



sLH2 refuelling through the entire equipment of HRS: concept, numerical modelling and simulation results

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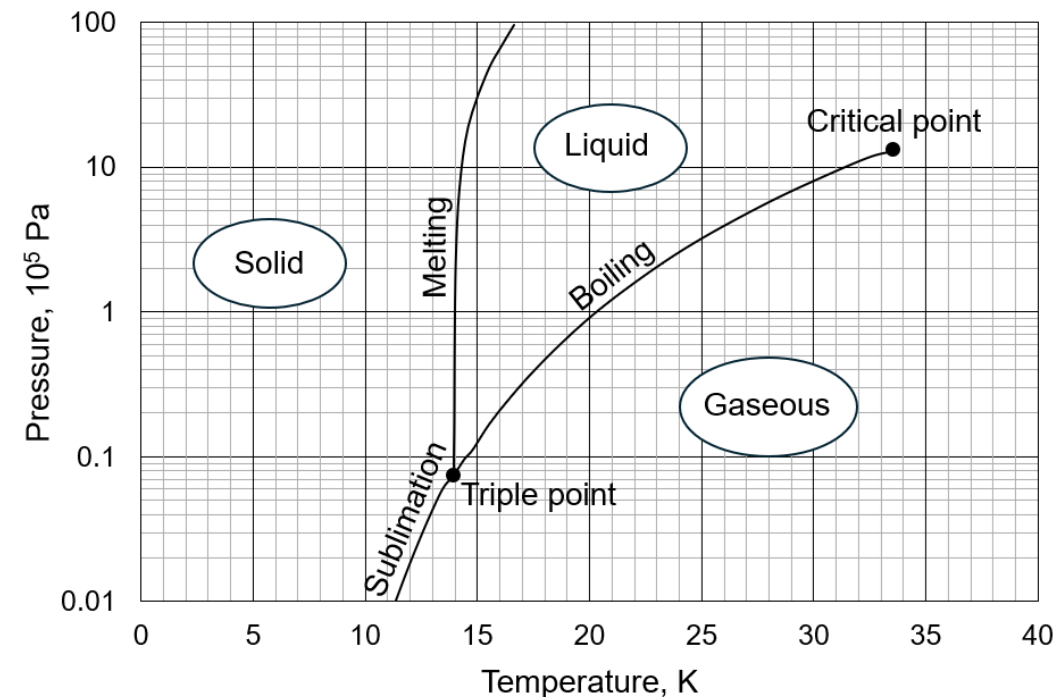


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The concept of efficient sLH2 refuelling

Complex heat and mass transfer

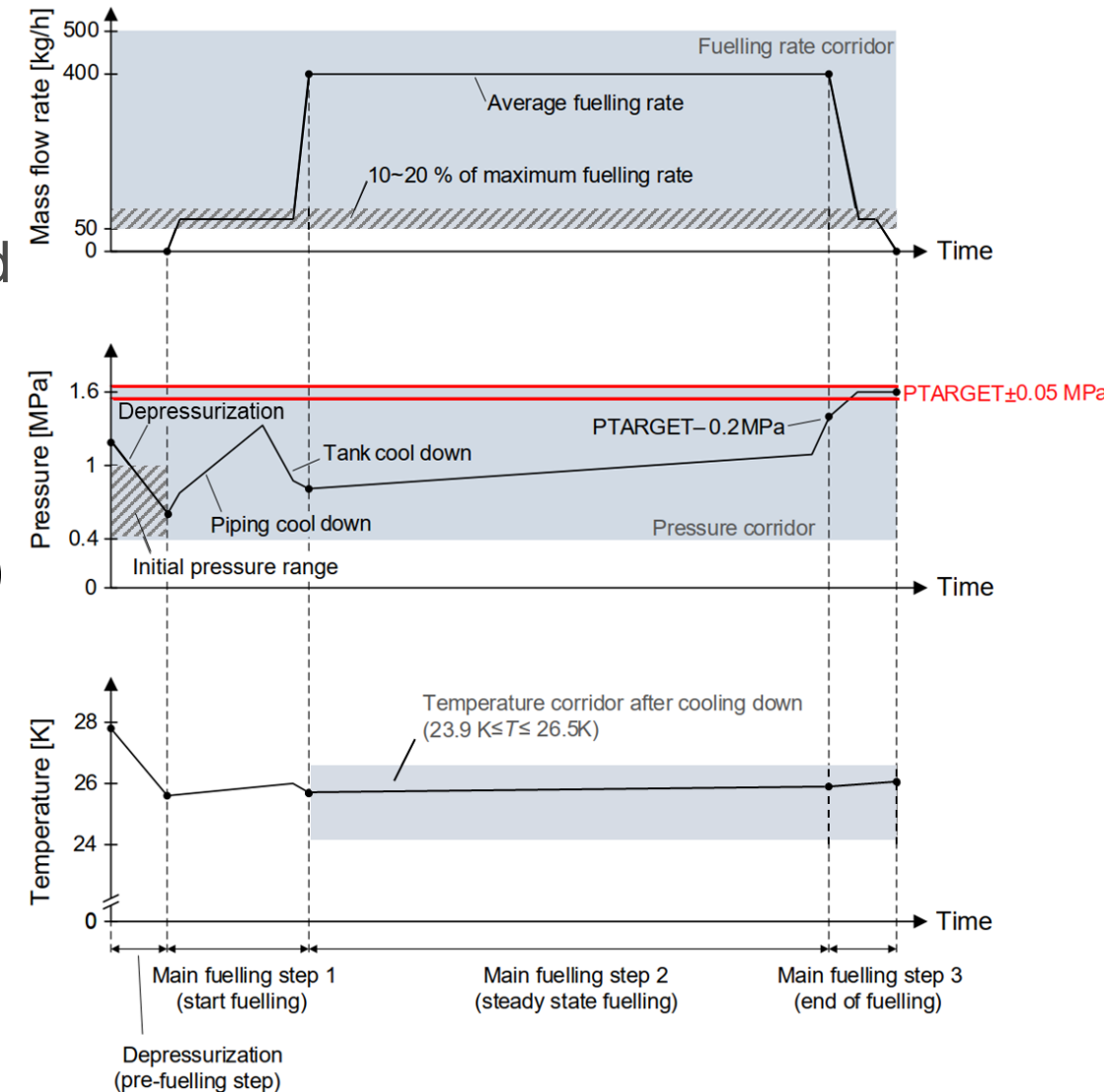
- The sub-cooled liquid hydrogen (sLH2) flows through pipes and valves toward onboard tanks “like water”. Heat transfer and flow losses along the sLH2 pathway are unavoidable. The **fluid undergoes multiple transformations** along the pathway, including two-phase transitions, superheating, non-uniform temperature distributions in a two-phase system, etc.
- The efficient sLH2 fuelling technology implies filling of the tank with a liquid at a non-equilibrium state (above the saturation “Boiling” curve). **sLH2 will flow as “non-vaporising” liquid** unless heat transfer from warmer equipment “returns” **sLH2** (*subcooled conditions*) to **LH2** (*saturated conditions*), if this is the case.



The concept of efficient sLH2 refuelling

Conceptual fuelling protocol: mass flow rate, P and T profiles

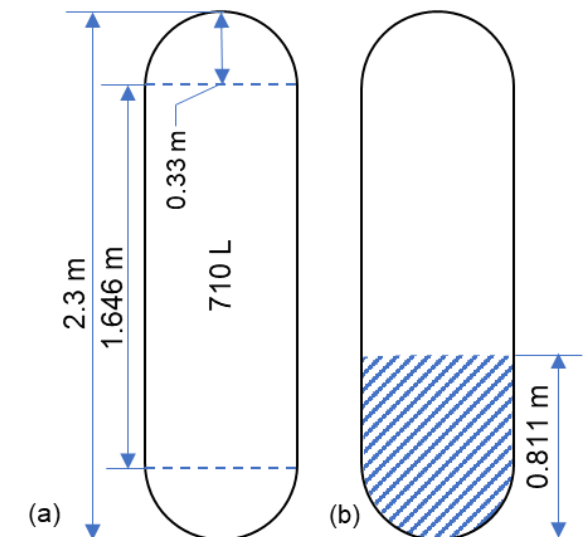
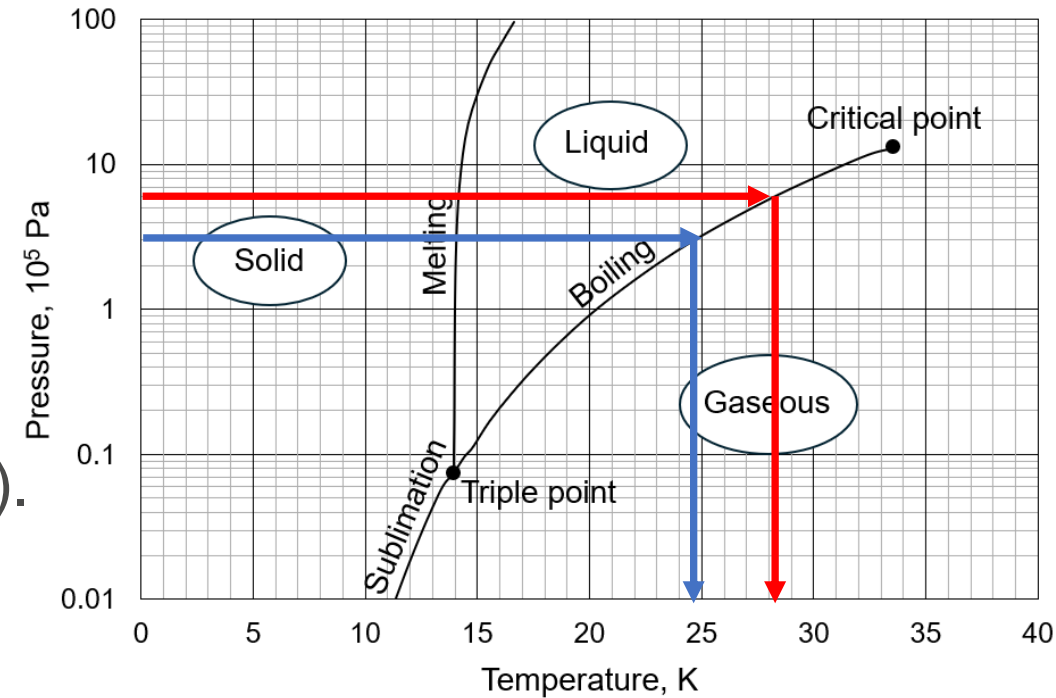
- CFP presented by Pizzutilo et al. in 2022-2024.
- During **depressurisation** (out of the scope of this numerical study), the temperature drops **in the ullage space** (due to vapour expansion) and **in the bulk liquid** (due to liquid evaporation during the pressure reduction).
- Three steps of the main refuelling:
 - **Reduced mass flow rate** (10-20% of maximum) to cool down piping and storage systems.
 - Refuelling with a targeted average fuelling rate of **400 kg/h (111 g/s)**, and finally
 - End of fuelling with **reduction** of mass flow rate to zero **when pressure reaches 1.6 ± 0.05 MPa(a)**.



Modelling problem formulation

Assumptions 1/3

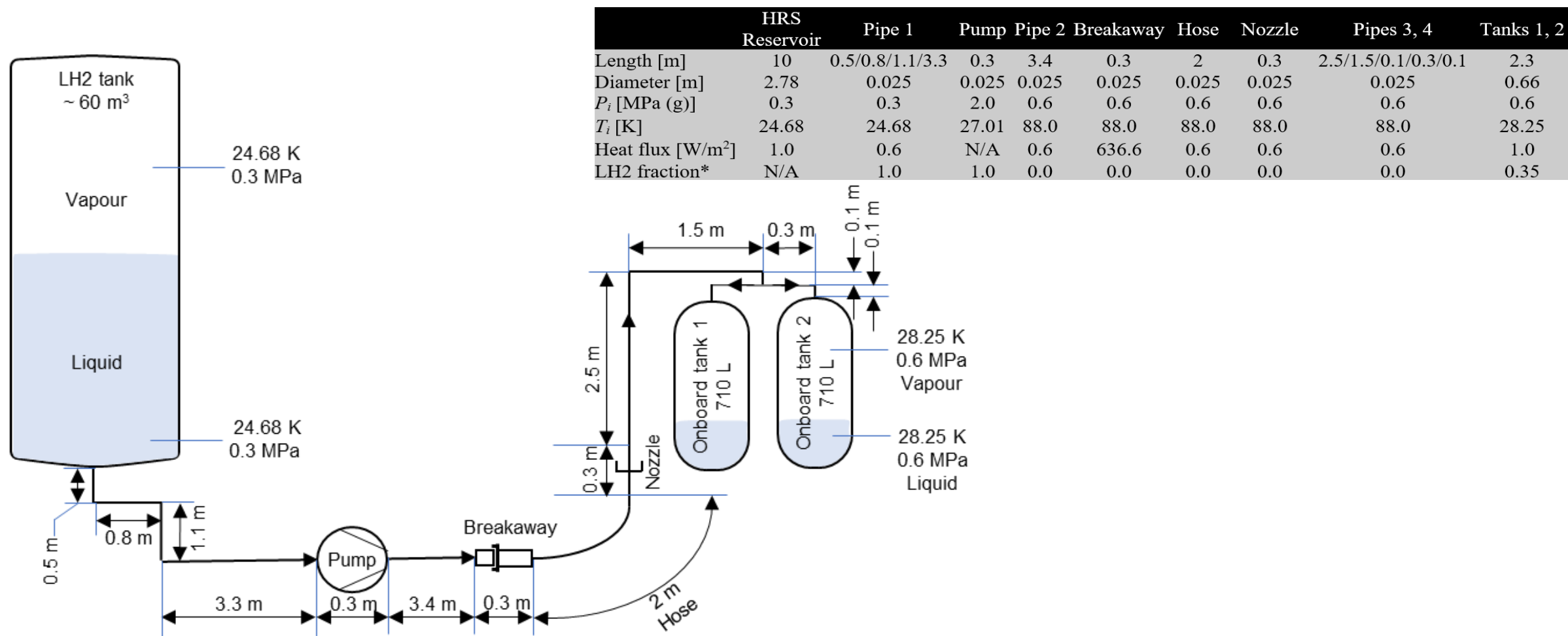
- The HRS storage reservoir is **61.36 m³** (4 tonnes of LH2 at **0.3 MPa** and a saturated temperature of **24.68 K**). The temperature in the reservoir remains constant due to its large volume (blue lines on the phase diagram).
- There are **two** vertical onboard tanks, each **0.71 m³** (44 kg of LH2 at 100% SoC, 63 kg/m³ at final 1.6 MPa and 29 K). The internal length is 2.3 m, and the diameter is 0.66 m. The tanks are **filled from the top**. Internal walls: stainless steel, 3 mm. Tanks are initially at **0.6 MPa** and saturated **28.25 K** (red lines). The initial LH2 filling level is **35%** by volume. A heat flux of **1 W/m²** is applied to all tank walls.



Modelling problem formulation

Assumptions 2/3

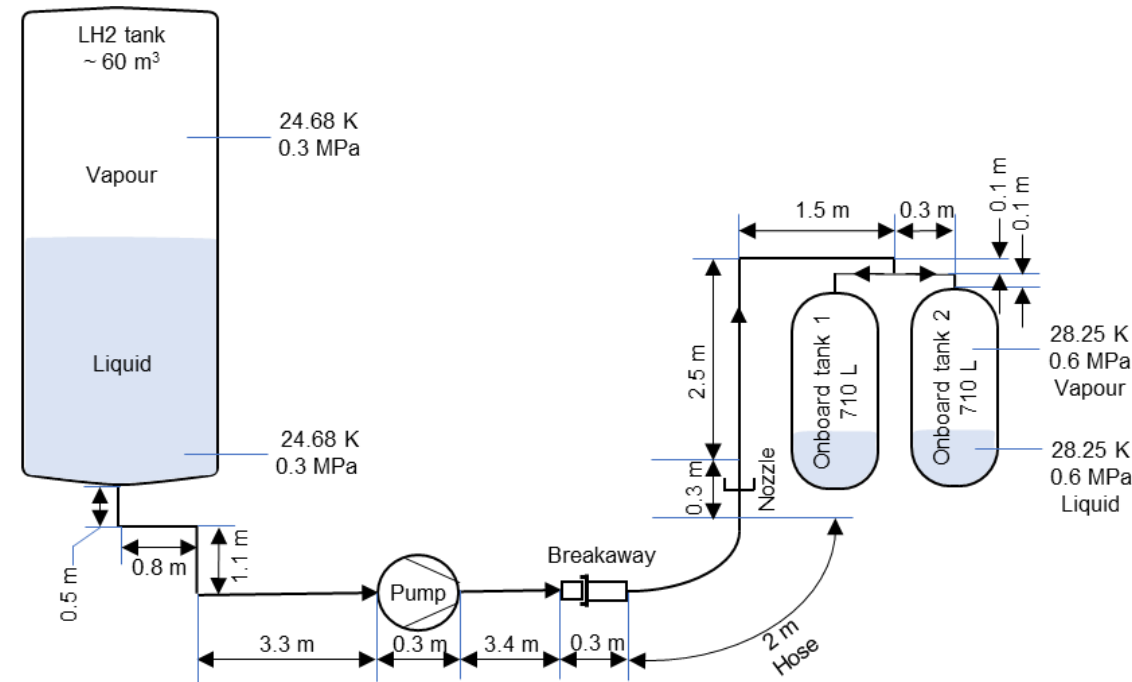
The heat transfer rate at the breakaway is 15 W (Maus and Schäfer, 2021). Piping and instrumentation diagram (PID), equipment parameters and initial conditions:



Modelling problem formulation

Assumptions 3/3

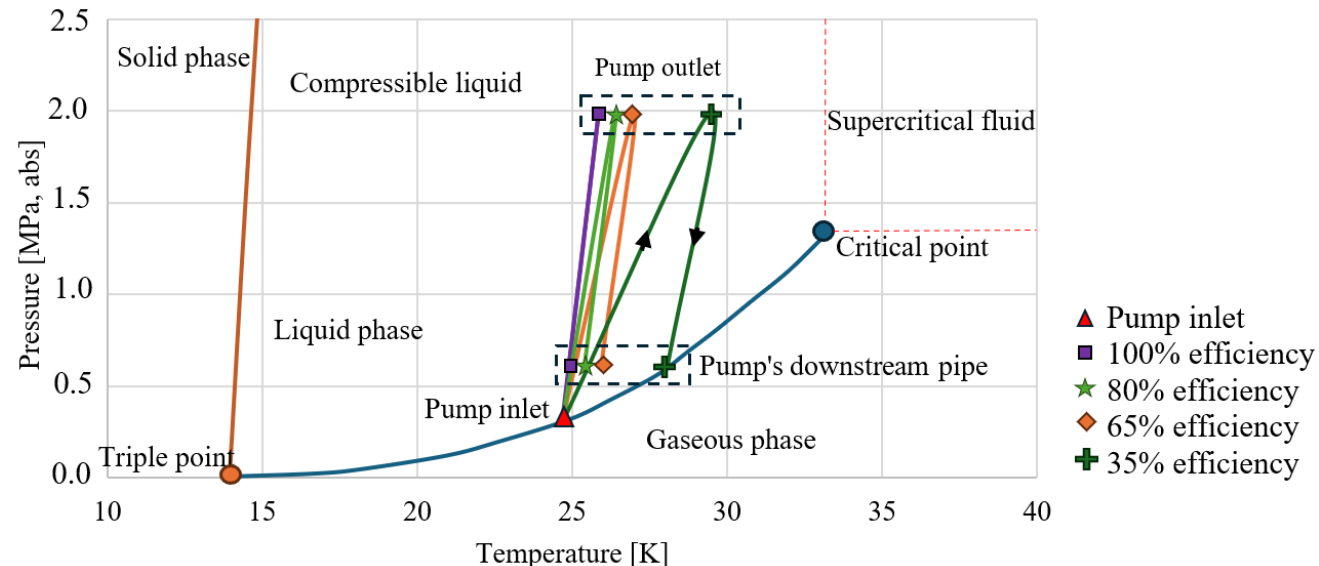
- The LH2 tank at HRS and all components down to the pump are assumed to be filled with LH2 at 0.3 MPa and a saturation temperature of 24.68 K.
- The components between the pump and the onboard tanks, i.e. nozzle, breakaway, hose, and connection pipes, are filled with gaseous hydrogen at 0.6 MPa. The pipes were somewhat “pre-heated” by external heat flux before refuelling began.
- The piping initial temperature of 88 K is assumed (higher than 28.25 K, i.e. the saturated temperature for 0.6 MPa, and even higher than the critical point, 33.2 K above which LH2 cannot exist (unless superheated at pressures below the critical point)).



Thermodynamic model

Pump exit conditions

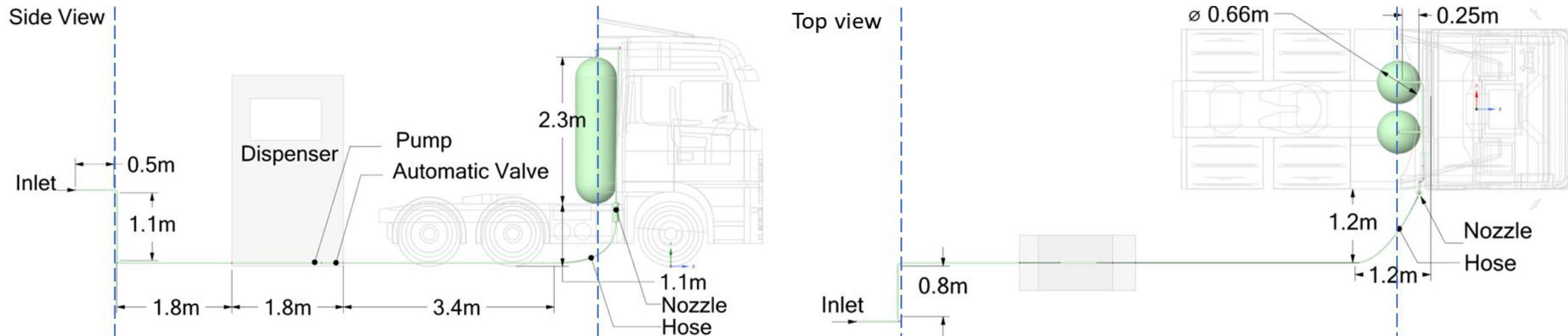
- The isentropic efficiency of LH2 pumps is **55-80%** (Franco and Giovannini, 2024). Using the NIST real gas model and **assuming the pump's efficiency of 65%**, the LH2 **temperature at the pump exit** may be **estimated**. For an upstream pump pressure of 0.3 MPa and a temperature of 24.68 K, and the maximum pump pressure of 2.0 MPa, the temperature at the ***pump exit*** at 0.6 MPa(g) is calculated as **26.98 K**.
- The **expansion** of pump-compressed LH2 in the pipes at 0.6 MPa(g) is assumed **adiabatic** (rapid process and the pipe insulation). The calculations give the LH2 temperature after the expansion of **25.98 K**, i.e. **in the recommended by the conceptual protocol hydrogen temperature corridor of 23.9-26.5 K**.



CFD model

Geometry and calculation domain

The calculation domain for CFD simulations was **from the pump exit through the equipment to the two onboard storage tanks.**



CFD model

Numerical details

- ANSYS Fluent 2023R1 is used as a CFD engine.
- The volume-of-fluid (VoF) model is applied to simulate the two-phase hydrogen flow.
- Governing equations: continuity for volume fraction, shared momentum, shared energy.
- The SST k-omega turbulence model.
- The pressure-based implicit solver. The SIMPLEC algorithm for pressure-velocity coupling. Convective terms and volume fractions were discretised using a second-order upwind numerical scheme. The PRESTO scheme is utilised for pressure discretisation.
- The time step was initially set as 0.001 s, then gradually increased to 0.01 s to maintain the acceptable convergence of the simulations. The mass imbalance over the fuelling period is less than 1% (good convergence and hydrogen conservation in the domain).
- The simulation of **525 s** of LH2 refuelling time takes about **14 days** on a 72-cores CPU.

CFD model

Numerical details: Lee's phase change model

- Lee's model (1980) is used to simulate evaporation and condensation.
- The explicit formulation for volume fraction in the multi-phase model is used, with a “**sharp interface**” option between the liquid and vapour phases.
- For condensation, when the saturation temperature is higher than the gas temperature ($T_{sat} > T_g$), the mass transfer rate from gas to liquid [kg/m³/s] is:

$$\dot{m}_c = r_c \alpha_g \rho_g \frac{T_{sat} - T_g}{T_{sat}},$$

and for evaporation ($T_l > T_{sat}$) the mass transfer rate from liquid to gas is:

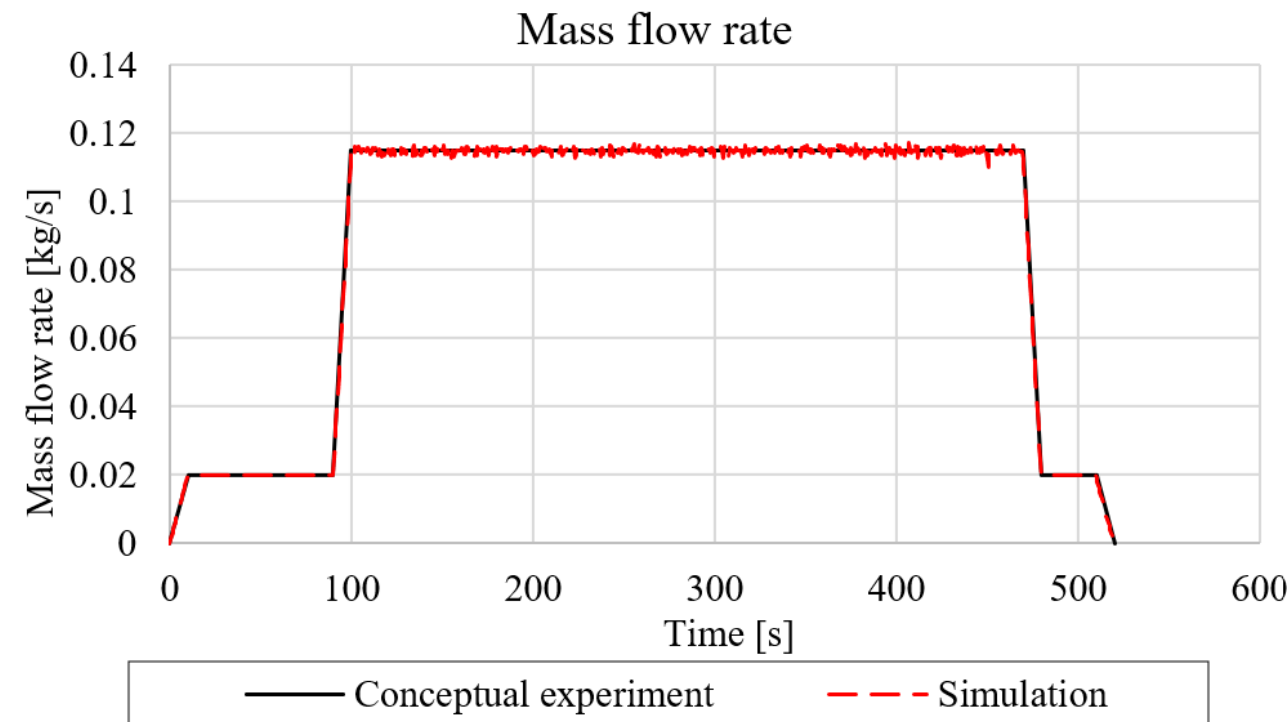
$$\dot{m}_e = r_e \alpha_l \rho_l \frac{T_l - T_{sat}}{T_{sat}},$$

where r_c and r_e are time relaxation parameters (1/s). In this study $r_c = r_e = 0.05$ is selected, following our previous work on the pressure recovery phenomenon during release from ullage space in the Kawasaki large-scale LH2 storage tank (Kangwanpongpan et al., 2023).

Input to CFD simulations

Mass flow rate (MFR)

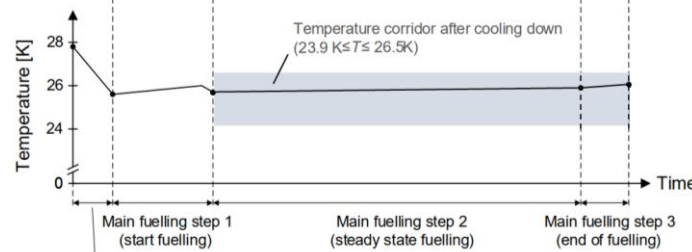
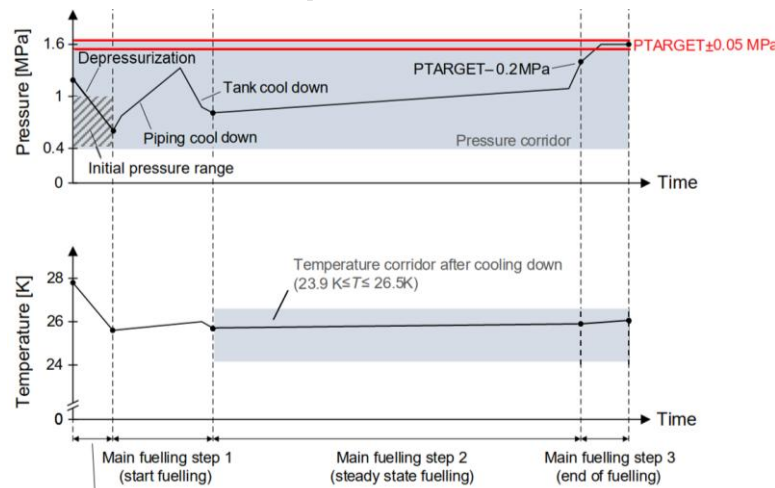
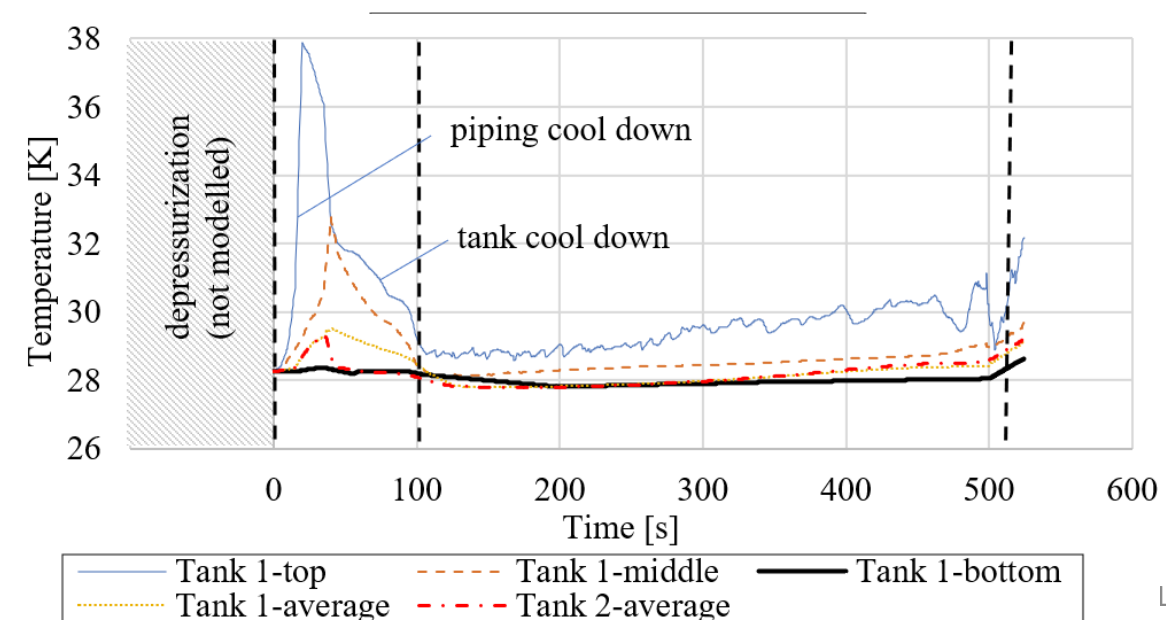
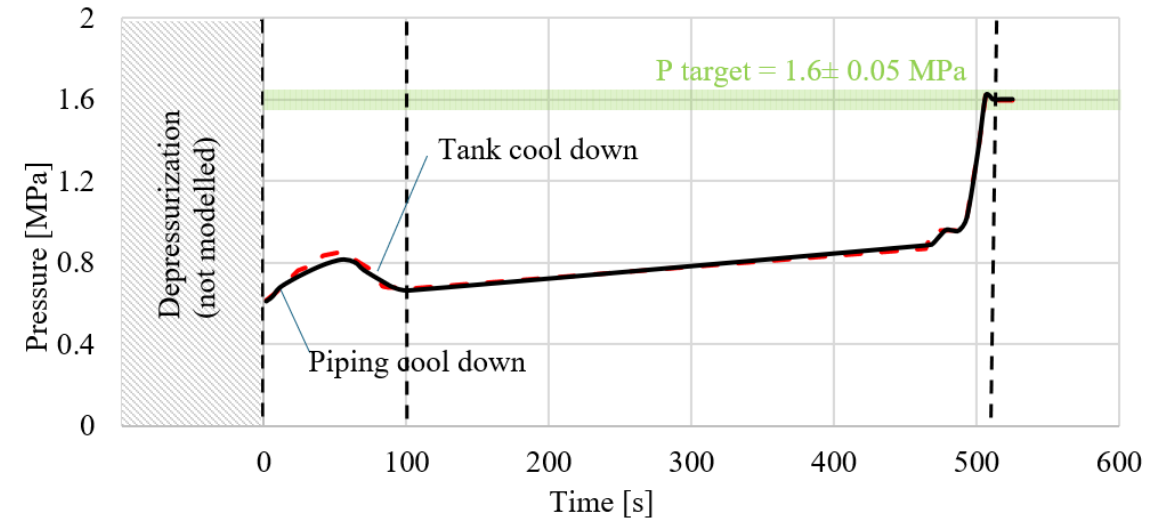
- The automatic LH2 valve is represented as a porous media in the model.
- The MFR in the conceptual refuelling protocol is digitised and used as an input to the UDF to regulate the porosity in the PCV to imitate the same MFR in the simulations.
- The simulated MFR deviates from conceptual MFR by less than 0.1%.
- This UDF can reproduce arbitrary MFR profile as needed by the protocol design approach.



Results of CFD simulations

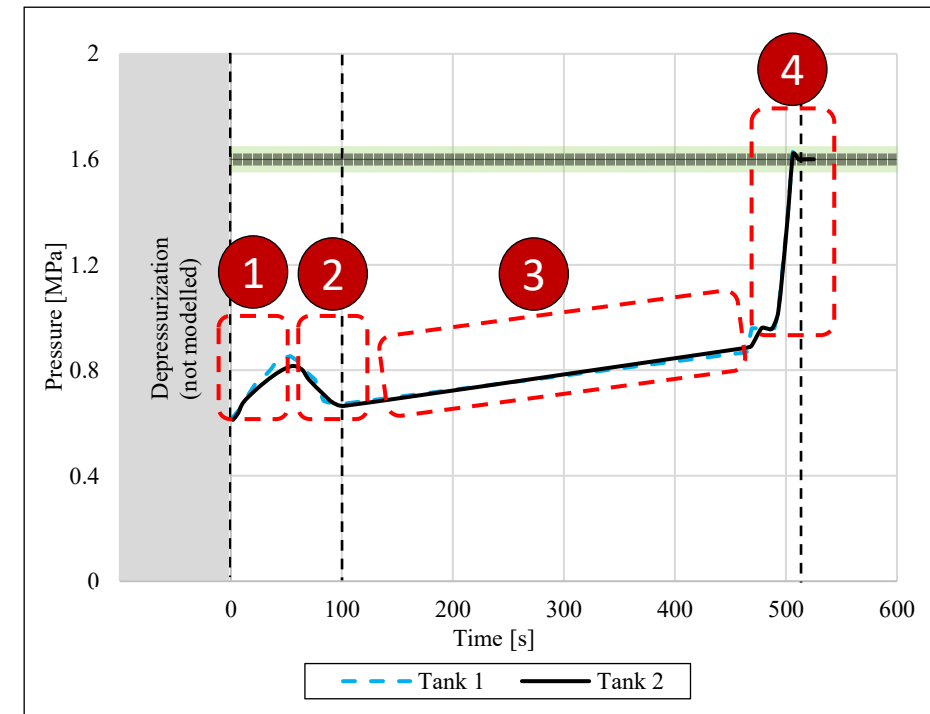
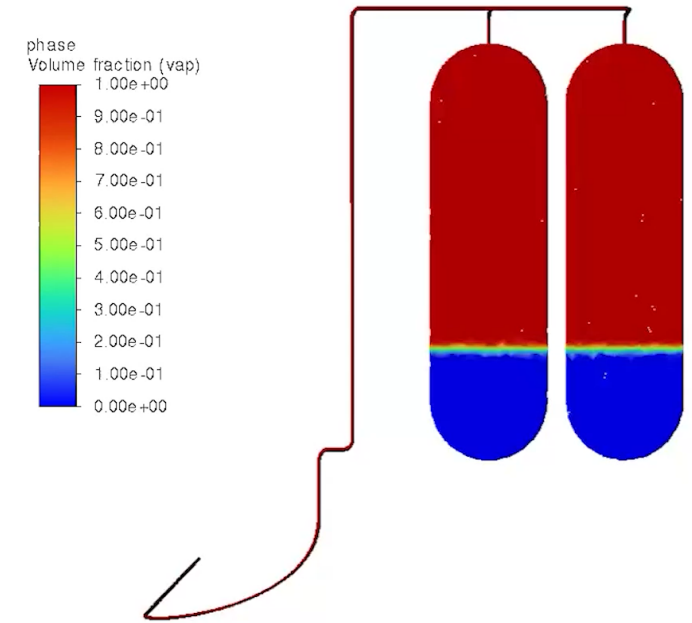
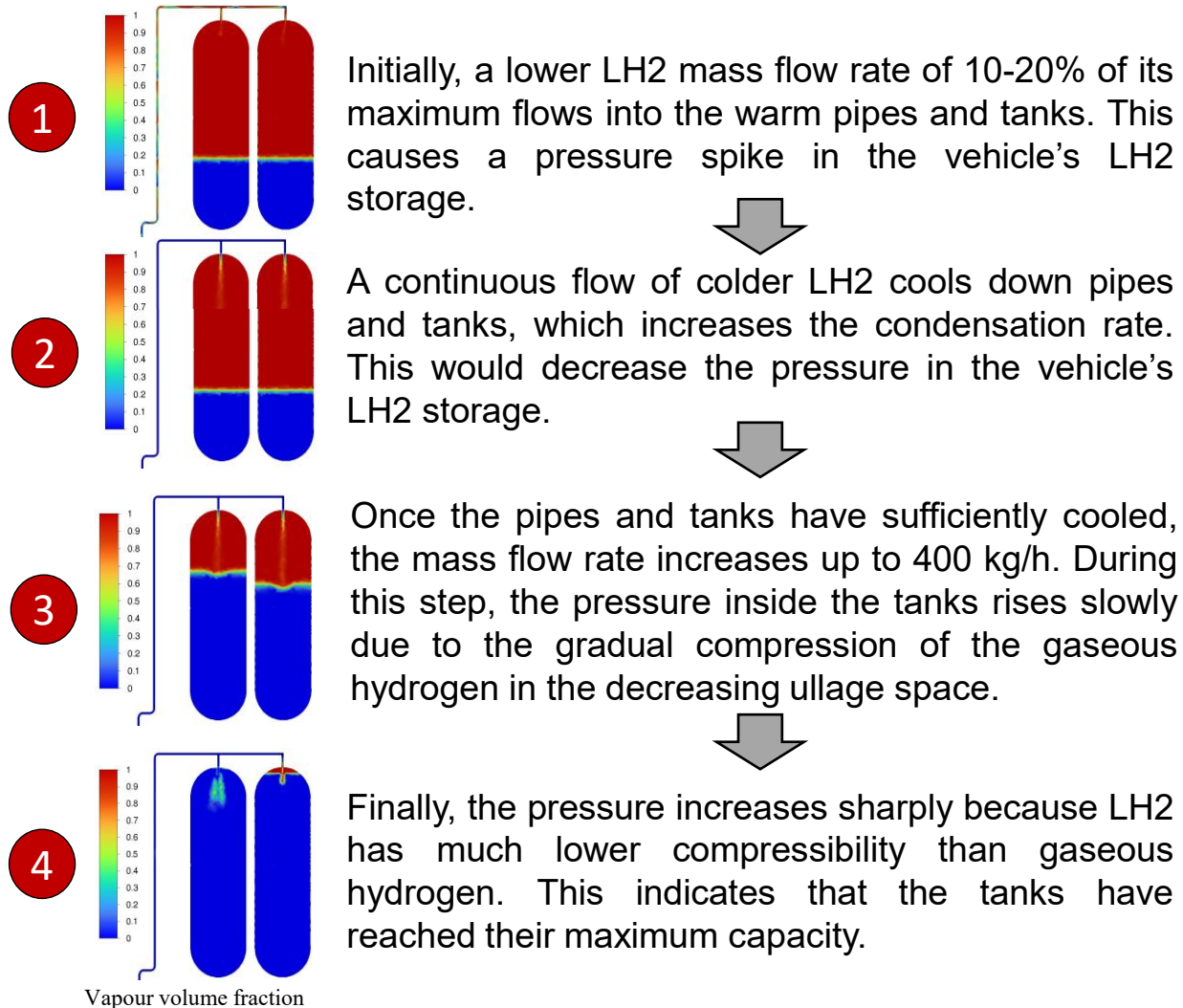
Onboard tank pressure and temperature dynamics

- The initial pressure in both onboard storage tanks is 0.6 MPa. The transient pressure difference between the two tanks is minimal.
- Temperature in the ullage space is, as expected, somewhat higher.
- LH2 temperature is decreasing over some time due to evaporation.



Results of CFD simulations

Pressure and vapour volume fraction

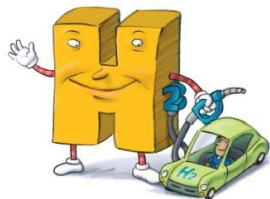


Concluding remarks

- The ***originality*** of this work is in the **development, for the first time**, of a novel CFD approach for sLH2 refuelling through the entire equipment of HRS, which is verified against the conceptual liquid hydrogen fuelling protocol.
- The ***significance*** lies in the development of a CFD model that reproduces the experimentally observed LH2 refuelling response (used to build the conceptual protocol), which can be utilised as a contemporary engineering tool for designing efficient refuelling protocols and inherently safer LH2 HRS equipment.
- The model accurately simulates heat and mass transfer and thus closely reproduces trends in pressure and temperature transients of the conceptual protocol. The study provided valuable insights into the underlying physical phenomena during LH2 refuelling, enhancing our understanding and even visualisation of the process.

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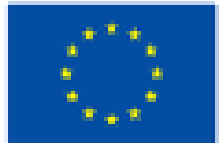
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Thank you for your attention

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