



Understanding the heat and mass transfer at HRS during an attempt to refuel the warm LH2 tank: numerical analysis of experimental data

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Attempting to fuel a warm tank

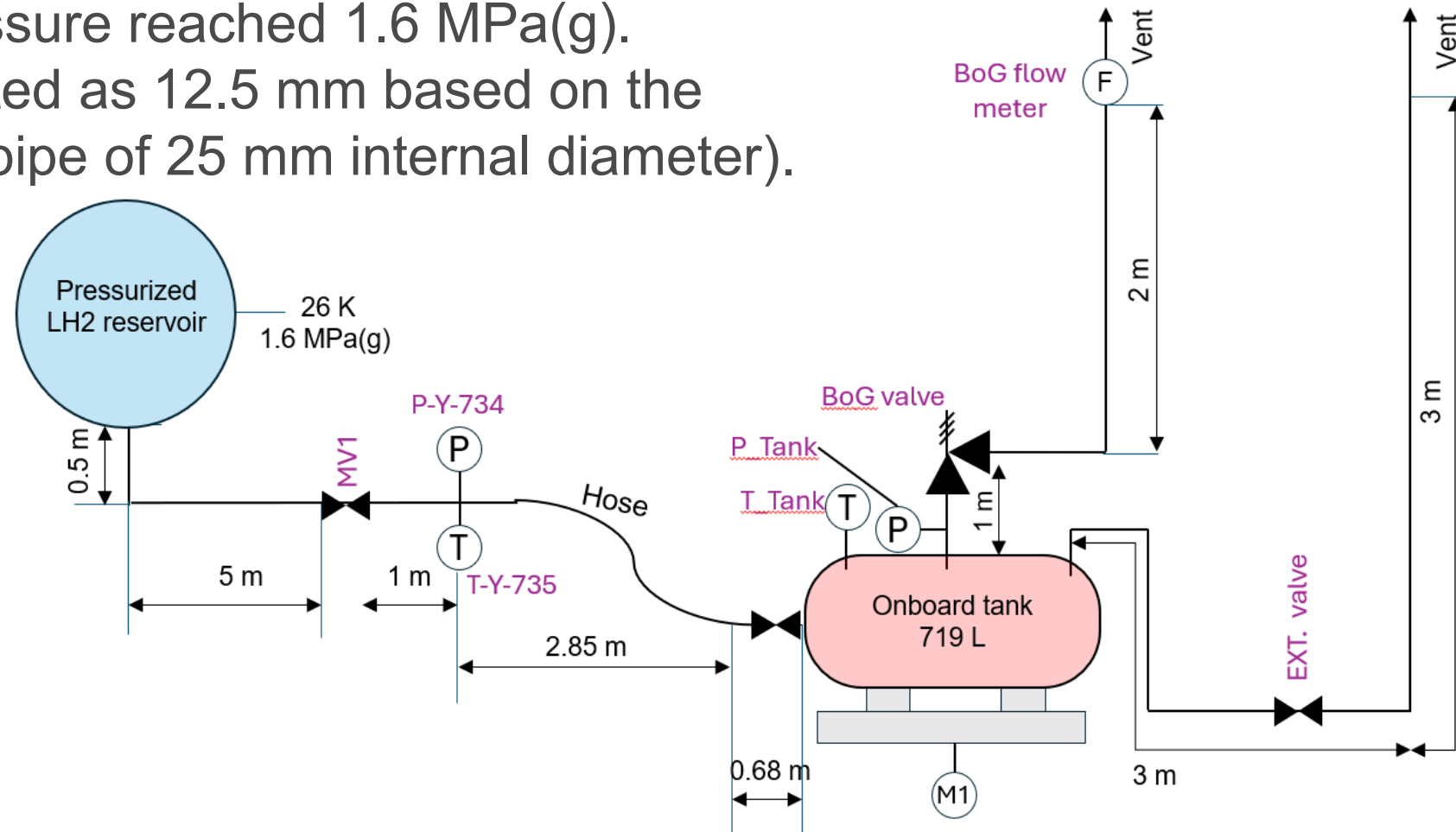
Brief scope and resume of main results

- Simulations by the Ulster multiphase model are **compared** against the experimental data by Daimler Truck AG and KIWA ET GmbH for the following parameters:
 - Pressure and temperature transients in the **piping** and onboard **tank** (9 cm below the top),
 - The boil-off gas (BoG) **flowrate**, and
 - About 1 kg of **hydrogen accumulated** in the tank in the first 18 s (a rough estimate by scale); a more accurate estimate is 1,183 kg by the flowmeter.
- Investigation of valve operation shows that a fully open “**numerical valve**” causes unacceptable pressurisation. This is in-line with the reduced mass flow rate (10-20% of the maximum) at the start in the conceptual protocol to cool piping and storage tanks.
- The importance of pipe/hose **inclination** (following the experiment) to reproduce experimental temperature transients is demonstrated.
- Flash boiling in a warm refuelling system requires the increase of the **time relaxation parameter** from $r = 0.05 \text{ s}^{-1}$ (typical for “normal” sLH2 refuelling) to $r = 10.00 \text{ s}^{-1}$ in simulations of warm tank refuelling (a **200-fold increase** due to the “unresolved” liquid-vapour surface in simulations).

Attempting to fuel a warm tank

Schematic of the experimental setup

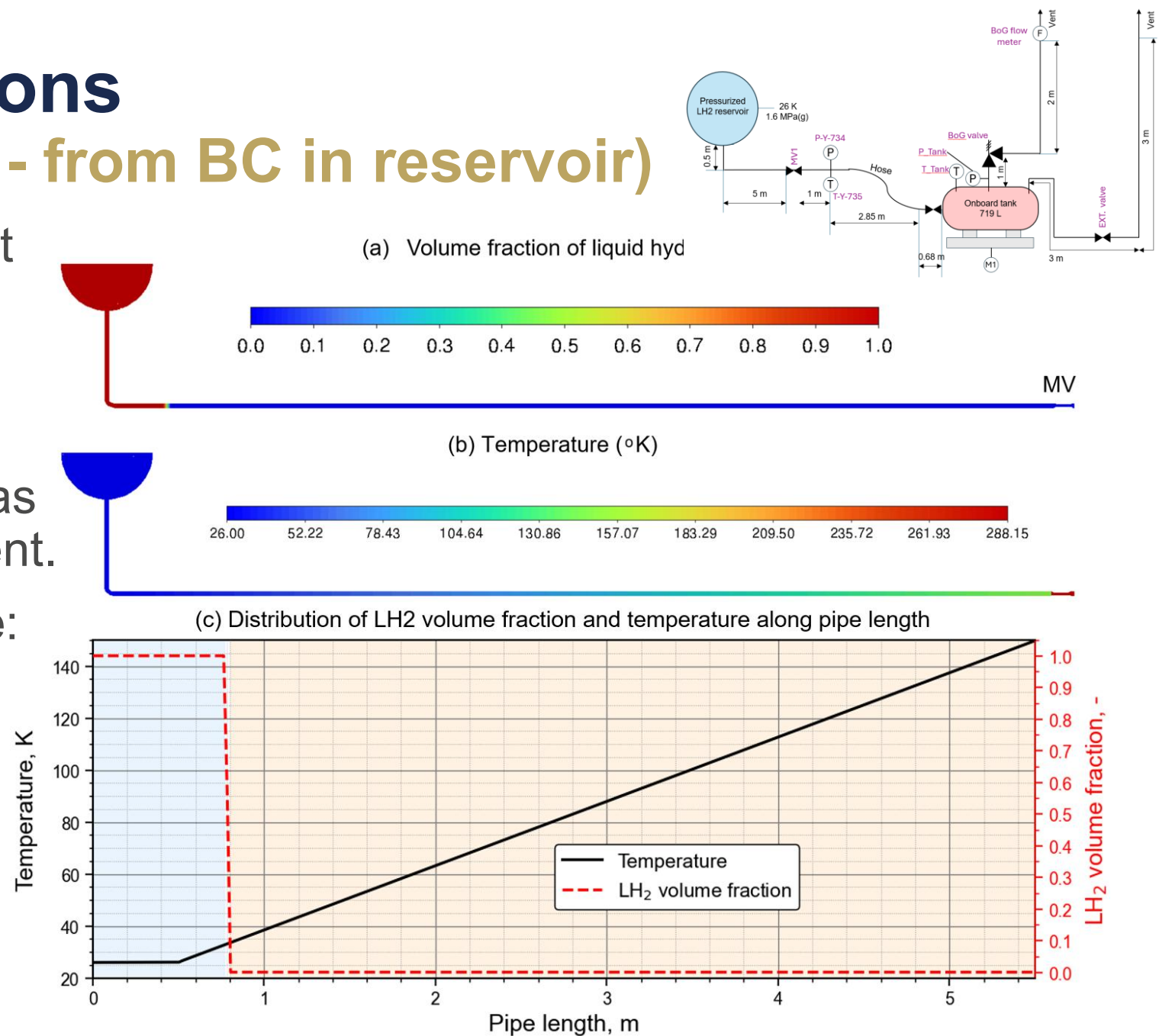
sLH₂ (!) is in 35 kg reservoir at 1.6 MPa(g) and 26 K. The reservoir remained pressurised using GH₂. The manual valve MV1 controls the flow and was closed during 2 s when the pressure reached 1.6 MPa(g). MV1 diameter is calculated as 12.5 mm based on the manufacturer's Kv (in a pipe of 25 mm internal diameter).



Warm tank simulations

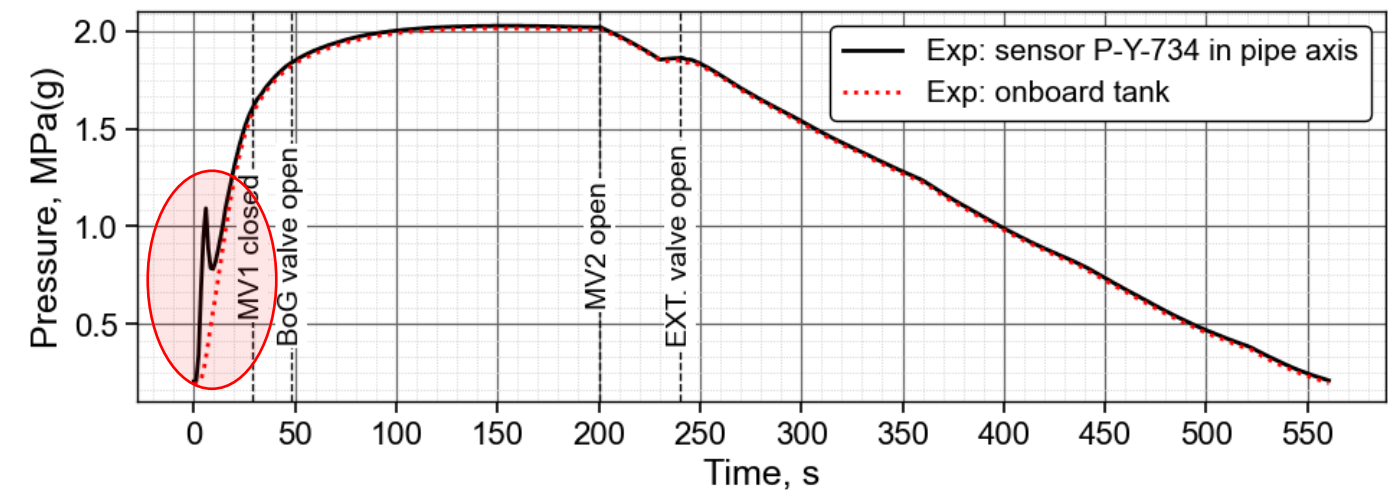
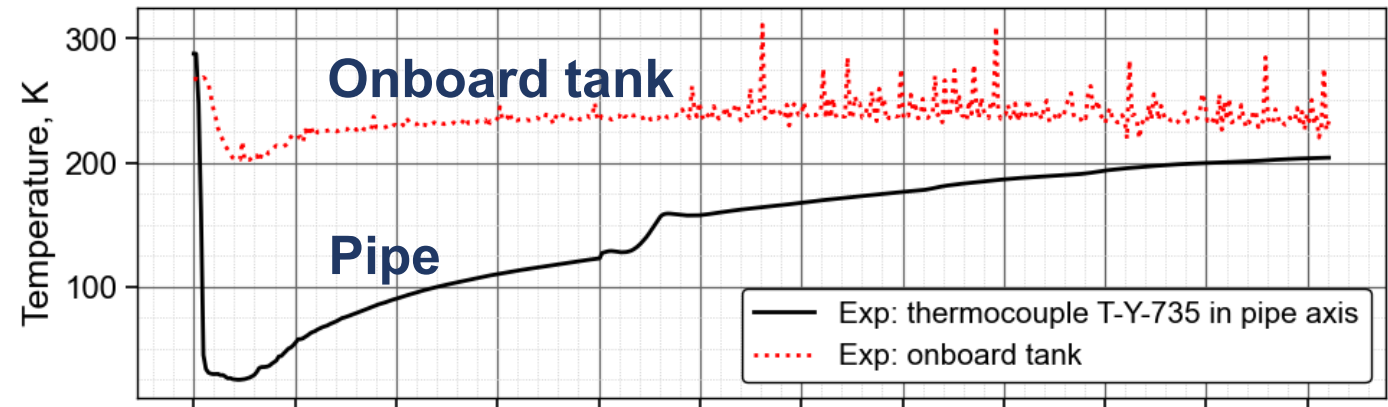
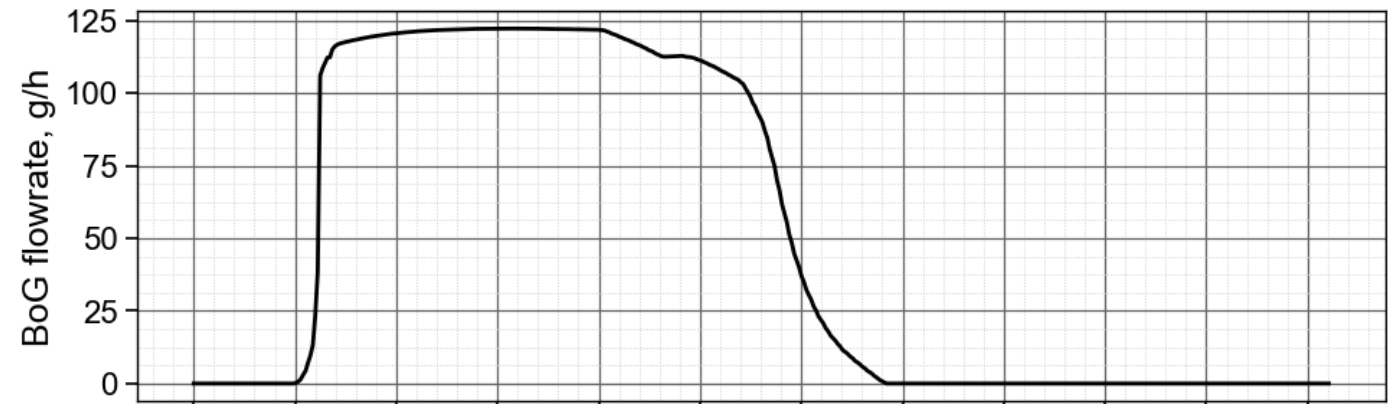
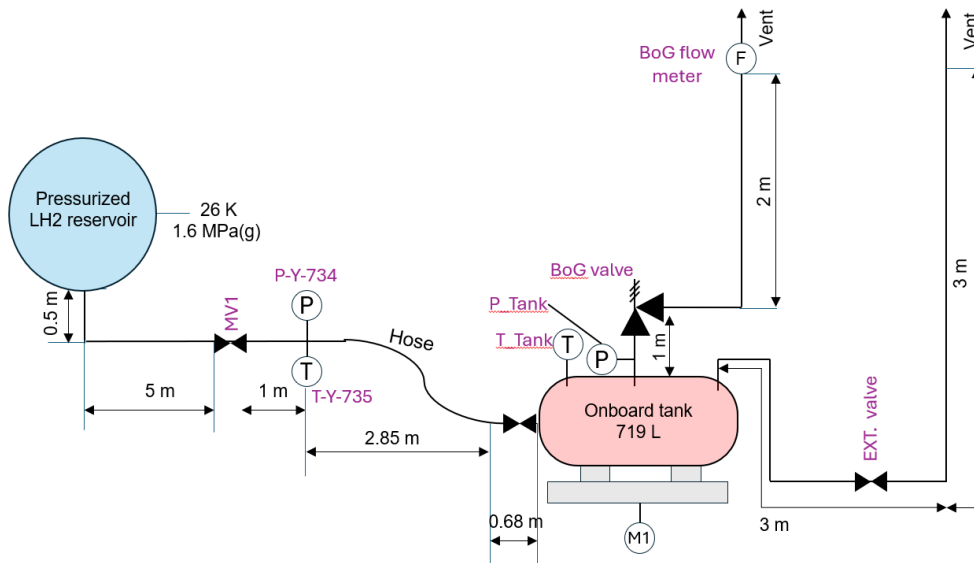
Initial conditions (lines - from BC in reservoir)

- **Onboard tank:** warm GH2 at 0.196 MPa(g) and 267 K.
- **Piping downstream MV1:** 288.15 K and 0.207 MPa(g).
- **Upstream MV1 piping:** T was not recorded in the experiment.
- **Upstream of the BoG valve:** 0.196 MPa(g) and 313 K.
- **Extraction line:** 291.5 K.
- Heat ingress 2 W/m² (flexible hose: 5 W/m²).
- Piping **downstream** of BoG and extraction valves: **no insulation.**



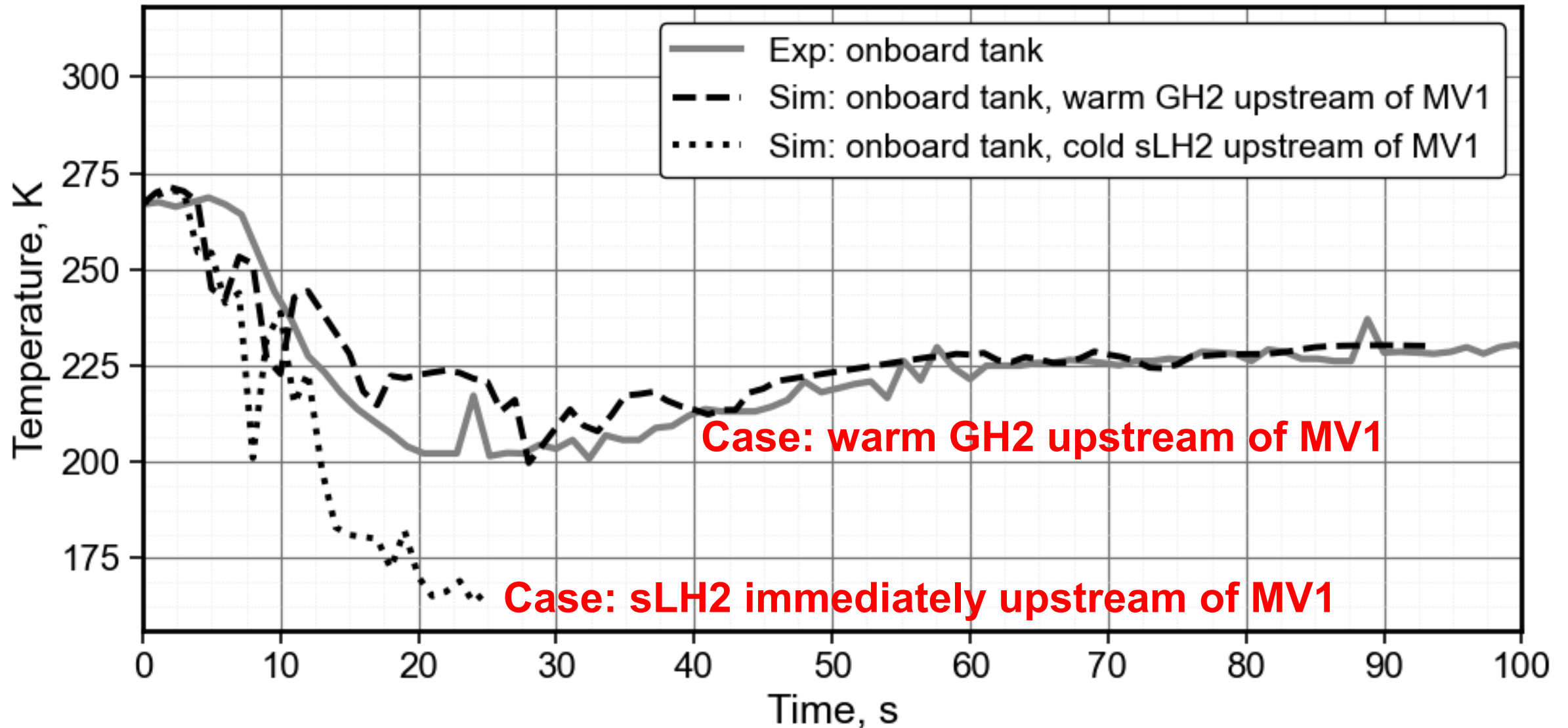
Warm parts affect the LH2 fraction and temperature upstream MV1

Experimental data



Warm tank simulations

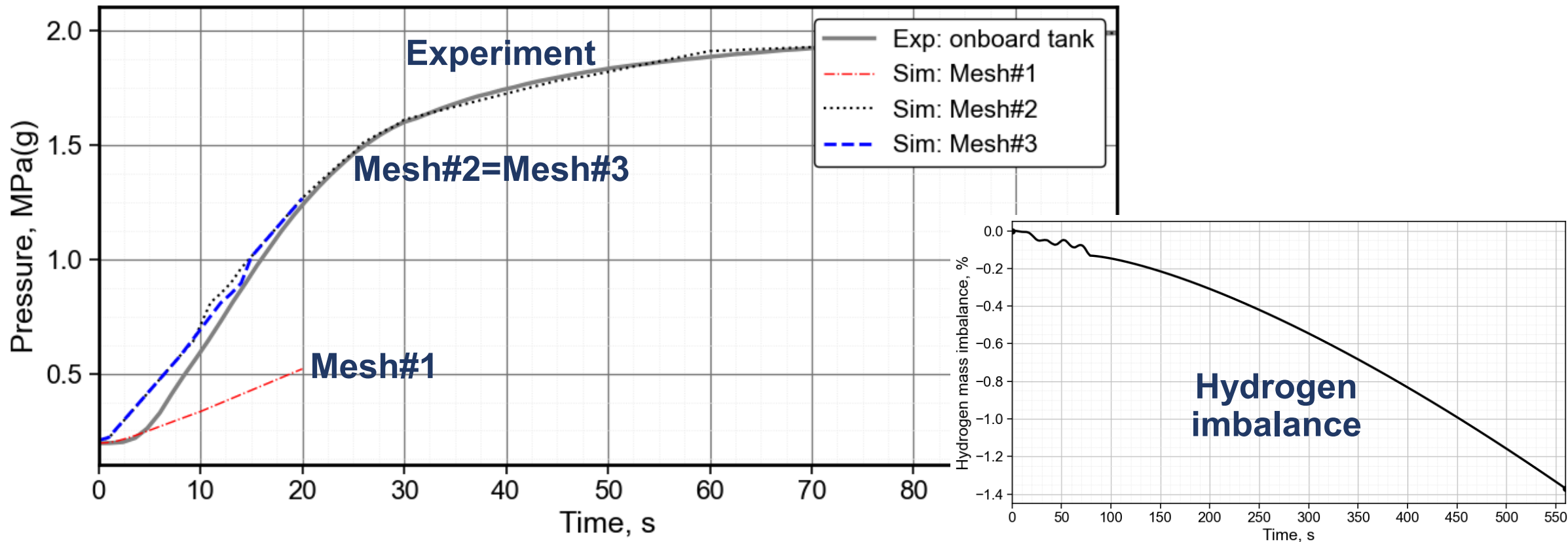
Effect of initial conditions upstream MV1 on tank temperature



Warm tank simulations

Grid independence (by onboard pressure) and mass imbalance

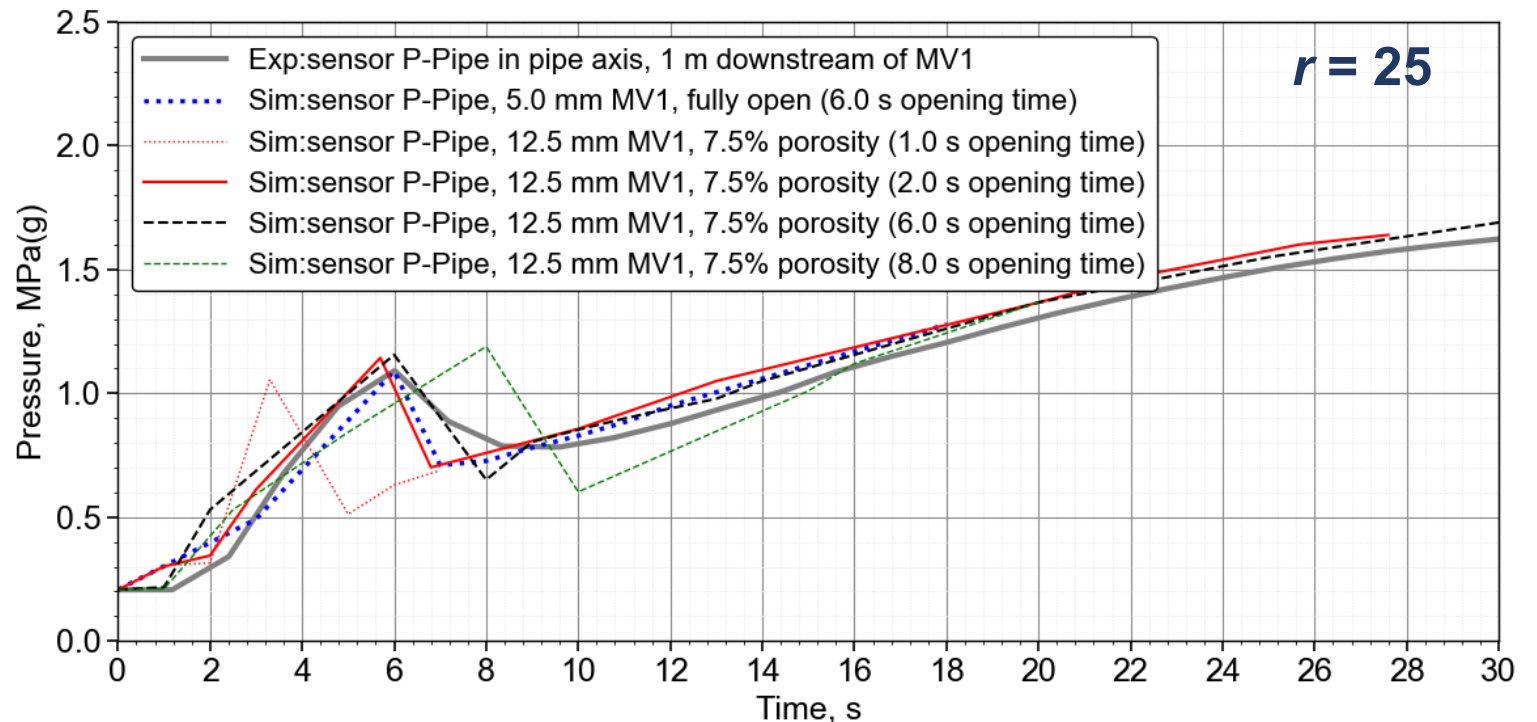
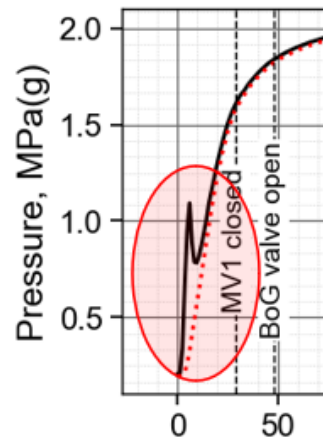
- Mesh#1: 171k CVs. Mesh#2: 389k CVs. Mesh#3: 612k CVs.
- Simulations on 64-core Dell PowerEdge R6525 workstation require a total computation time of **10.2 days** for a total duration of **560 s**.



Warm tank simulations

Peak pressure in the pipe: MV1 opening area and time

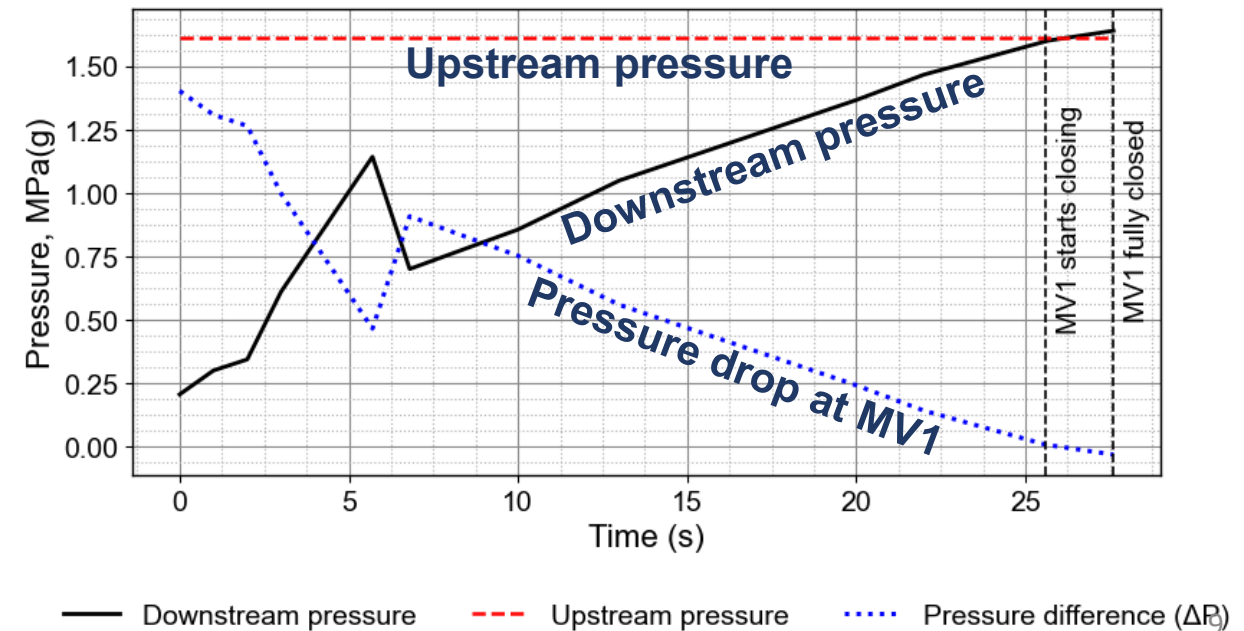
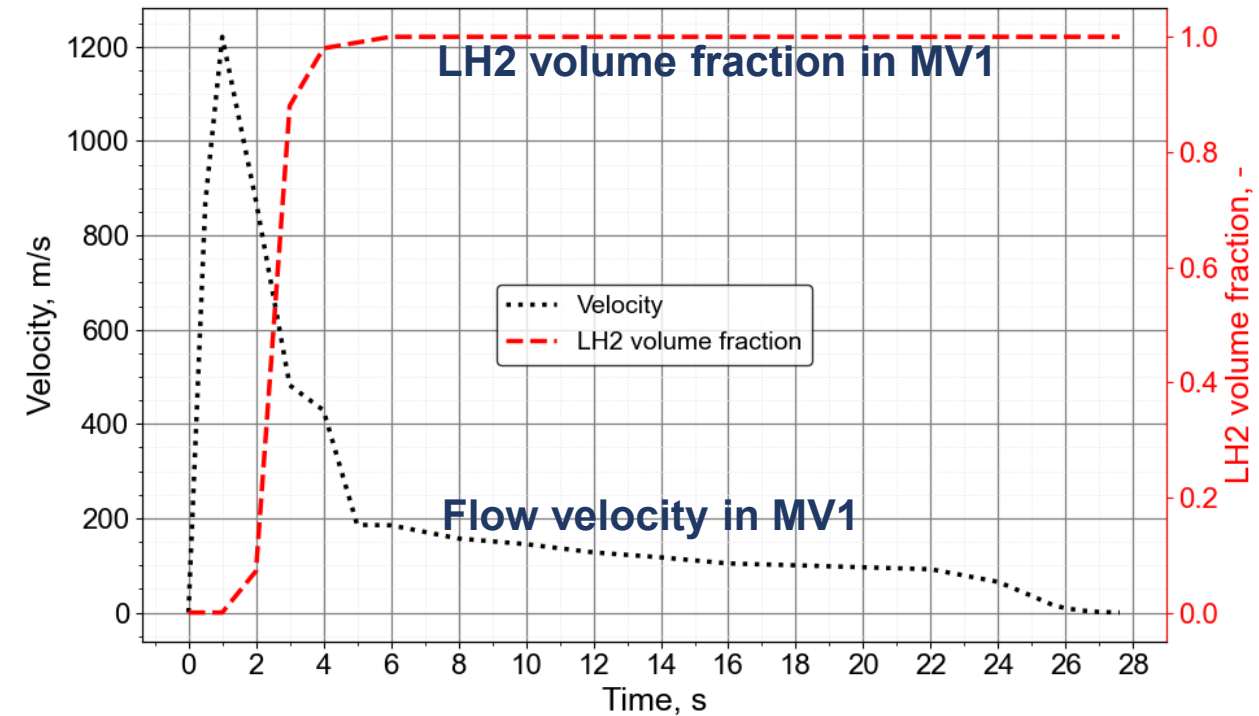
- The opening area of MV1 is defined as 7.5% of 12.5 mm “numerical valve”, i.e. a straight piece of pipe without real losses (100% of 5 mm). A larger opening area increases transient pressure unacceptably.
- The MV1 opening time is defined as 2-6 s (both 1 s and 8 s shift the peak). Experimentalists recommended 1-2 s. Final simulations used 2 s.



Warm tank simulations

MV1 velocity and LH2 fraction

- MV1 opens during 2 s (7.5% area).
100% LH2 flow after first 4 s.
- **First velocity drop:**
Two-phase flow has an essentially lower speed of sound.
- **Second velocity drop:**
Reduction of pressure drop at MV1 (only LH2 flow).

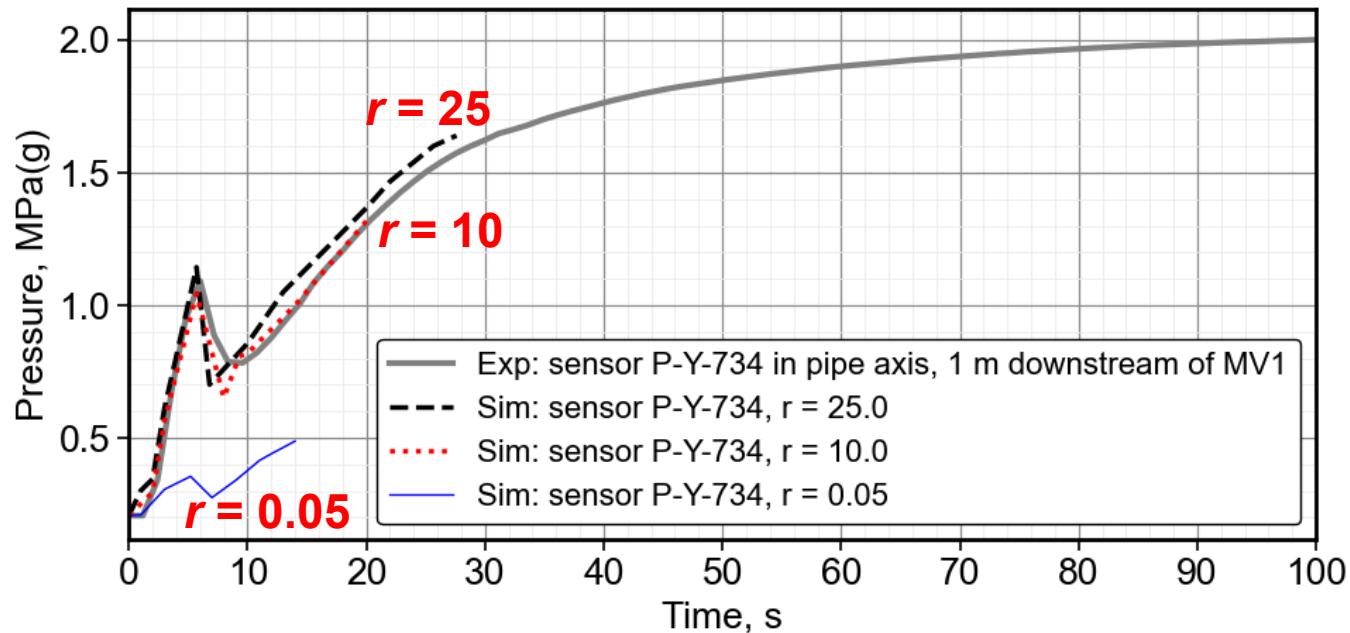
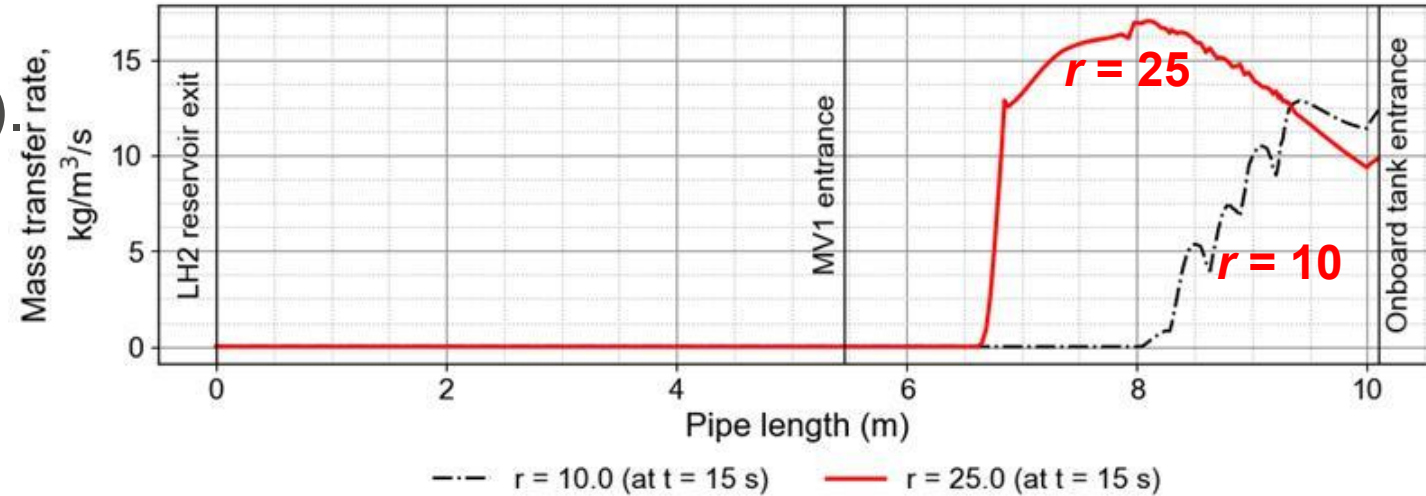


Warm tank simulations

Effect of the time relaxation parameter (Lee model coefficient)

Pressure transient in the pipe (▼).

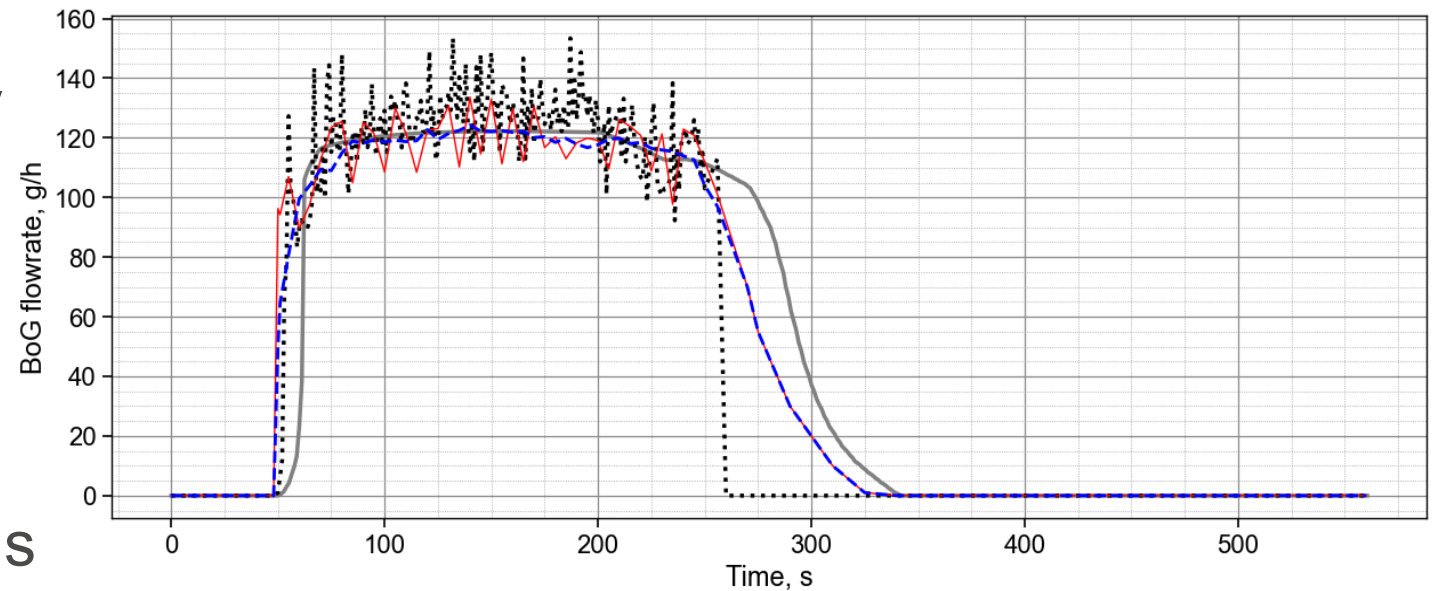
Mass transfer rate after MV1 (►).



Warm tank simulations

BoG flow rate

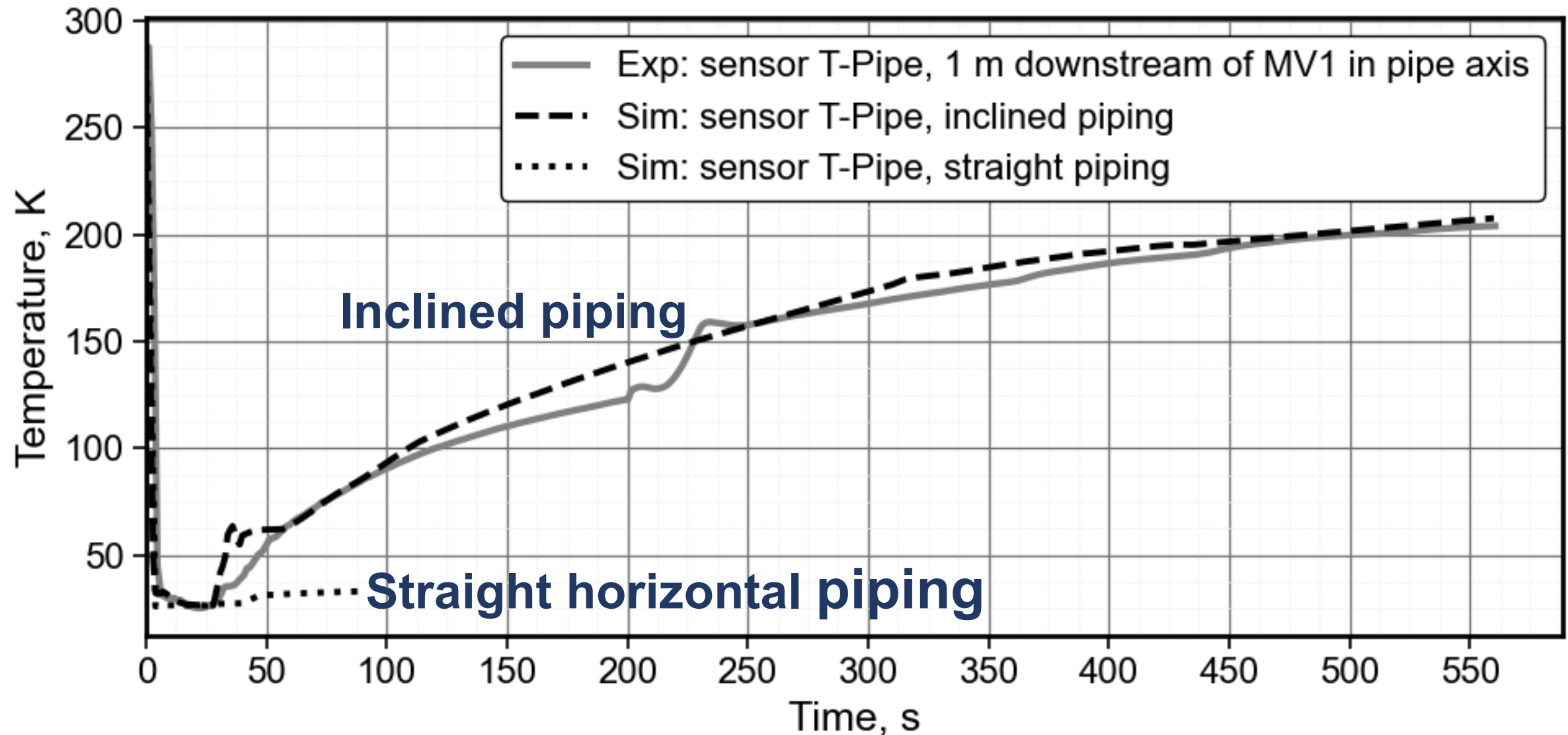
- The simulated BoG flow rate is shown as: BoG flowrate recorded at valve exit, BoG flowrate recorded at 2.5 m downstream of the BoG valve, and a Centred Moving Average (CMA) at 2.5 m downstream.
- The BoG valve was of ID=0.22 mm. The porosity concept was used with the computational diameter equal to the pipe diameter of 16 mm. Calibration against the experimental mass flow rate, gave maximum porosity 4.1×10^{-3} .
- The porosity was increased from 0 to maximum value over 0.5 s, starting at 48 s, to represent BoG valve opening (until closure at 240 s when the pressure dropped below the threshold).



— Exp: BoG flowrate (2.5 m downstream of BoG valve) — Sim: BoG flowrate (2.5 m downstream of BoG valve)
..... Sim: BoG flowrate (BoG valve exit) - - - Sim: CMA_BoG flowrate (2.5 m downstream of BoG valve)

Warm tank simulations

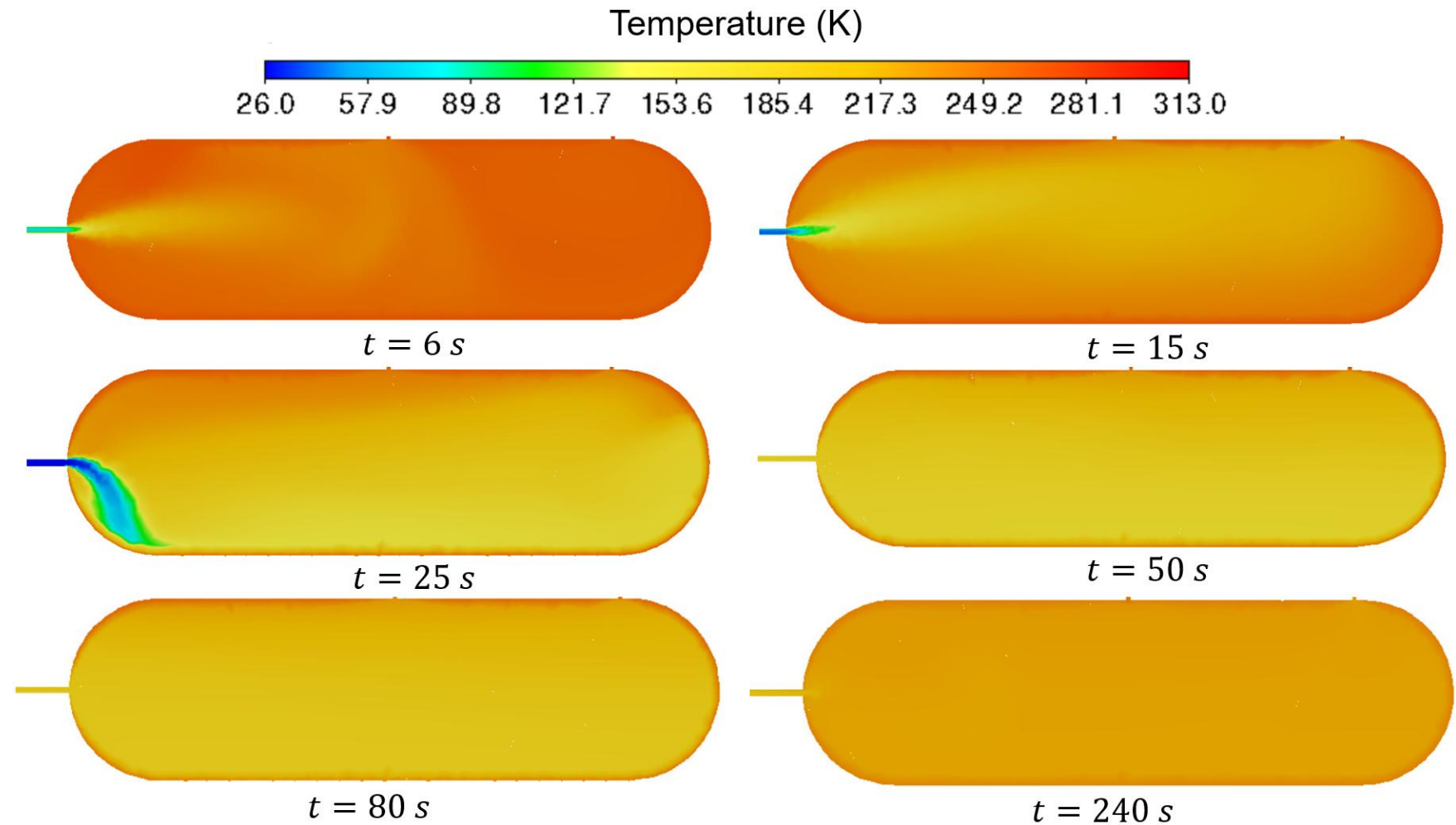
Temperature in the pipe: effect of pipe inclination



Warm tank simulations

Temperature distribution in the initially warm piping and tank

No spray bar.



Validation of simulations

Pressure in tank and pipe as a function of time

A: 1,183 kg of hydrogen in the onboard tank at 18 s (flowmeter), the simulated mass is 1.221 kg, i.e. only 3.2% higher.

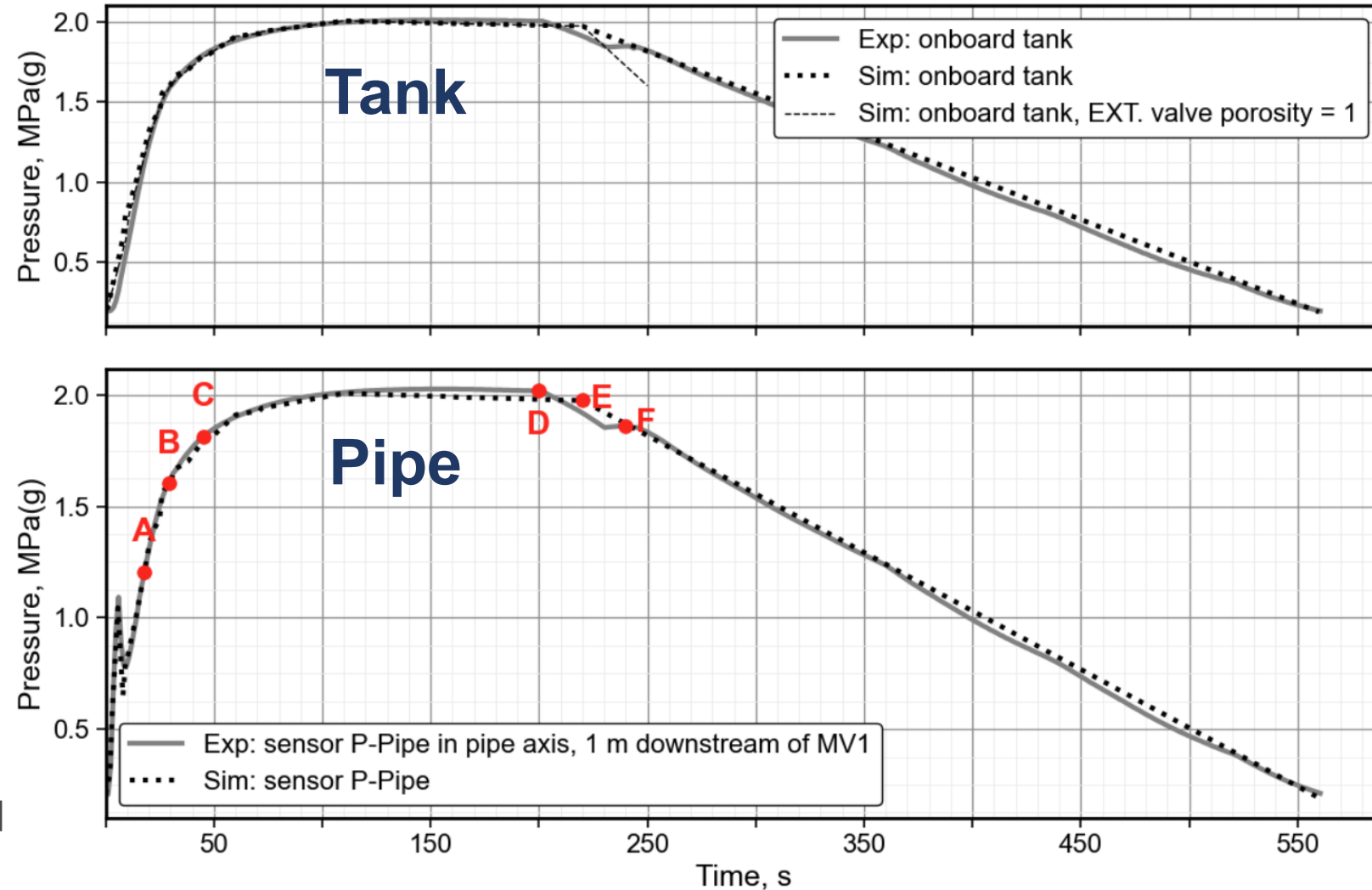
B: MV1 starts to close at 25.6 s, with a closing time of 2 s, when the pipe sensor reached **1.6 MPa(g)** [1.58 MPa(g) in simulations].

C: BoG valve triggered at **1.8 MPa(g)** in the onboard tank at 48 s (opening modelled via a porous-media formulation over 0.5 s).

D: Pressure starts dropping at 200 s (opening of the not-shown MV2 on the instrumentation diagram connecting the tank to the extraction venting line).

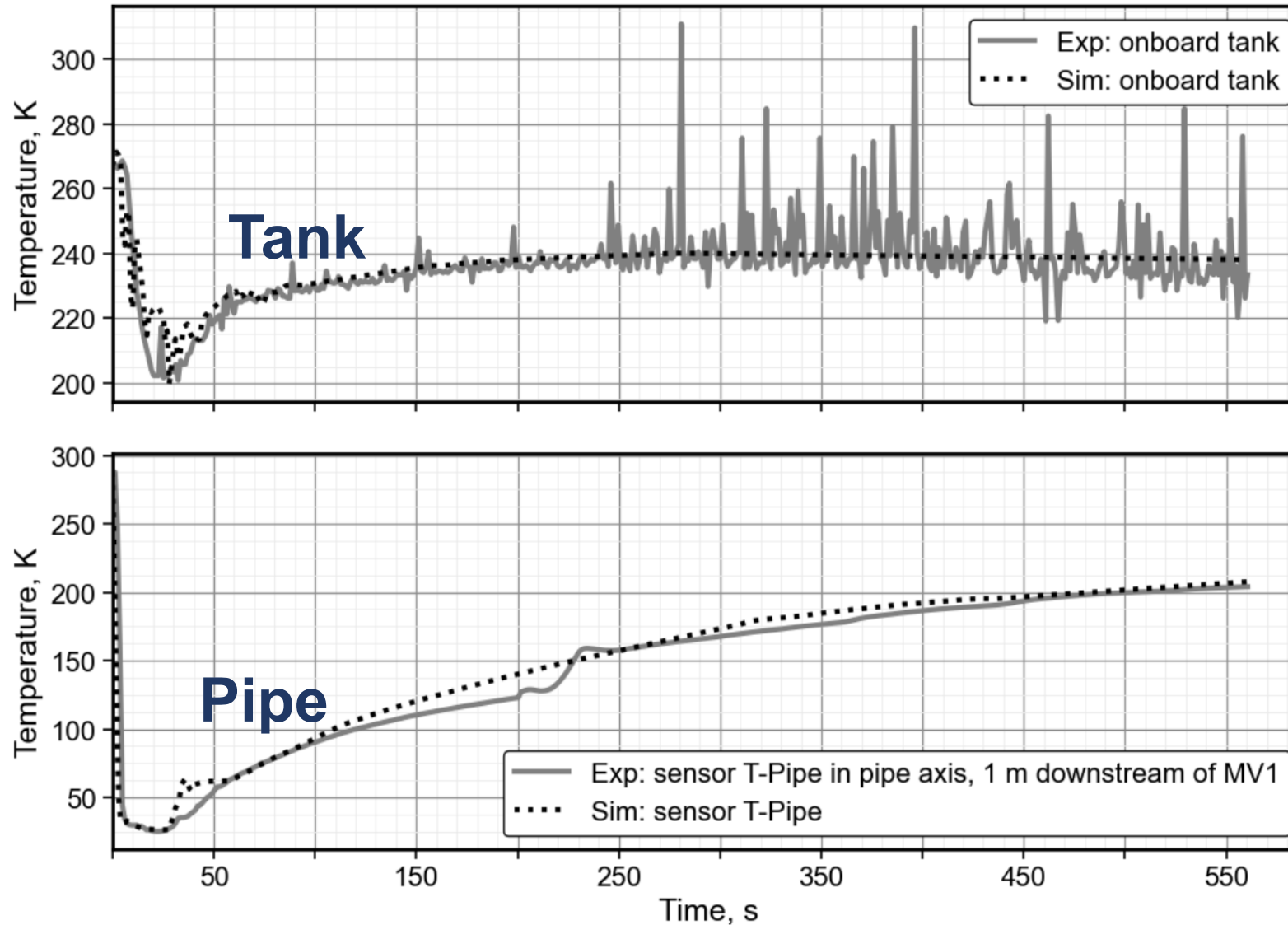
E: The extraction valve was opened at 220 s in simulations.

F: The extraction valve was opened at 240 s in the experiment.



Validation of simulations

Temperature in tank and pipe as a function of time

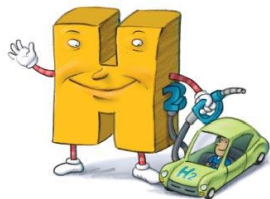


Concluding remarks

- The **originality** of this work lies in the first numerical investigation and modelling of the off-nominal scenario of sLH2 refuelling into a warm tank system at the HRS. The modelling approach integrated the full range of thermodynamic states encountered during LH2 refuelling, including subcooled conditions in the reservoir, saturated phase-change behaviour during LH2 flow to the warm piping section, and supercritical states beyond hydrogen's critical point.
- The study's **significance** lies in the development of a CFD model that reproduces the experimentally observed LH2 refuelling response, which can be utilised as a contemporary engineering tool for designing efficient LH2 refuelling protocols. This model accurately and efficiently simulated heat and mass transfer throughout the attempted refuelling process and afterwards. The validated model offers an accurate alternative to full-scale experimental testing.
- The study's **rigour** is evident from the extensive simulation and validation against the experiment conducted by Daimler Truck AG and KIWA ET GmbH. The model accurately reproduced the pressure and temperature dynamics in the piping and in the onboard tank, as well as the mass flow rate recorded downstream of the BoG valve.

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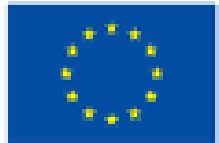
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Thank you for your attention

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