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Modelling the non-adiabatic blowdown of pressurised cryogenic hydrogen storage tank

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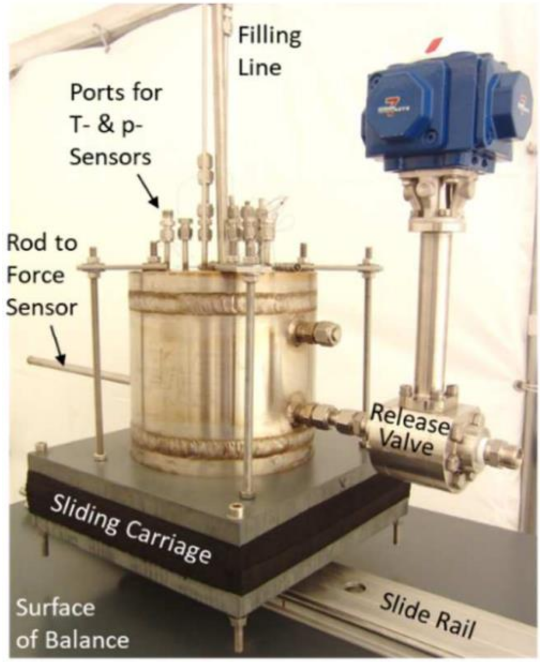
Introduction

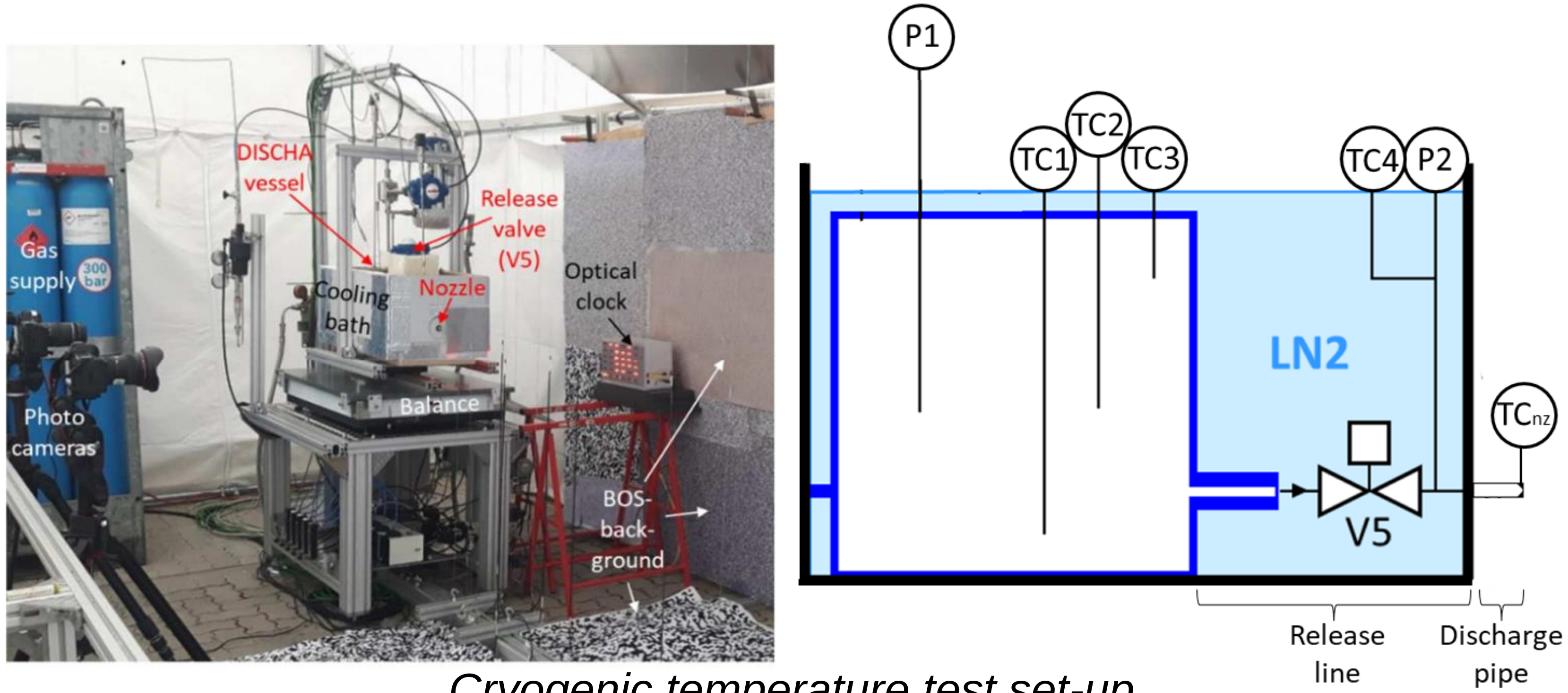
- The fast-growing market of hydrogen technologies requires competitive techniques to store and transport large quantities of this energy carrier.
- The cryo-compressed hydrogen (CcH2) storage is being investigated as it may optimise the gravimetric and volumetric capacities against the energy required for the compression and cooling down of the gas in comparison to commercially used compressed gaseous (CGH2) and liquid hydrogen (LH2).
- In case of a release through the Thermally Activated Pressure Relief Device (TPRD) or other relief device installed on a storage system, the hydrogen blowdown dynamics and transient mass transfer will be affected by the heat transfer in the system.
- Previous investigations demonstrated that the heat transfer through a pipe wall affects significantly the flow of cryogenic hydrogen and ultimately the thermal hazards from the resulting jet fires.
- The present study proposes a new physical model expanding the work in Molkov et al. (2021) to accurately represent the blowdown dynamics of CcH2 tanks, accounting for the non-ideal behaviour of CcH2 and the heat transfer through the storage tank and discharge pipe walls.
- The model performance is assessed through comparison with experimental measurements of temperature and pressure during blowdown of hydrogen storage tanks at initial ambient and cryogenic (80 K) temperature in tests performed within PRESLHY project.

Validation experiments

- Tests were performed at the DISCHA facility by Pro-Science within the PRESLHY project.
- The tank was made of stainless-steel and had volume V=2.81 L, internal diameter D_{int}=160 mm and internal height of 140 mm.
- The tank was exposed to ambient air for the ambient temperature tests, whereas the tank was immerged in a liquid nitrogen (LN2) bath with temperature equal to 77 K for the cryogenic tests.
- Sixteen tests were selected to maximize the validation domain: initial storage pressure P_s=0.6-20 MPa abs, initial storage temperature T_s=80-310 K, release nozzle diameter d_n=0.5-4.0 mm.



Ambient temperature test set-up



Cryogenic temperature test set-up

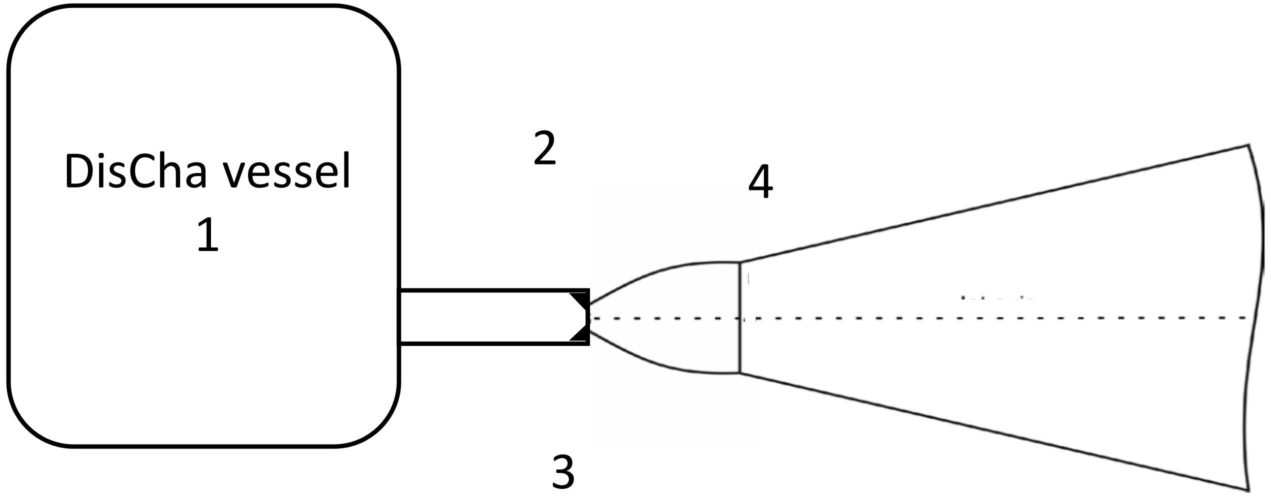
Physical model description

General aspects

- The present physical model advances the non-adiabatic blowdown model accounting for heat transfer through the wall of high pressure hydrogen storage tanks developed in Molkov et al. (2021).
- The non-ideal behaviour of cryo-compressed hydrogen is accounted through the EoS based on high-accuracy Helmholtz energy formulations implemented via the opensource CoolProp C++ library.
- The first law of thermodynamics is used to assess the change of storage conditions during blowdown:

$$\frac{dU}{dt} = \frac{dQ}{dt} - h_{out}\frac{dm}{dt}$$

- The under-expanded jet theory cannot be applied in a straightforward way and must be expanded to account for the heat transfer through the discharge pipe and non-ideal gas behaviour by the NIST EoS.



Schematic of the model:
1 - storage tank in LN2 bath;
2 - end of pipe prior to the nozzle;
3 - real nozzle exit;
4 - notional nozzle exit.

Physical model description

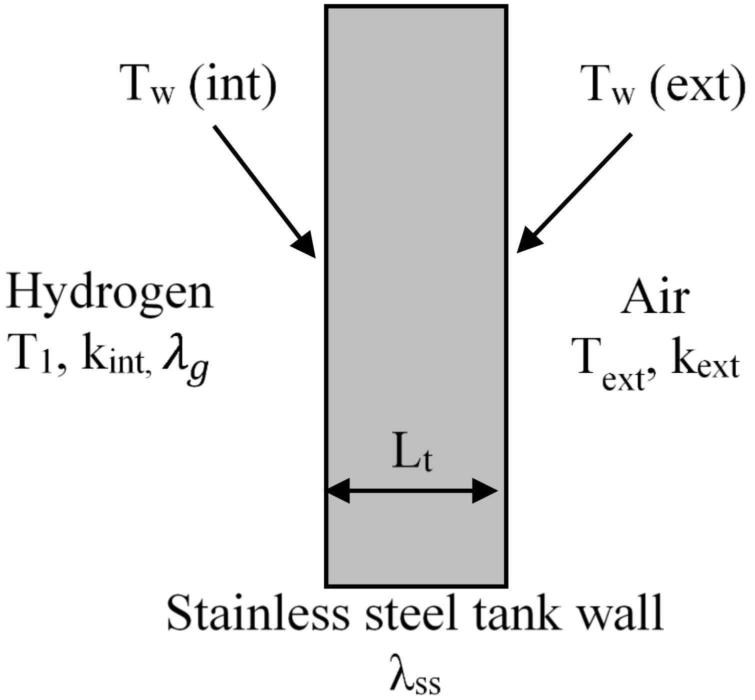
Convective and conductive heat transfer for the storage tank

- The rate of heat transfer by convection at the internal wall is calculated as:

$$\frac{dQ}{dt} = k_{int} A_{int} \left(T_{w(int)} - T_1 \right)$$

- The convective heat transfer inside the tank and within the discharge pipe is calculated according to the convection regime:

$$k_{int} = \frac{\lambda_g \times Nu}{D_{int}}$$



- The model solves the 1D unsteady heat conduction equation through the tank and discharge pipe walls.
- The convective heat transfer coefficient at external tank wall is assumed to be 6 W/m^2/K for air at ambient temperature and 120 W/m^2/K for the LN_2 bath in the cryogenic tests.

Physical model description

Heat transfer through the discharge line wall

- The developed model takes into account the heat transfer through the release pipe wall.
- Due to the presence of a nozzle of smaller diameter at the pipe end, it is assumed $P_2 = P_1$.
- The heat transfer through the discharge pipe wall is calculated at each time step *t* as:

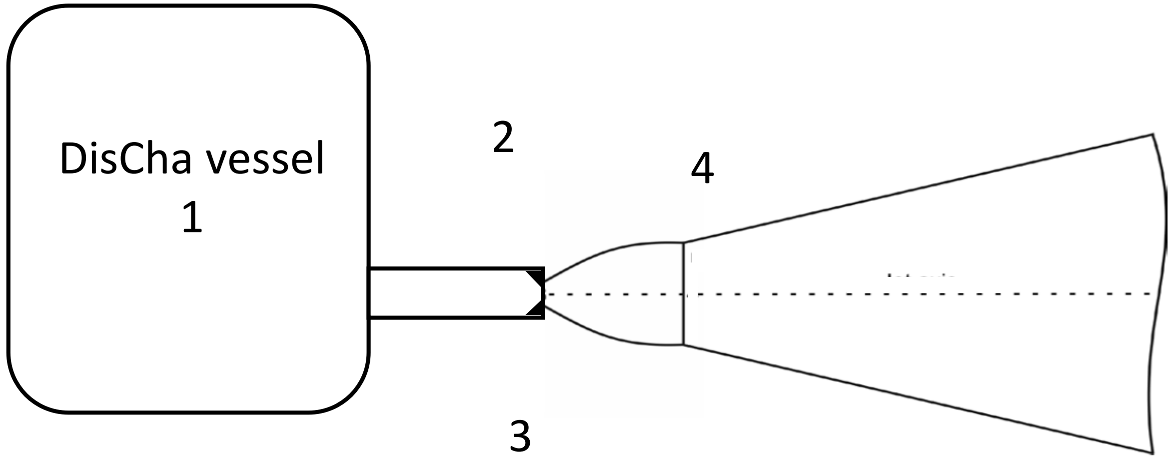
$$\frac{dQ}{dt} = k_{int,pipe} A_{int,pipe} \left(T_{w,pipe(int)} - T_1\right)$$

- The energy conservation equation is used to retrieve the thermodynamic state h_2:

$$h_2 + \frac{v_2^2}{2} = q + h_1$$

with velocity $v_2 = \dot{m}_3/(A_{int}\rho_2)$ and

specific heat transfer $q = \frac{dQ}{dt}/\dot{m}_3$.



Physical model description

Calculation procedure and assumptions

- The first law of thermodynamics differentiated in time can be used to calculate the specific internal energy, u, with advancement of time $t+\Delta t$ from parameters calculated at the time step t:

$$u_1^{t+\Delta t} = \left(m_1^t u_1^t + \Delta t\left[k_{int}^t A_{int}\left(T_{w\,(int)} - T_1\right)^t - h_1^t \dot{m}_3^t\right]\right)/m_1^{t+\Delta t}$$

where: $m_1^{t+\Delta t} = m_1^t - \dot{m}_3^t \Delta t$.

- The density of hydrogen in the tank at the time $t+\Delta t$ is calculated as:

$$\rho_1^{t+\Delta t} = \frac{m_1^{t+\Delta t}}{V_{tank}}$$

- $u_1^{t+\Delta t}$ and $\rho_1^{t+\Delta t}$ can then be used as input to CoolProp database to determine the thermodynamic state of hydrogen at the time $t+\Delta t$: $T_1^{t+\Delta t}, P_1^{t+\Delta t}, h_1^{t+\Delta t}$.

Step	**Calculation algorithm until $P_1/P_{amb}>P_{lim}$***
1	Hydrogen mass in the tank
2	Convective heat transfer in the hydrogen tank
3	Change of internal energy to find storage parameters at time t+Δt
4	Temperature distribution through the tank wall
5	Heat transfer rate through the discharge pipe wall
6	Real and notional nozzle exits parameters

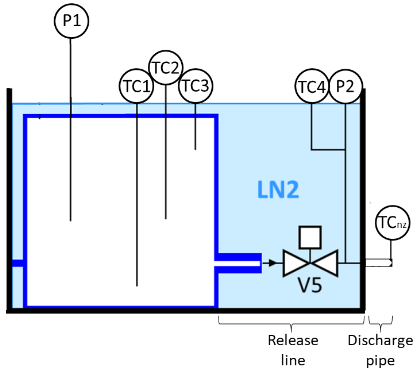
Physical model validation

Procedure

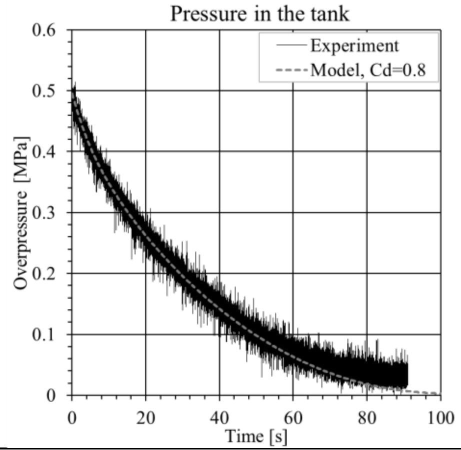
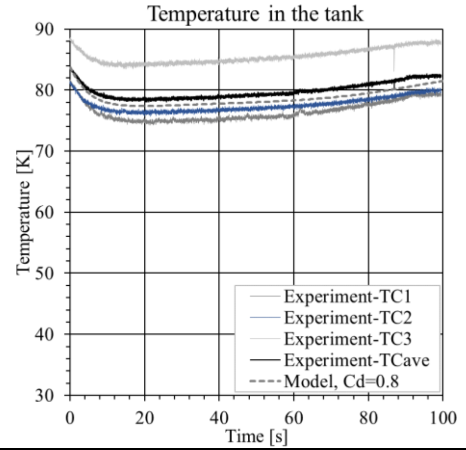
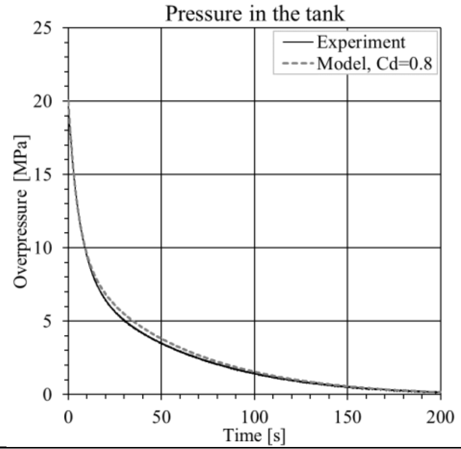
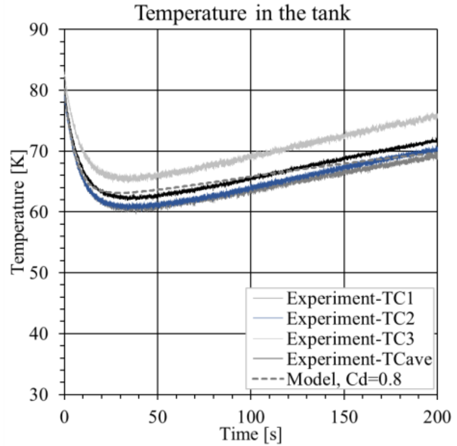
- The developed non-adiabatic blowdown model for CcH2 provides as output the transient dynamics of temperature, pressure and density in the tank; mass flow rate; temperature, pressure, density and velocity of hydrogen at the real nozzle exit.
- The calculations of temperature and pressure dynamics inside the storage tank by the physical model are compared against experimental data.
- The discharge coefficient, C_d, is applied in calculations to account for friction and minor losses in the piping system and real nozzle compared to the ideal case of no losses with $C_d=1$.
- For each of the simulated tests, different discharge coefficients are applied to find the optimum characteristic for this experiment.

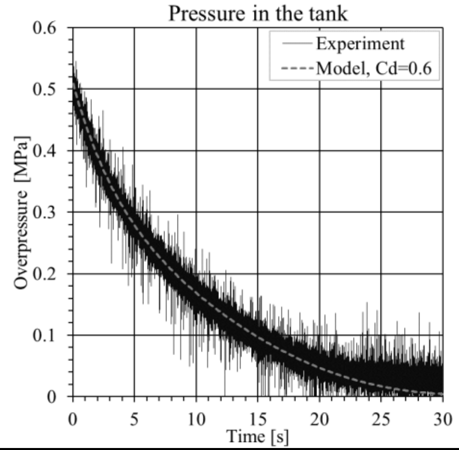
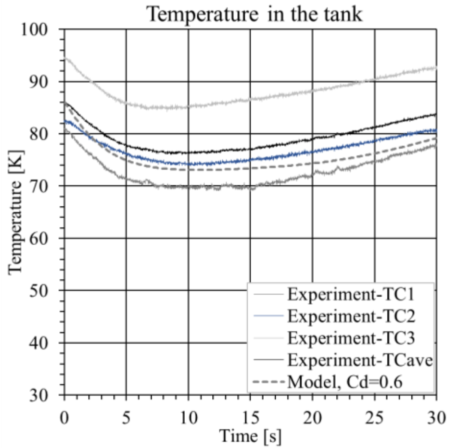
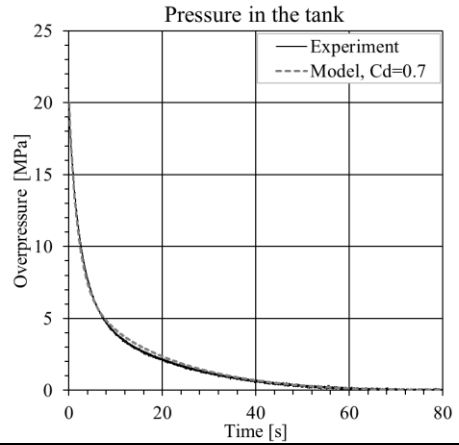
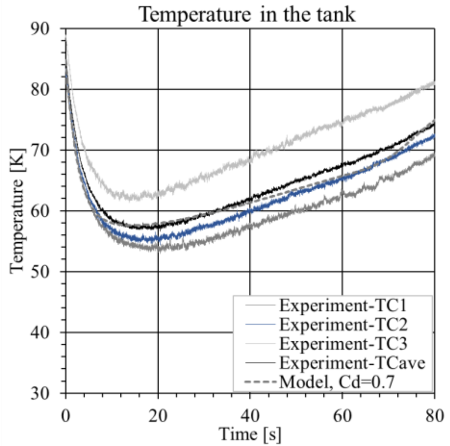
Physical model validation

Tests at initial cryogenic temperature (1/2)



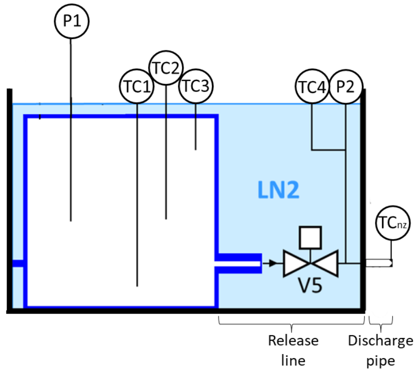
- The developed model reproduces well the experimental pressure and temperature dynamics.
- Tests with lower initial storage pressure (about 0.6 MPa abs) present a certain level of noise when approaching the ambient pressure, whereas as expected calculations tend to zero.

Case	Overpressure dynamics	Temperature dynamics
Test 1c - P_1=0.59 MPa abs, T_1=83.7 K, d_n=0.5 mm		
Test 4c - P_1=20.12 MPa abs, T_1=80.2 K, d_n=0.5 mm		

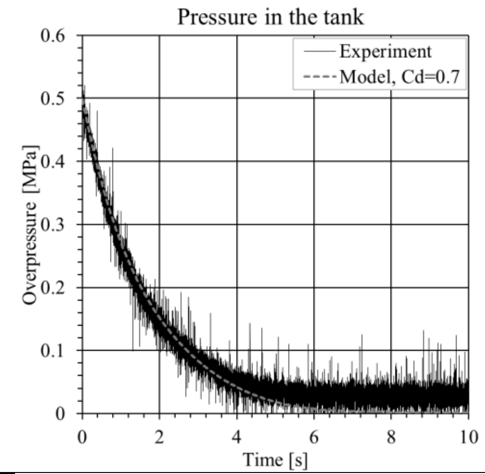
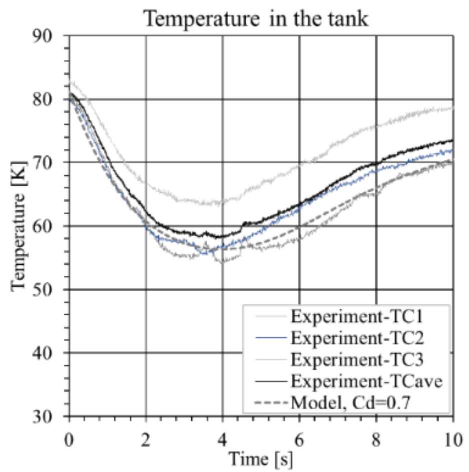
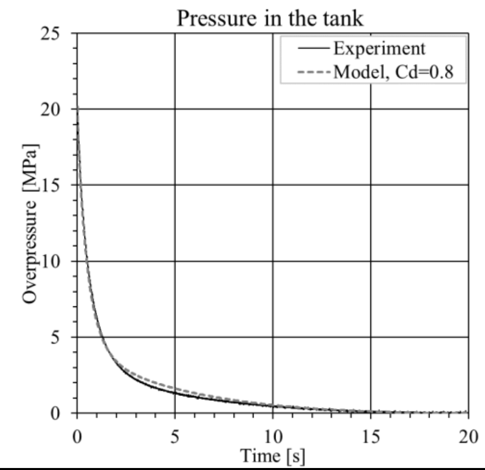
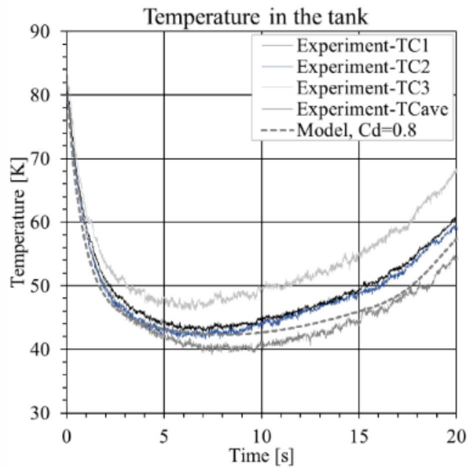
Case	Overpressure dynamics	Temperature dynamics
Test 5c - P_1=0.61 MPa abs, T_1=86.0 K, d_n=1.0 mm		
Test 8c - P_1=20.10 MPa abs, T_1=84.8 K, d_n=1.0 mm		

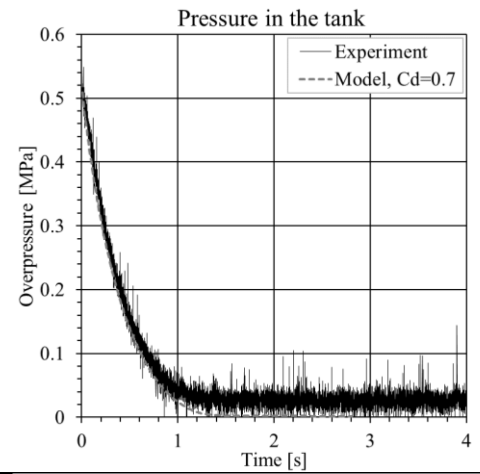
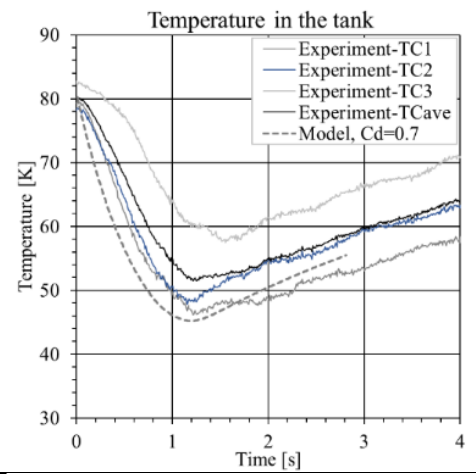
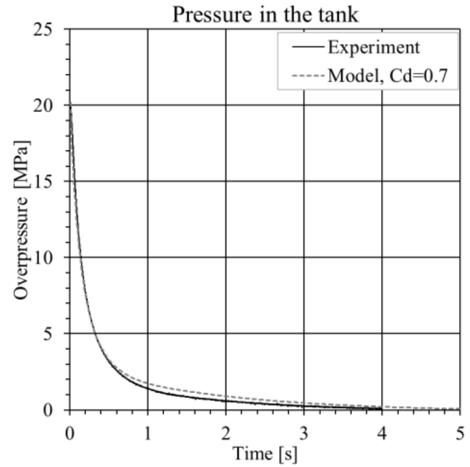
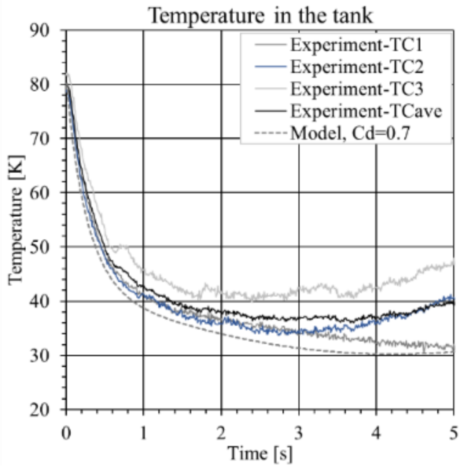
Physical model validation

Tests at initial cryogenic temperature (2/2)



- Tests with the largest diameter (d_n=4.0 mm) show a larger deviation between calculations and the records of the three thermocouples inside the tank and a lower temperature compared to experiments.
- The optimum discharge coefficients for the whole set of tests are found to be in the range C_d=0.6-0.8.

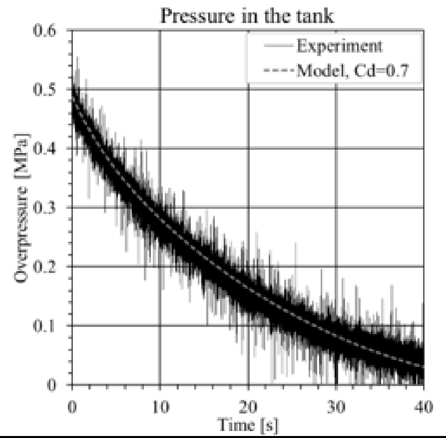
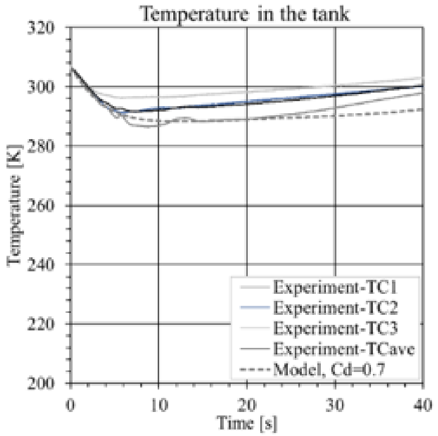
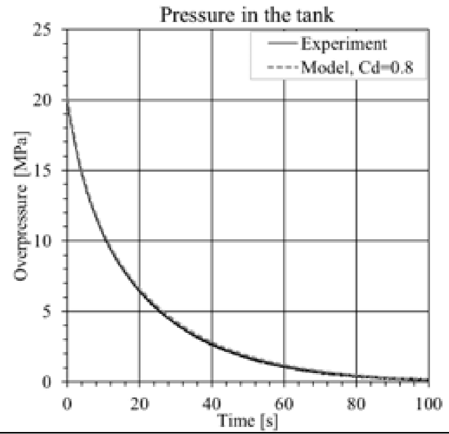
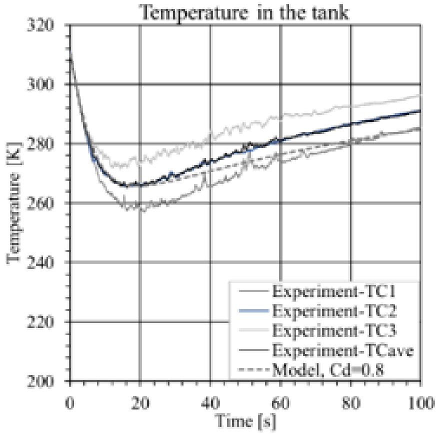
Case	Overpressure dynamics	Temperature dynamics
Test 9c - P_1=0.60 MPa abs, T_1=81.2 K, d_n=2.0 mm		
Test 15c - P_1=20.25 MPa abs, T_1=81.5 K, d_n=2.0 mm		

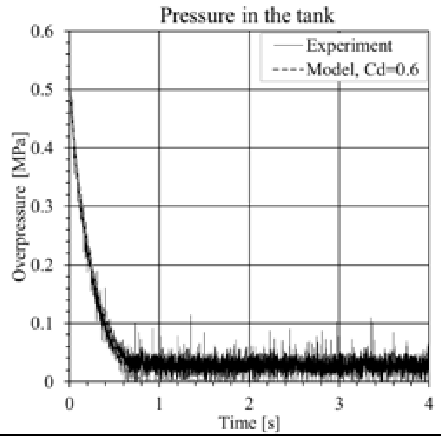
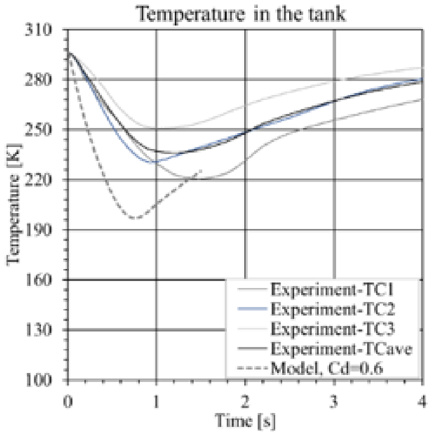
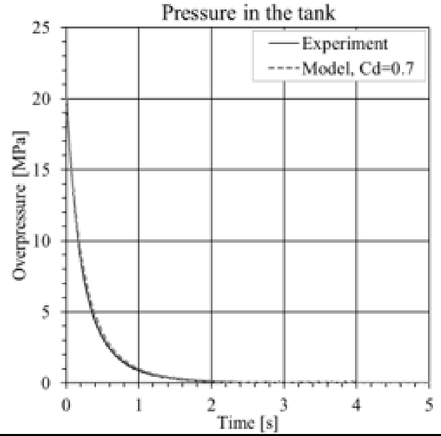
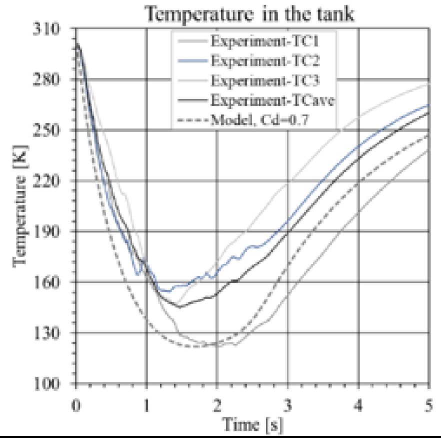
Case	Overpressure dynamics	Temperature dynamics
Test 16c - P_1=0.61 MPa abs, T_1=80.2 K, d_n=4.0 mm		
Test 22c – P_1=20.27 MPa abs, T_1=80.2 K, d_n=4.0 mm		

Physical model validation

Tests at initial ambient temperature

- The comparison of calculations against experiments with initial ambient temperature confirms the accurate predictive capability of the developed physical model.
- Tests 16w and 22w present similar behaviour to cryogenic tests with largest diameter.
- The optimum discharge coefficient for all the set of tests is found for C_d=0.6-0.8.

Case	Overpressure dynamics	Temperature dynamics
Test 1w - P_I=0.59 MPa abs, T_I=310.4 K, d_n=0.5 mm		
Test 4w - P_I=20.19 MPa abs, T_I=310.4 K, d_n=0.5		

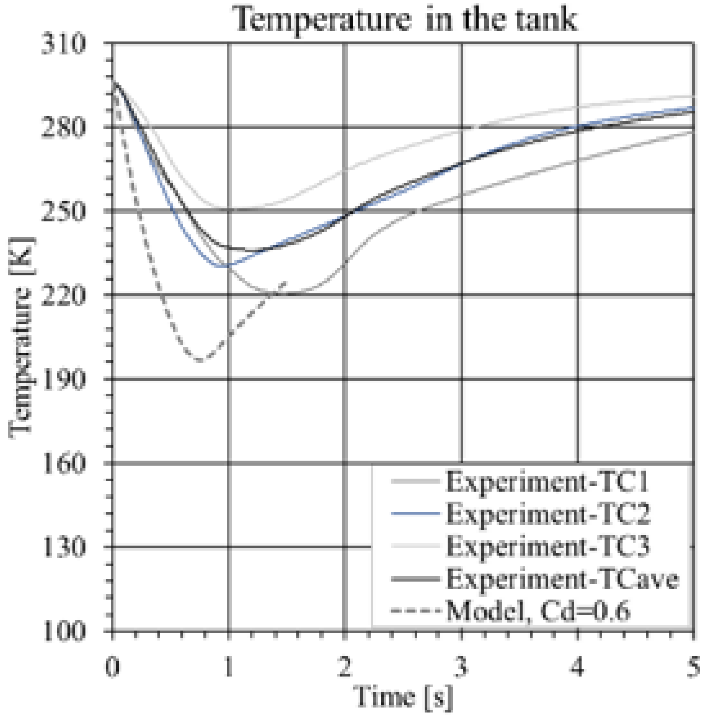
Case	Overpressure dynamics	Temperature dynamics
Test 16w - P_I=0.59 MPa abs, T_I=296.0 K, d_n=4.0		
Test 22w - P_I=20.03 MPa abs, T_I=300.9 K, d_n=4.0		

Physical model validation

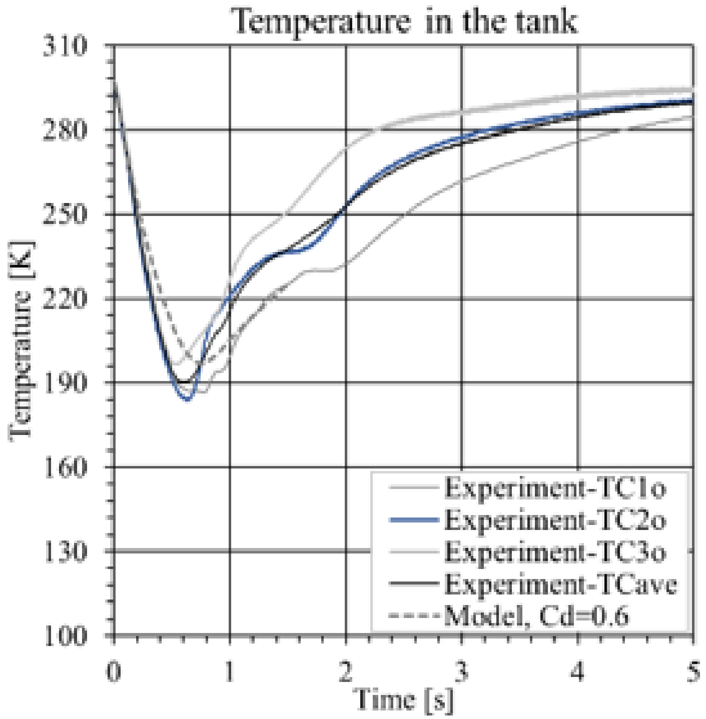
Tests at initial ambient temperature

- Tests with largest diameter showed a larger deviation between calculations and experiments.
- This is deemed to be caused by the inertia of the "closed" thermocouples for short blowdown durations.
- The "open" thermocouples measurements better agree with the model calculations due to reduced sensors inertia. However, these sensors may lose accuracy for cryogenic temperatures, and "closed" thermocouples were used in the experiments and in the model validation process.

"Closed" thermocouples



"Open" thermocouples



Test 16w:
P_1=0.59 MPa abs,
T_1=296.0 K, d_n=4.0 mm

Conclusions

- A physical model has been developed to predict the dynamics and characteristics of transient cryo-compressed hydrogen releases during storage tank blowdown.
- The model accounts for the effect of conjugate heat transfer through the storage tank and discharge pipe walls, and the non-ideal behaviour of cryo-compressed hydrogen.
- The model was extensively validated against experiments performed within the PRESLHY project at initial ambient and cryogenic (80 K) temperatures. The initial storage pressure was in the range 0.6-20 MPa abs, whereas the release diameter varied from 0.5 mm to 4.0 mm.
- The model reproduced well the experimental pressure and temperature dynamics inside the tank during blowdown experiments. The deviations observed for the tests with larger release diameters of 2 mm and 4 mm were seen to be associated with the thermocouples' inertia.
- Further research is envisaged towards the validation and applicability of the developed physical model to larger hydrogen storages, full bore ruptures and longer discharge lines once detailed experiments will be available.

Thank you for your attention!

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