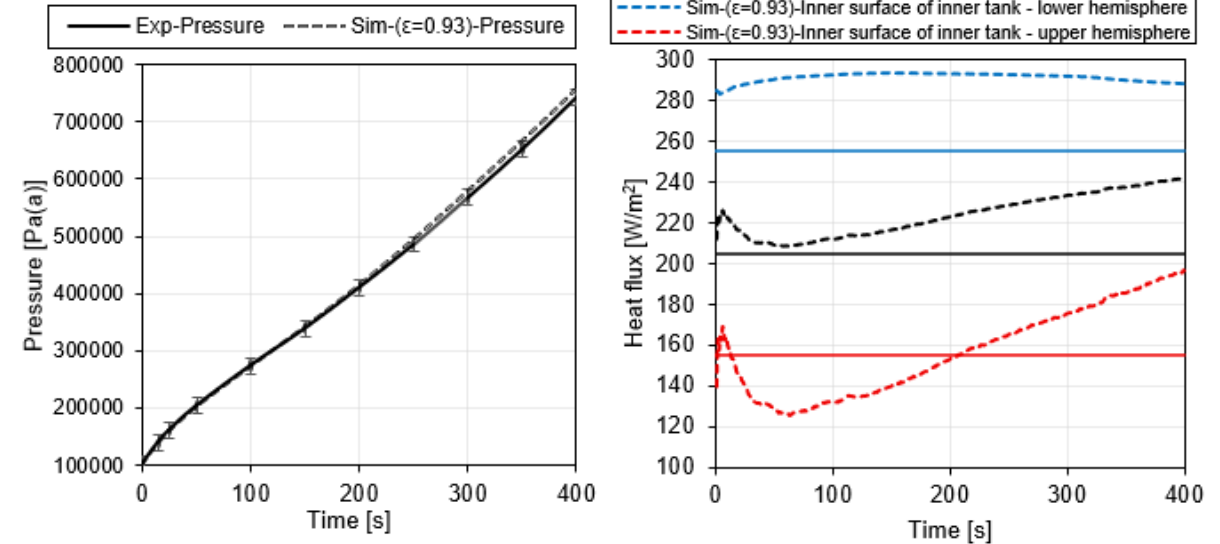
Volume fraction
– LH2 [-]



CFD 6/7: Var vs const. properties

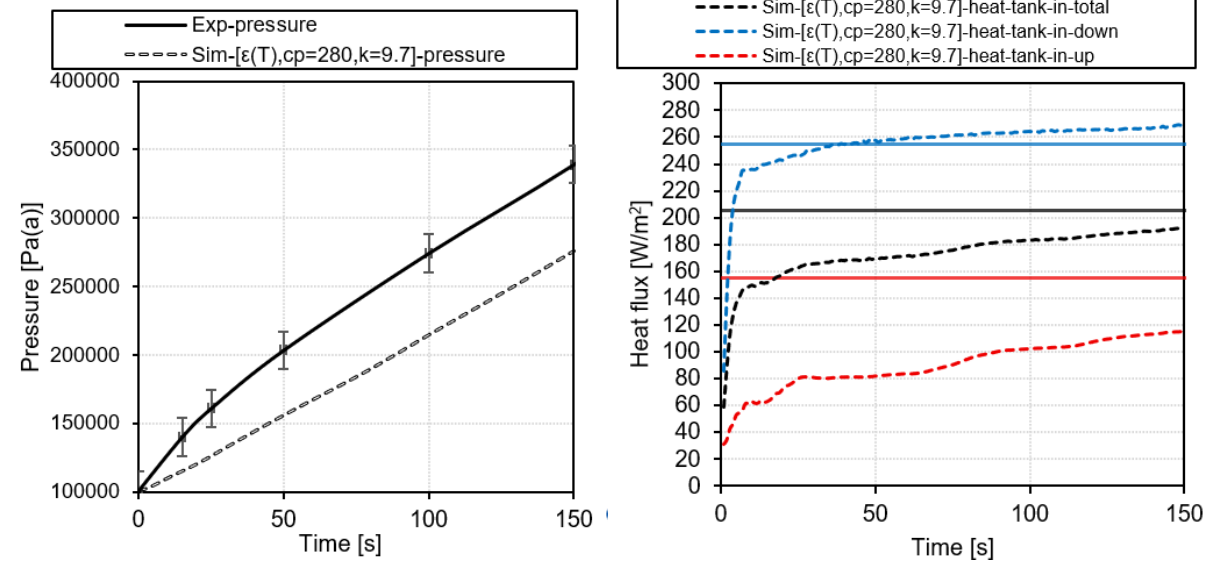
Case 3

- Radiator temperature = 274 K
- Constant Emissivity = 0.93
- Thermal conductivity = $k(T)$ W/m K
- Specific heat = $C_p(T)$ J/kg K



Case 4

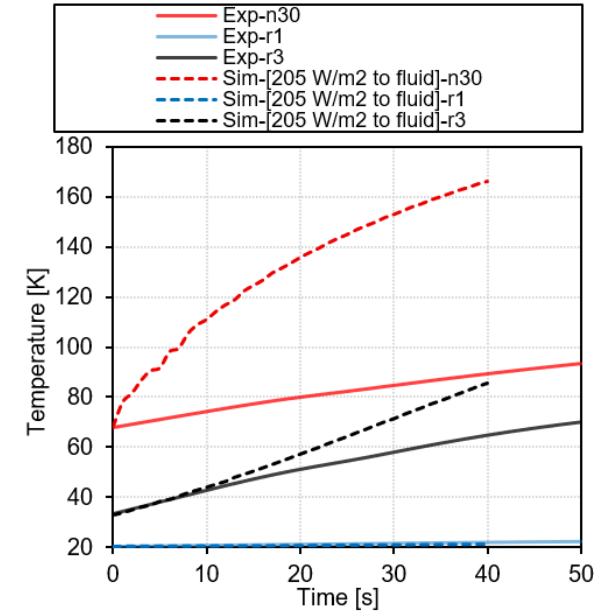
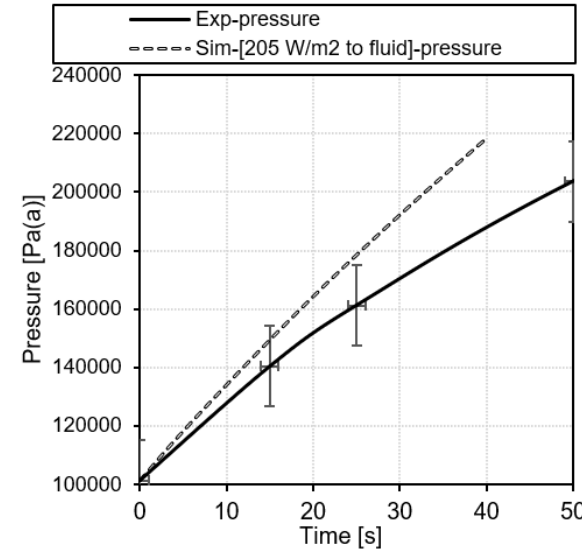
- Radiator temperature = 274 K
- Emissivity = $\epsilon(T)$
- Thermal conductivity = 9.7 W/m K
- Specific heat = 280 J/kg K



CFD 7/7: Constant and uniform heat flux

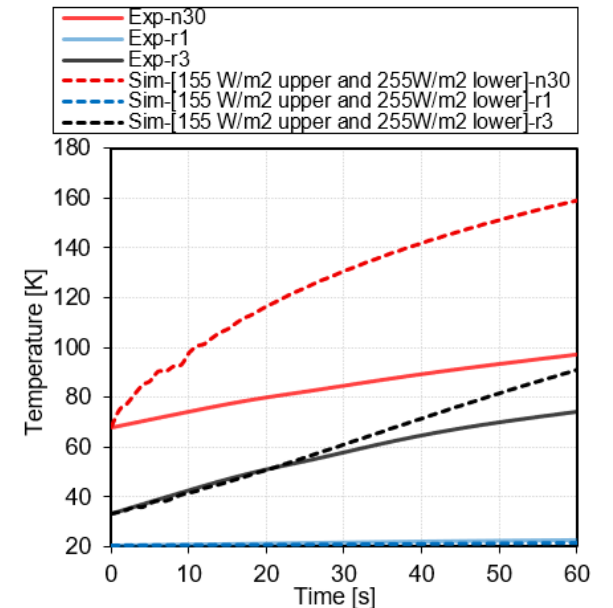
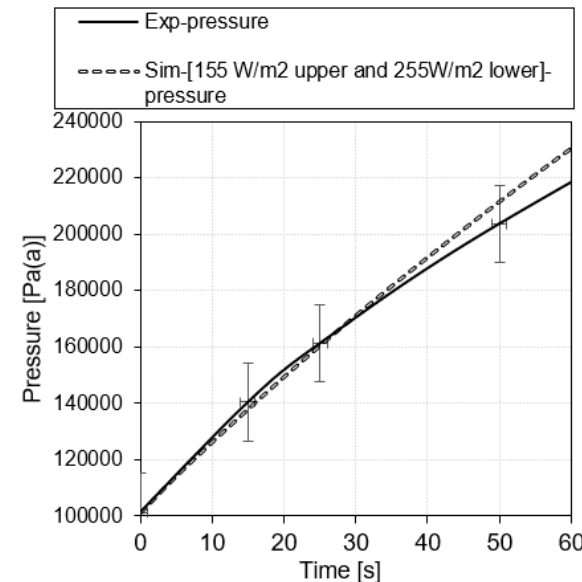
Case 5

- Constant and uniform heat flux 205 W/m^2 to fluid



Case 6

- Constant and uniform heat flux 155 W/m^2 and 255 W/m^2 to fluid at upper and lower hemisphere respectively



Conclusions

- Despite constant temperature radiation heaters, distribution of the heat flux going to the fluid exhibits substantial spatial and temporal variation.
- Pressure, was mainly affected by the gas phase behaviour in the initial stage and influence of mass transfer become relatively significant at a later stage.
- Using a constant and uniform heat flux or exclusion of temperature-dependent tank shell material and fluid properties could lead to deviations from real-world values.
- 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.
- LH2-GH2 interface rises over time as LH2 heating decreases its density and increases its volume, offsetting the LH2 loss due to vaporisation.

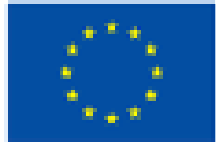
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Thank you for your attention

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