ELVHYS 4th safety workshop
4th December 2024, Trondheim, Norway

Effect of heat transfer through the tank and pipe walls on releases of cryogenic hydrogen

Cirrone, D., Makarov, D., Molkov, V.
Hydrogen Safety Engineering and Research Centre (HySAFER), Ulster University, UK
d.cirrone@ulster.ac.uk

Introduction

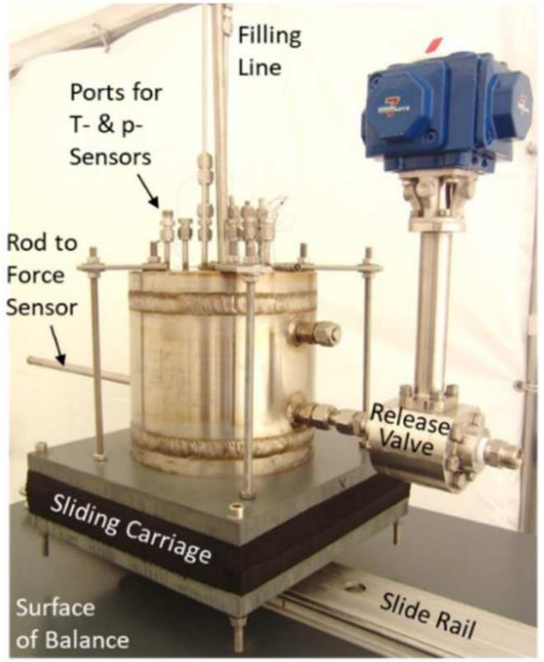
- In case of a release through the Thermally Activated Pressure Relief Device (TPRD) or other relief device installed on a storage system, the hydrogen blowdown dynamics and transient mass transfer will be affected by the heat transfer in the system.
- A new physical model expanding the work in Molkov et al. (2021) is proposed 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 reduced 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.
- A CFD modelling of the cryogenic flow in the pipe is performed to characterise the flow parameters accounting heat transfer between the cryogenic flow, the pipe wall and ambient atmosphere.
- CFD investigations were performed to assess the effect of heat transfer through a pipe wall on the thermal hazards from the resulting cryogenic hydrogen jet fires.

Ulster University

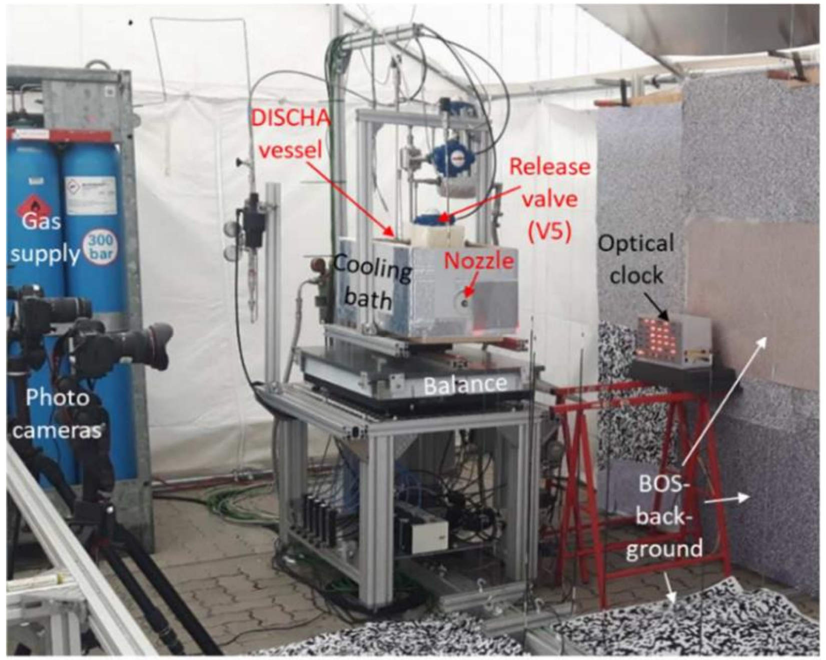
Validation experiments

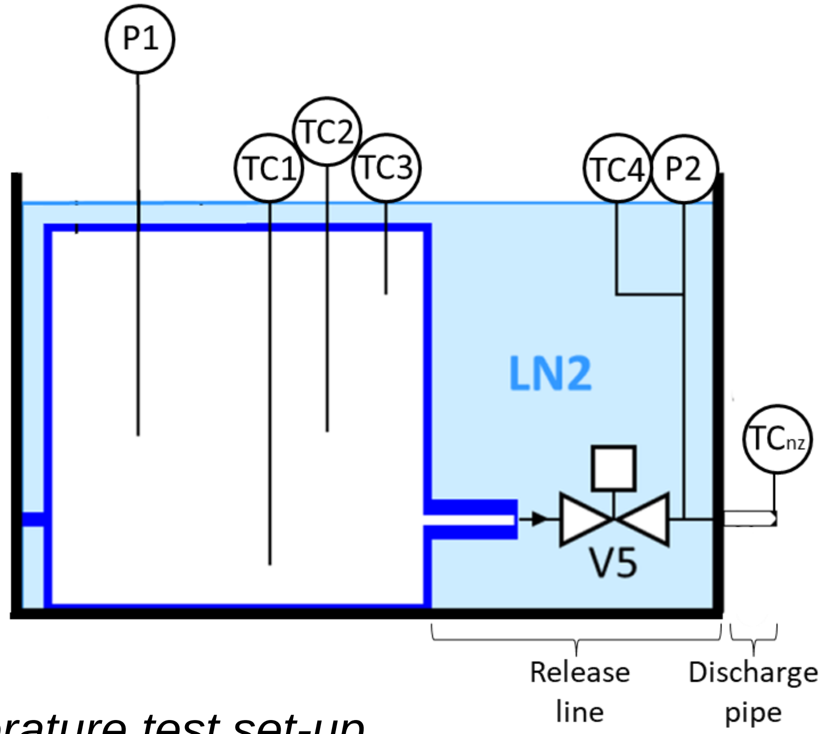
Transient cryogenic hydrogen releases

- 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

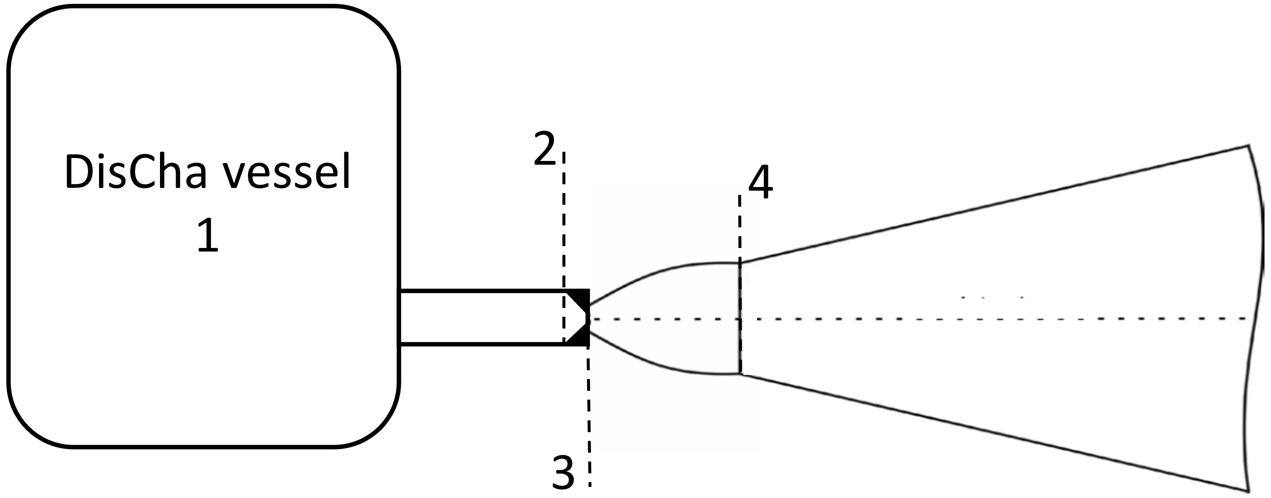
Physical model description

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.

Ulster University

Physical model description

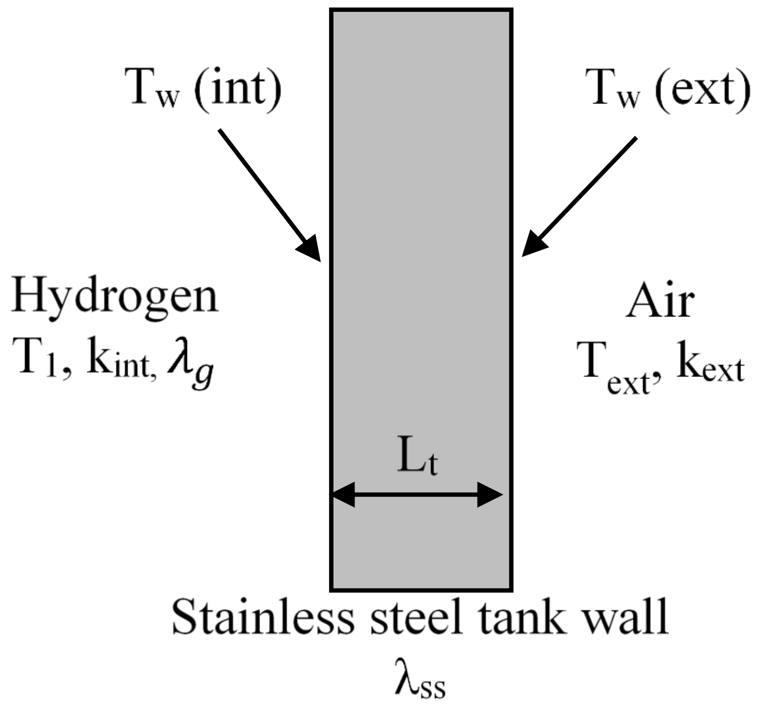
Convective and conductive heat transfer for the storage tank

- 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 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.
- The model solves the 1D unsteady heat conduction equation through the tank and discharge pipe walls.

Ulster University

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:

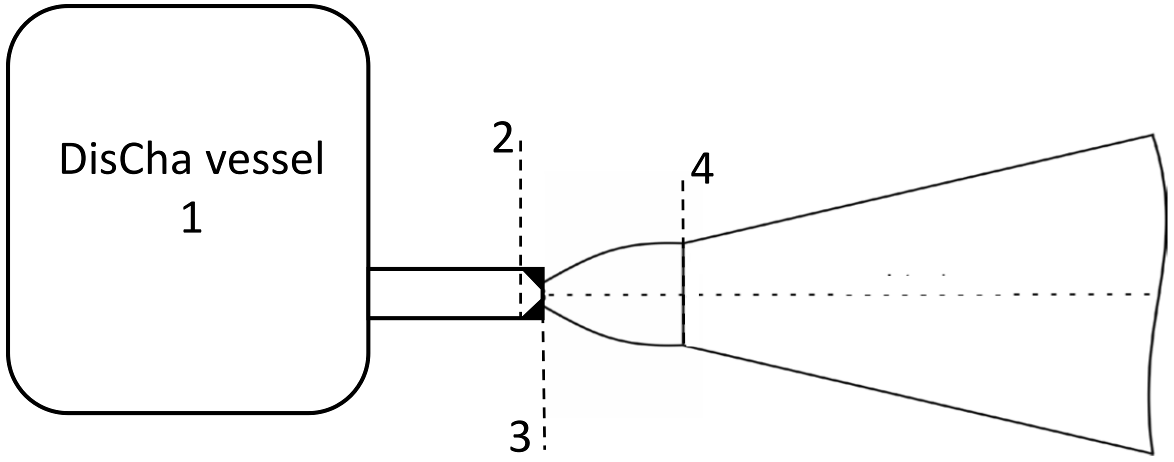
$$\frac{dQ}{dt} = k_{int,pipe} A_{int,pipe} \left(T_{w,pipe(int)} - T_1\right)$$

- 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 $q = \frac{dQ}{dt}/\dot{m}_3$.

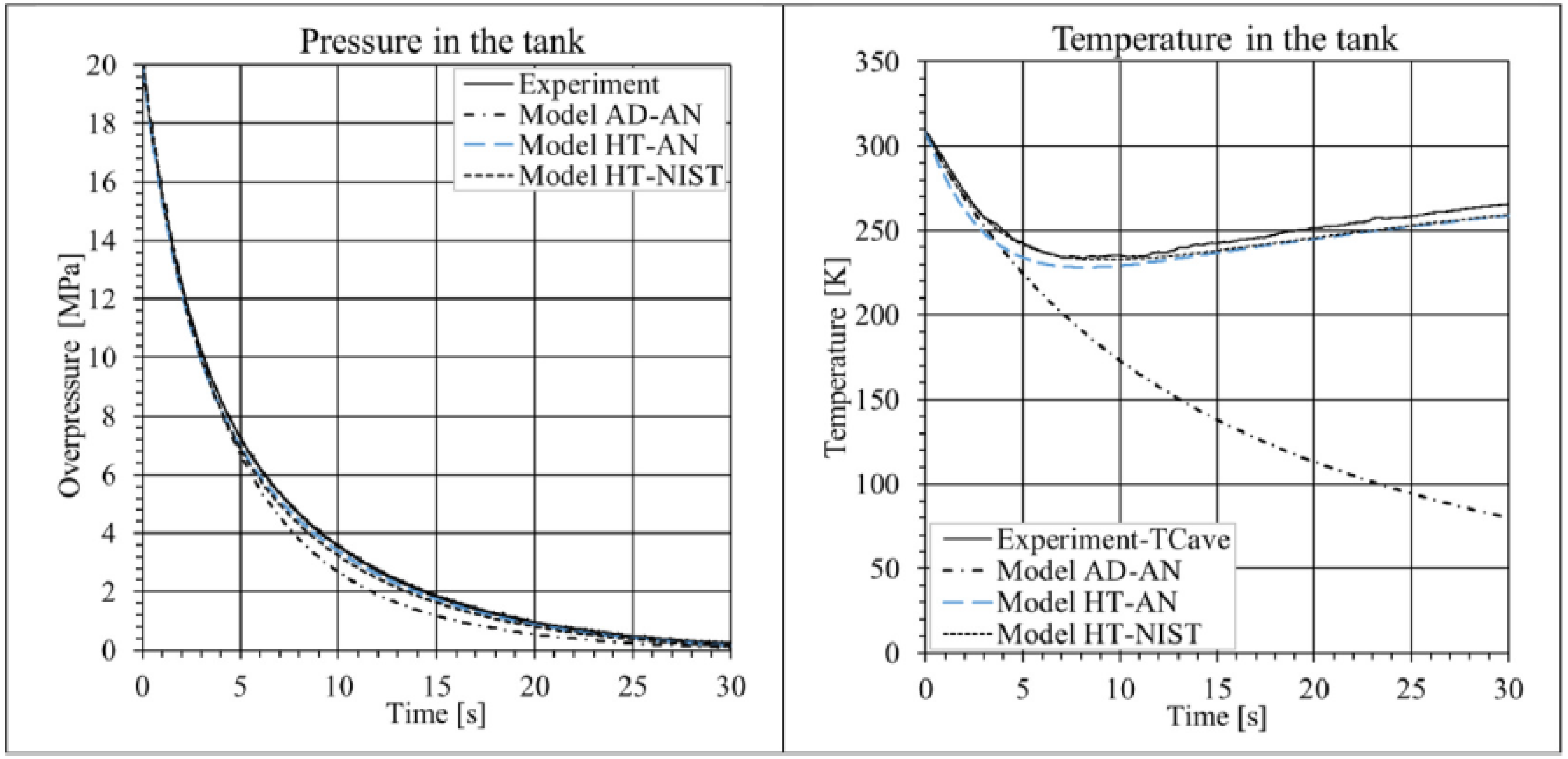


Ulster University

Results and discussion

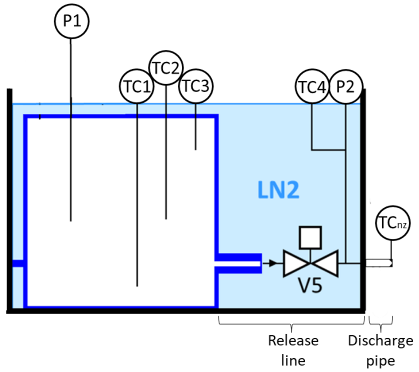
Comparison of three blowdown models

- Experimental pressure and temperature dynamics for Test 8w (P1=20.19 MPa ab, T1=307.7 K, d=1.0 mm, Cd=0.7) against calculated by three different blowdown models.

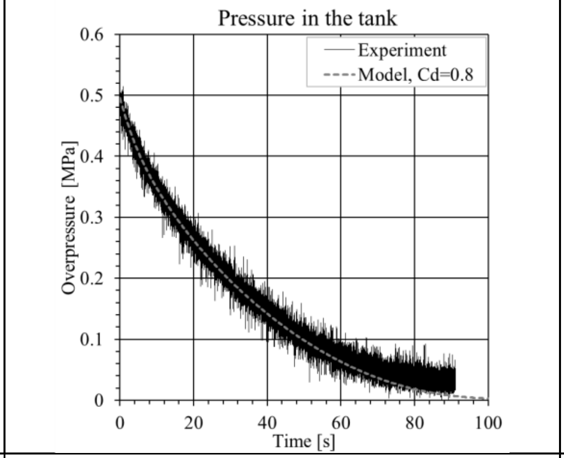
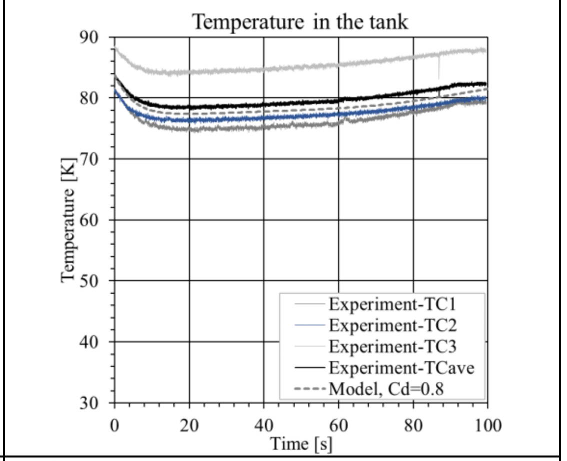
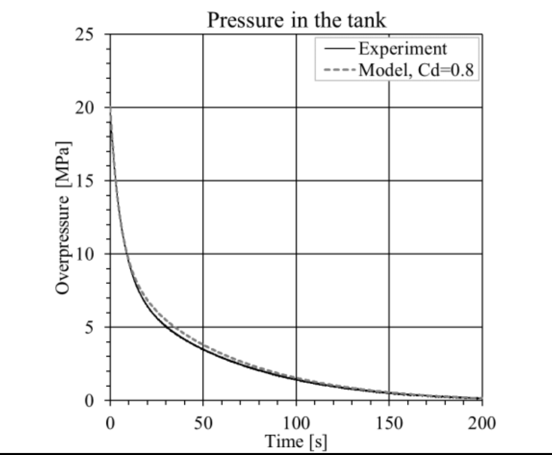
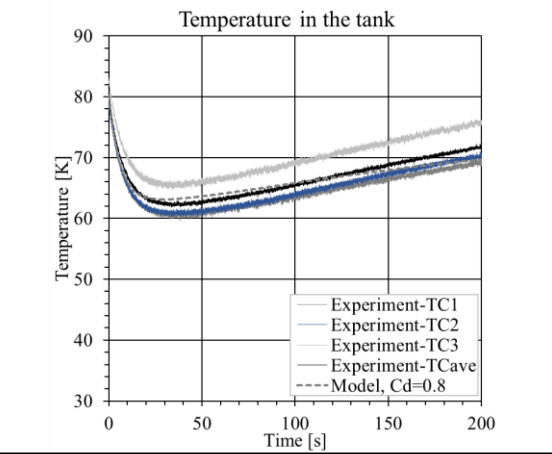


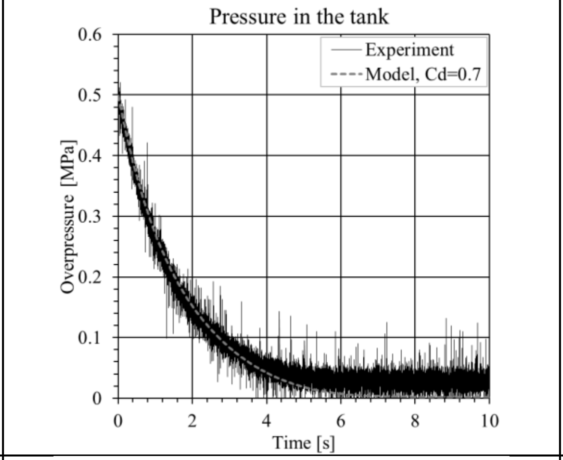
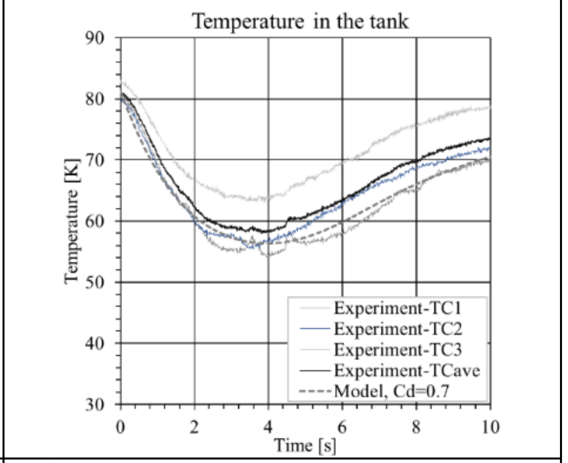
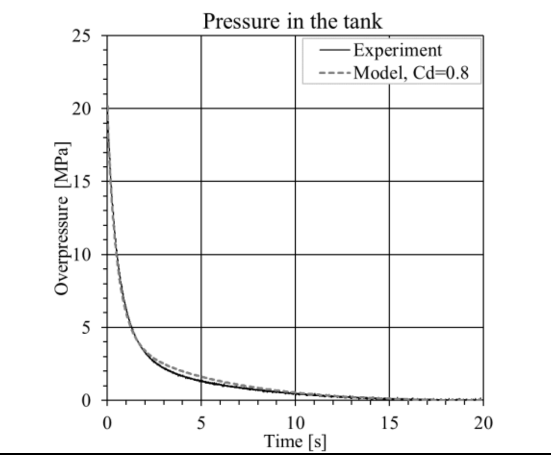
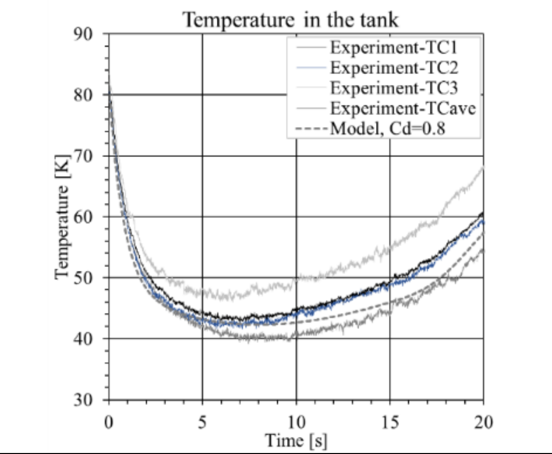
Physical model validation

Tests at initial cryogenic temperature



- 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		

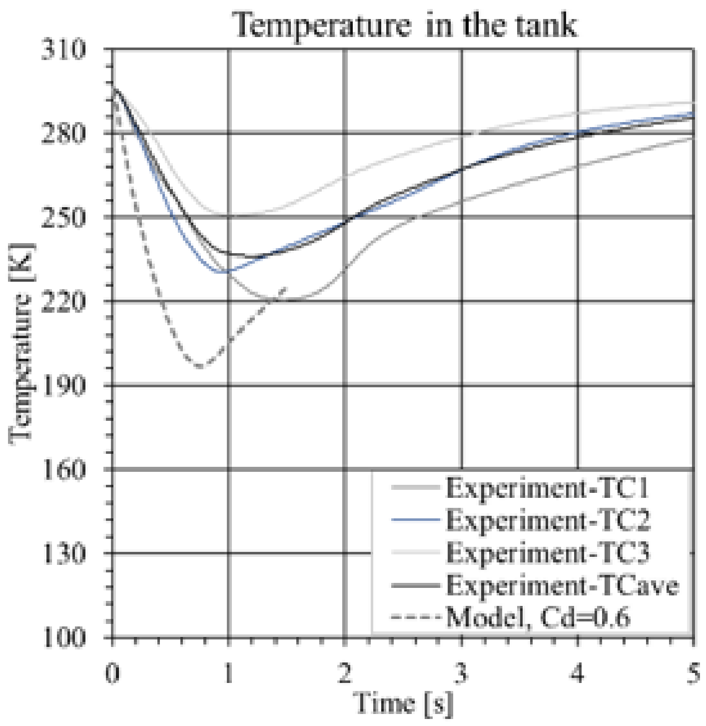
Case	Overpressure dynamics	Temperature dynamics
Test 9c - P_1=0.60 MPa abs, T_1=81.2 K, d_n=2.0 mm		
Test 15c - P_1=20.25 MPa abs, T_1=81.5 K, d_n=2.0 mm		

Physical model validation

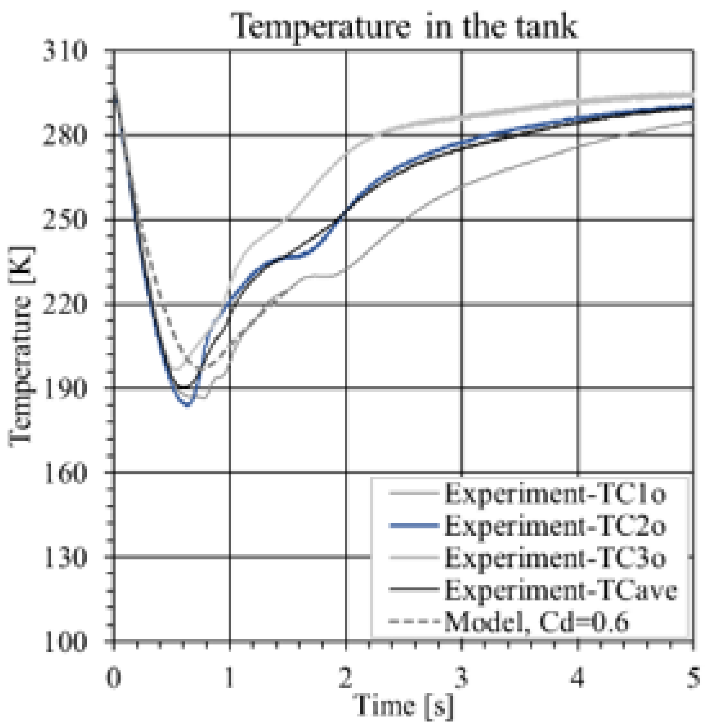
Tests at initial ambient temperature

- Tests with larger 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



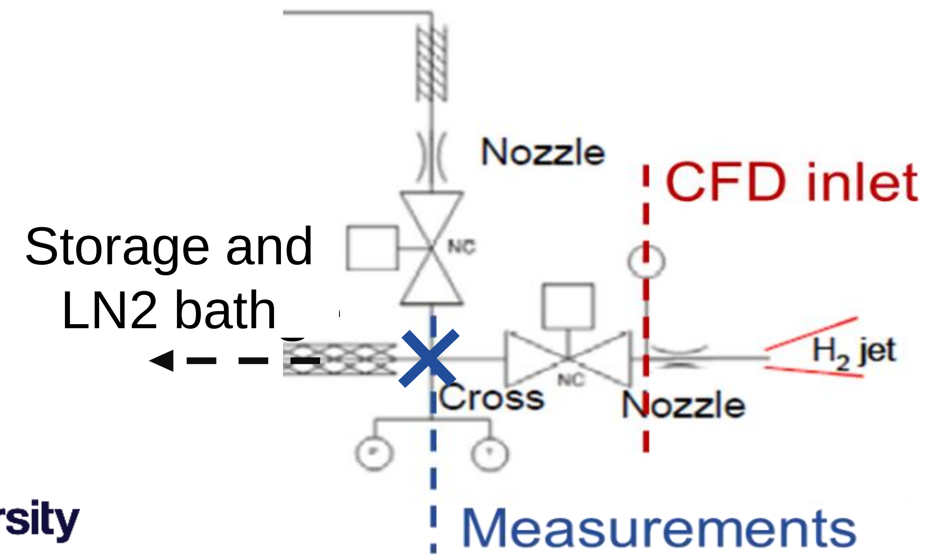
“Open” thermocouples

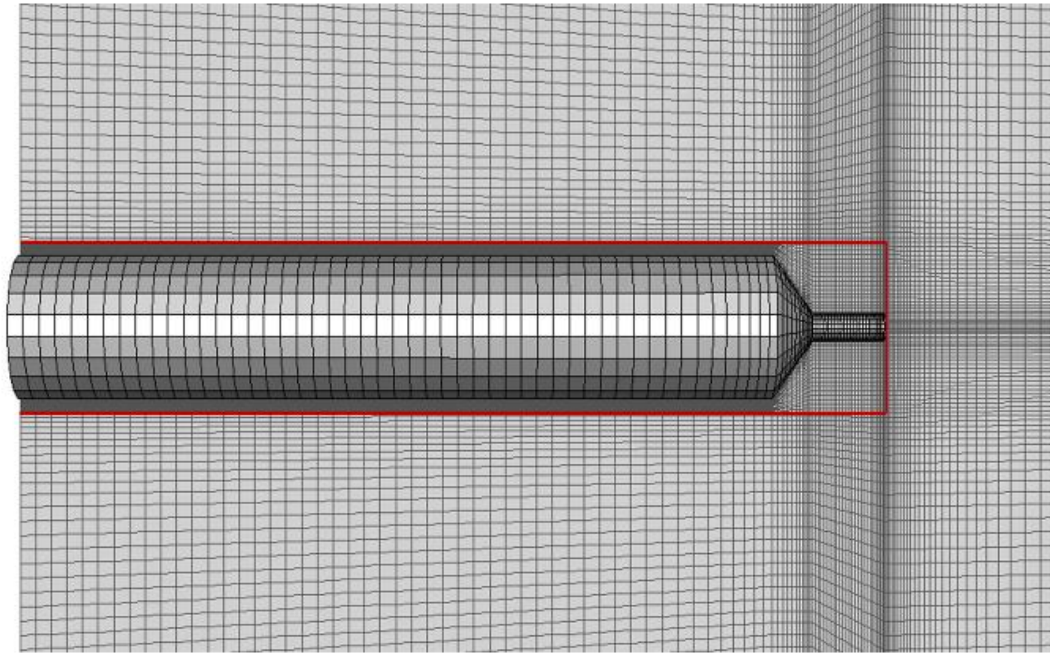


Test 16w:
P_1=0.59 MPa abs,
T_1=296.0 K, d_n=4.0 mm

CFD modelling of cryogenic hydrogen flow in a pipe

- Simulations of cryogenic release experiments performed at KIT (2009) on cryogenic hydrogen jet fires with storage T=80 K, P=0.3-2.0 MPa and d=2 and 4 mm.
- The simple application of the discharge coefficient to match the experimental mass flow rate is not sufficient as the heat transfer to/through the wall of a release pipe connecting the storage system to the nozzle affects the cryogenic flow characteristics.
- A CFD modelling of the cryogenic flow in the pipe is performed to characterise the flow parameters accounting heat transfer between the cryogenic flow, the pipe wall and ambient atmosphere.





Ulster University

Simulation results (1/2)

Modelling of cryogenic hydrogen flow in a pipe

Test 3: T=80 K, P=1.4 MPa, 2 mm

Adiabatic pipe walls:

$\dot{m}_{H2}$ = 4.65 g/s

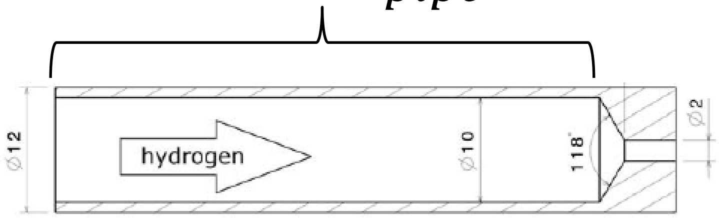
T_n=56 K

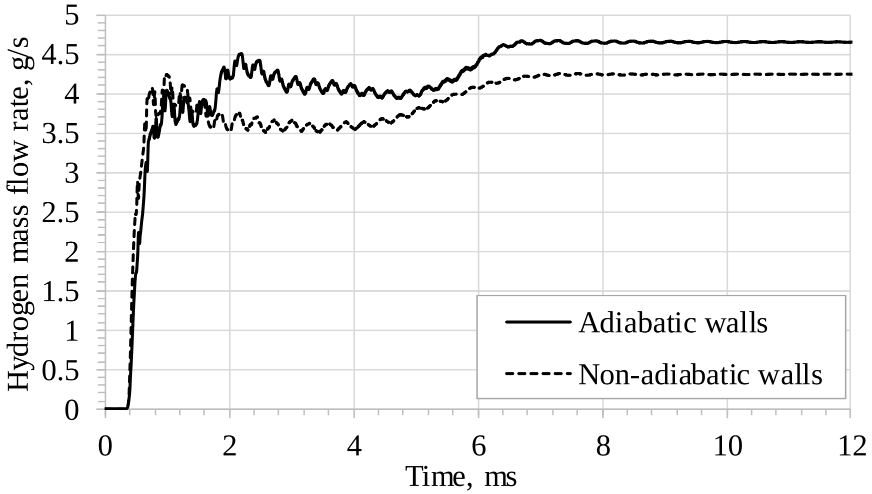
Inclusion of heat transfer through the pipe walls:

$\dot{m}_{H2}$ = 4.25 g/s

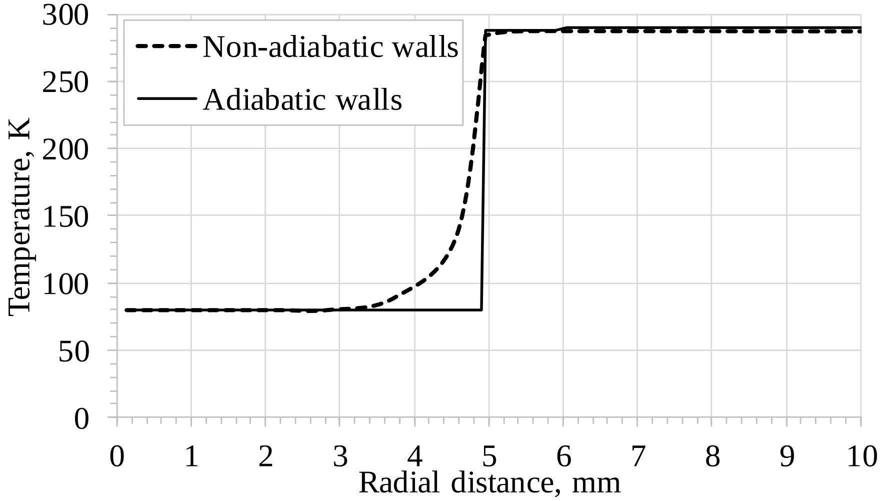
T_n=72 K

75% Q_{pipe}

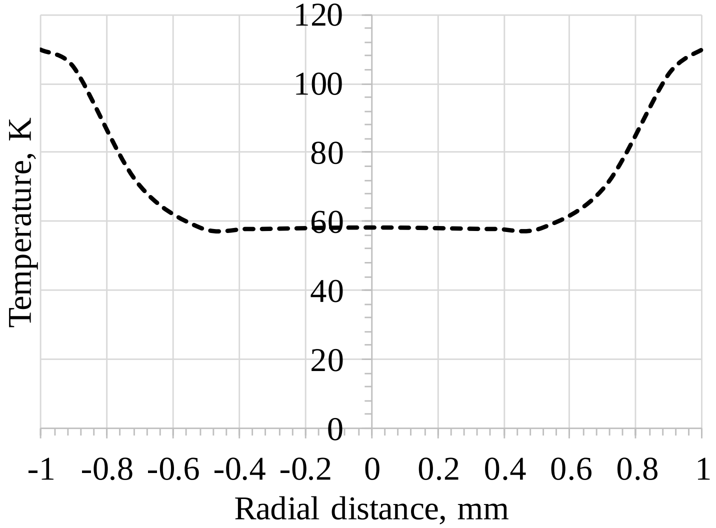


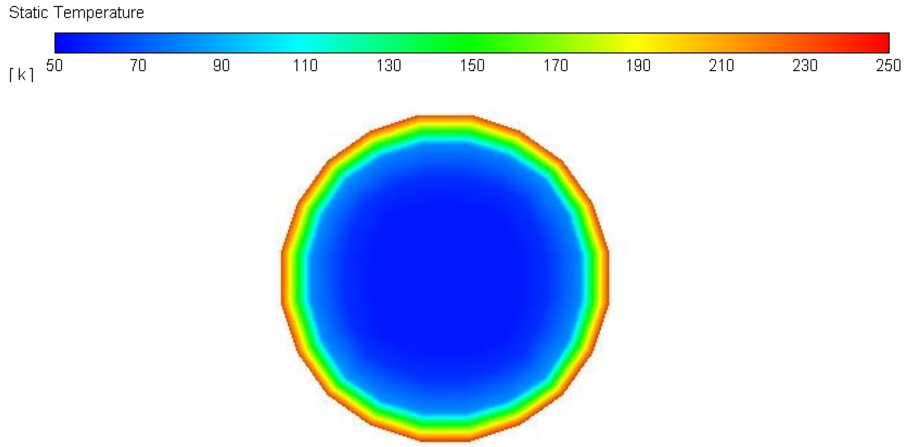


Hydrogen mass flow rate



Temperature distribution at 50 mm axial distance at 12 ms.





Temperature distribution at the real nozzle exit at 12 ms: non-adiabatic pipe walls

Simulation results (2/2)

Modelling of cryogenic hydrogen flow in a pipe

Simulated parameters at the real nozzle exit and adjustment of inlet conditions

- "Measured": the inlet temperature to the pipe is defined as the measurement at the "cross" upstream the release pipe.
- "Adjusted": the inlet temperature to the pipe is modified to include the effect of heat transfer in the release system upstream of the simulated 60 mm release pipe ending with the real nozzle.

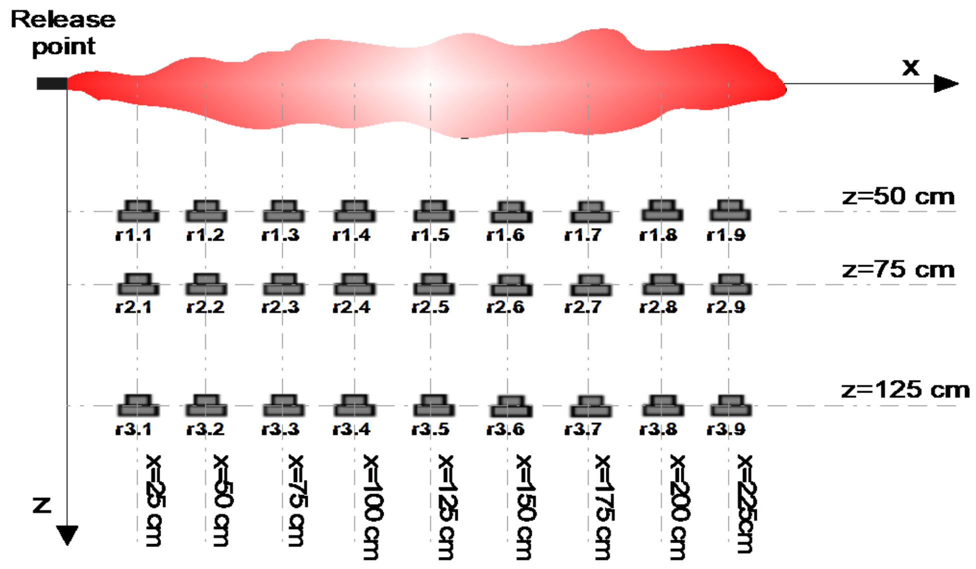
Test No.		3		4		5		6	
Inlet boundary conditions (BC)		Measured	Adjusted	Measured	Adjusted	Measured	Adjusted	Measured	Adjusted
Inlet BC	Temperature, K	80	140	80	150	80	110	80	110
	Pressure, MPa	1.4	1.4	2	2	0.3	0.3	0.4	0.4
Real nozzle exit	Diameter, mm	2	2	2	2	4	4	4	4
	Temperature, K	71.4	120.7	70.7	126.7	75.9	100.0	73.3	98.4
	Velocity, m/s	798.7	967.5	801.2	989.2	746.1	835.9	750.9	844.7
	Variation of calculated $\dot{m}_{H2}$ from experiment, %	22.4	-0.6	27.8	3.6	15.0	1.2	15.4	1.6

Calculated **notional nozzle exit** parameters accounting for the effect of conjugate heat transfer in the release pipe and hydrogen path downstream to the location "cross" with measured temperature and pressure.

Test No.	3	4	5	6
Temperature, K	120.6	126.8	99.4	97.7
Velocity, m/s	834.4	855.6	757.4	751.0
Density, kg/m^3	0.204	0.194	0.247	0.252
Diameter, mm	5.0	6.0	4.8	5.6

Validation of simulations

Modelling of cryogenic hydrogen jet fires

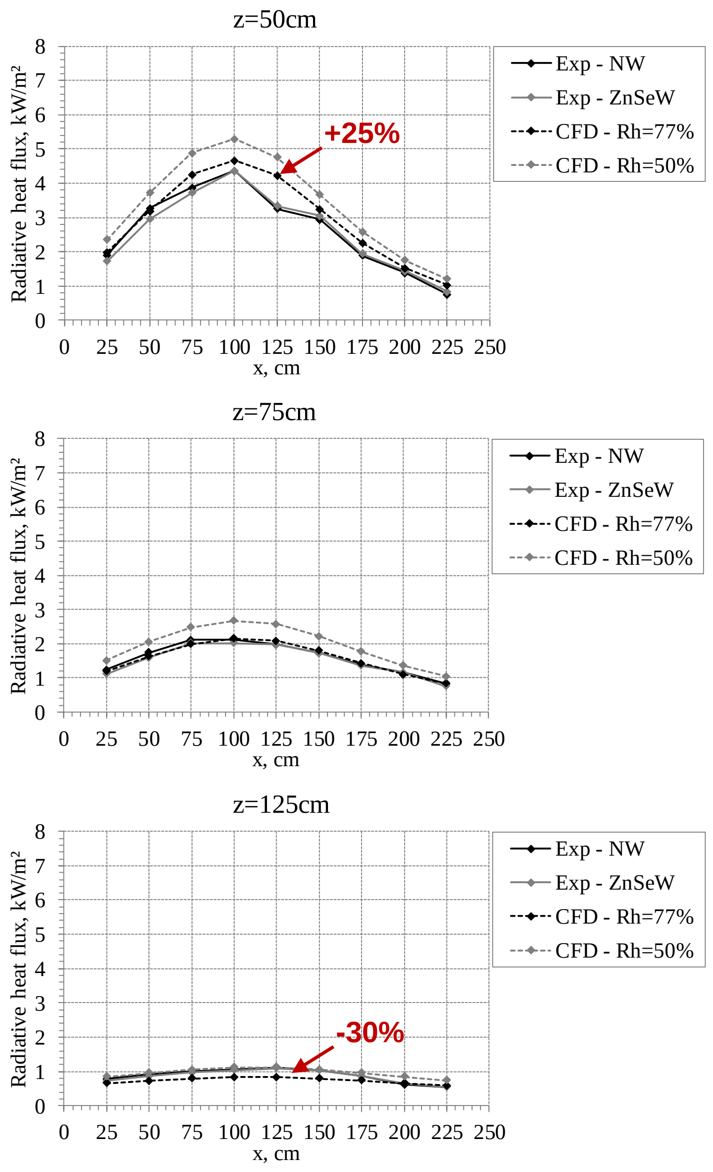


Test 3, Rh=77%: prediction accuracy is within 10%, with few exceptions at z=50 cm and z=125cm.

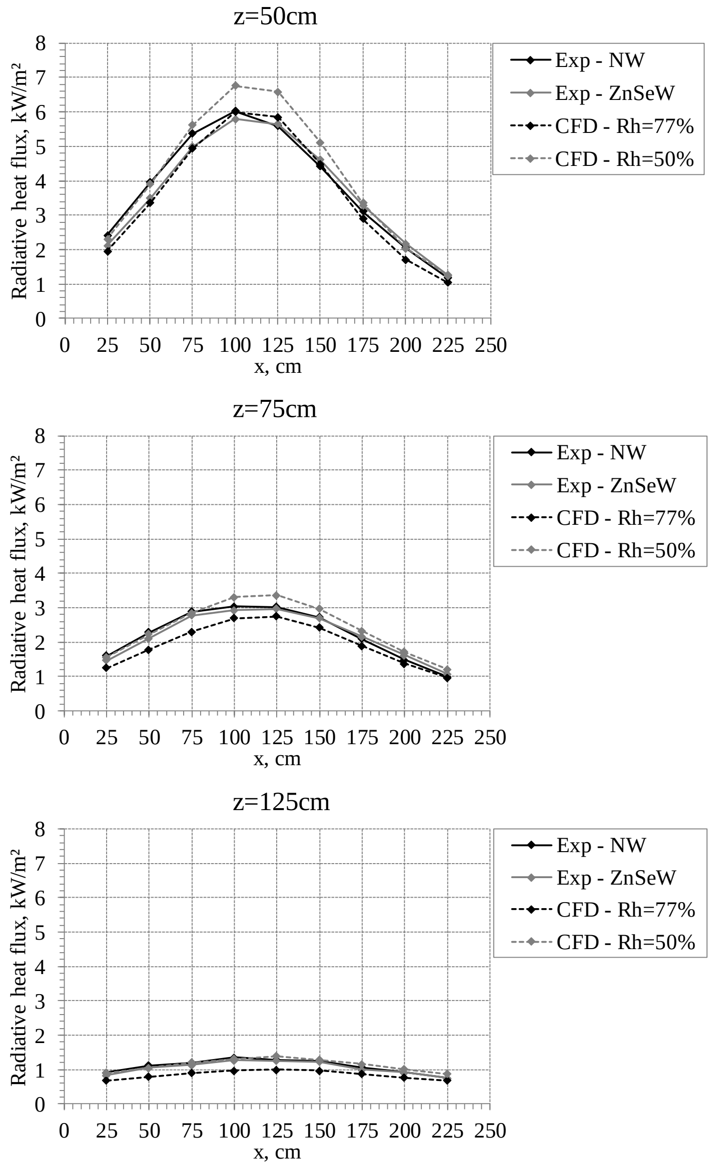
Test 5, Rh=77%: prediction accuracy is within 10%, for sensors at z=50 cm. Measurements at z=125cm are underpredicted (up to -40%).

Test 3 and 5, Rh=50%: predictions overlap with experiments at z=125cm.

Test 3: *D*=2 mm, P=1.4 MPa



Test 5: *D*=4 mm, P=0.3 MPa



Hazard distances by temperature

Horizontal jet fires under investigation

- A jet fire leads to the production of hot currents harmful to people. Molkov (2012) correlated the temperature distribution along a jet fire trajectory from experiments to the distance normalised by the flame length in order to derive hazard distances for people.

Harm level (LaChance et al., 2011)	Hazard distances	
	Vertical jet fires	Horizontal jet fires*
“No-harm”: 70°C for any exposure duration	x=3.5L_f	x=2.2L_f
“Pain”: 115°C for 5 minutes exposure	x =3L_f	x =2.1L_f
“Fatality”: 309°C, third-degree burns for 20 s exposure	x =2L_f	x =1.75L_f

*along the flame tilting axis

- The buoyancy of combustion products reduces the “no harm” distance from x=3.5L_f for vertical jet fires to x=2.2L_f for horizontal jet fires.

- Conclusions and change of multiplier in hazard distance between vertical and horizontal jet are valid for these particular experiments.

Hazard distances by thermal radiation

Horizontal jet fires under investigation

Thermal radiation emitted by the jet fire in its surroundings:

- “No-harm” distance (1.6 kW/m^2) along the horizontal jet fire direction corresponds to x=3.2L_f, which is larger than hazard distance by temperature “no-harm” criteria.
- “First-degree burns” hazard distance (4.0 kW/m^2) along the jet fire direction corresponds to x=2.1L_f.
- “First-degree burns” hazard distance (4.0 kW/m^2) on the side of the horizontal jet fire is about 3.5 times shorter than hazard distance in axial direction.
- “No-harm” distance on the sides of the horizontal jet fires resulted > 2.7 m (domain size).

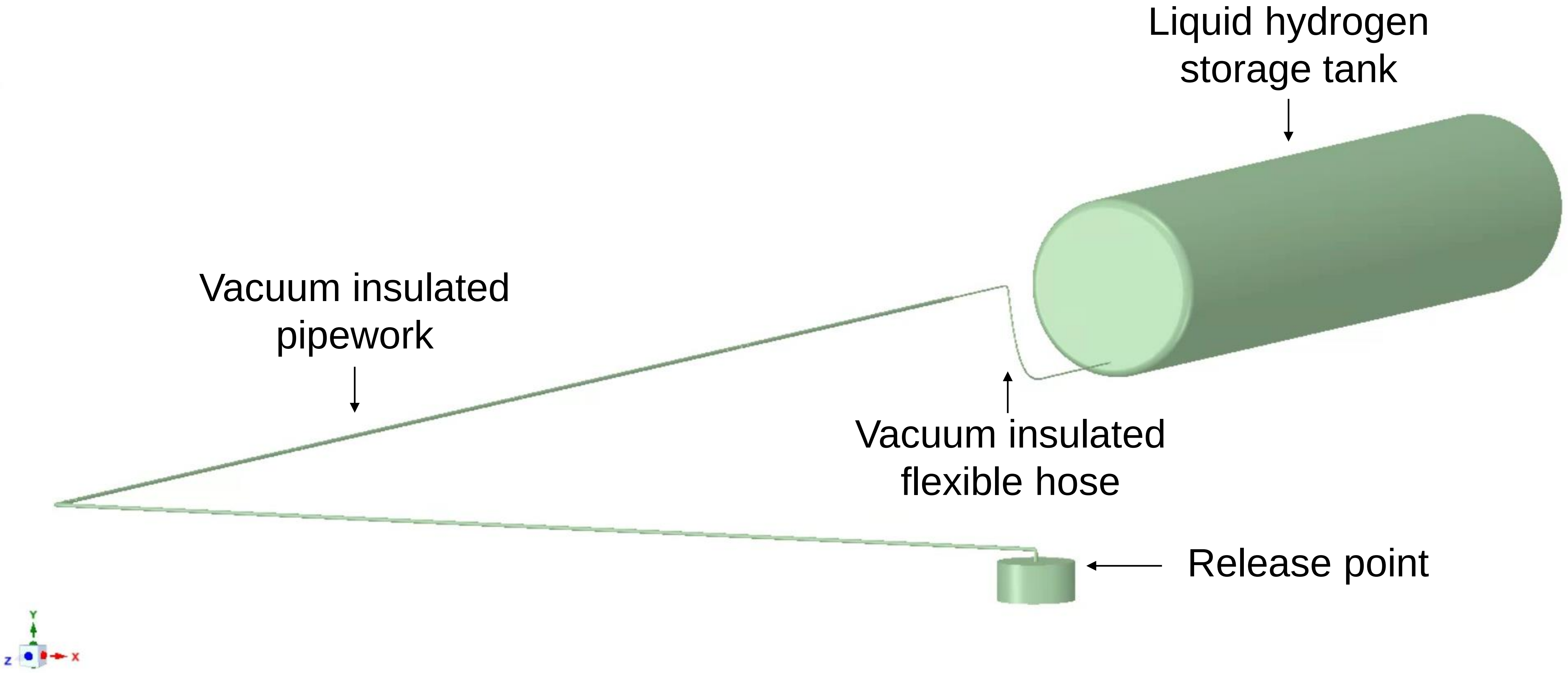
The thermal dose calculates the harm level as a function of exposure duration and incident thermal radiation:

$$TD = \int_0^t I(t)^{4/3}\,dt$$

- The thermal dose is a valuable tool to assess the feasibility of short-term activities and emergency operations.
- Firefighters can stand without harm as close as 0.71 m to the jet fire axis for a time < 168 s.

CFD modelling of LH2 flow in a pipework system

Ongoing research



Conclusions

- A physical model has been developed and validated 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.
- CFD simulations demonstrated that the heat transfer through the pipe wall increases temperature at the real nozzle exit depending on storage pressure and nozzle diameter. Heat transfer effect shall be included into modelling to reproduce mass flow rates for hydrogen safety engineering.
- For horizontal jet fires, the buoyancy of combustion products may have a significant mitigating effect on the reduction of hazard distances compared to vertical releases.
- A throughout assessment of thermal hazards and associated distances from a hydrogen jet fire should combine the analysis of temperature, thermal radiation and thermal dose, as these are found to be complementary to each other.

Ulster University

Ulster University

Thank you for your attention!

This research has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking (now Clean Hydrogen Partnership) under grant agreement No.779613 (PRESLHY), No.826193 (HyTunnel-CS), No.875089 (HyResponder) and No. 101101381 (ELVHYS). ELVHYS project is supported by the Clean Hydrogen Partnership and its members. UK participants in Horizon Europe Project ELVHYS are supported by UKRI grant numbers 10063519 (University of Ulster) and 10070592 (Health and Safety Executive).

Disclaimer: Funded by the European Union. Views and opinions expressed are however those of the authors only and do not necessarily reflect those of the European Union or the Clean Hydrogen Partnership. Neither the European Union nor the Clean Hydrogen Partnership can be held responsible for them.

Clean Hydrogen Partnership

Co-funded by the European Union

UK Research and Innovation