Pro-Science/KIT experimental work on cryogenic H_2 releases as part of the PRESLHY project

A. Friedrich, A. Veser, M. Kuznetsov, A. Denkewitz, W. Breitung, N. Kotchourko, J. Gerstner, J. Rietz, T. Jordan

ELVHYS-Workshop “Experimental research and case studies of cryogenic hydrogen incidents”

28.-30.11.2023, Buxton (UK)

ELVHYS project No. 101101381 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)

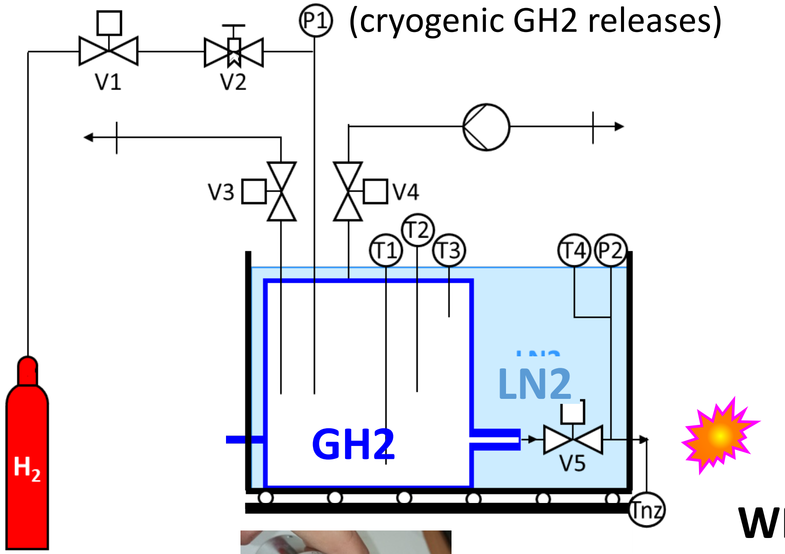
Overview

PS/KIT-Experiments for the PRESLHY-Project

WP3.1a & WP5.1

Unignited & Ignited DISCHA-Experiments

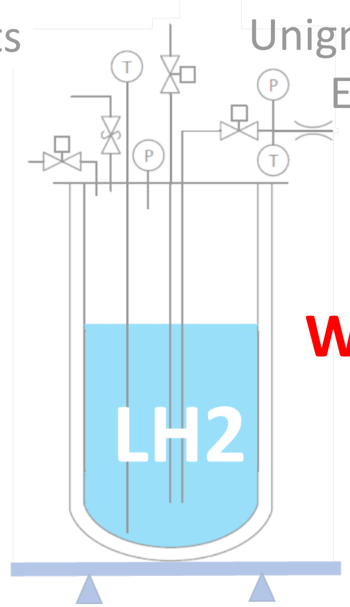
(cryogenic GH2 releases)



WP3.1b

Unignited CRYOSTAT-Experiments

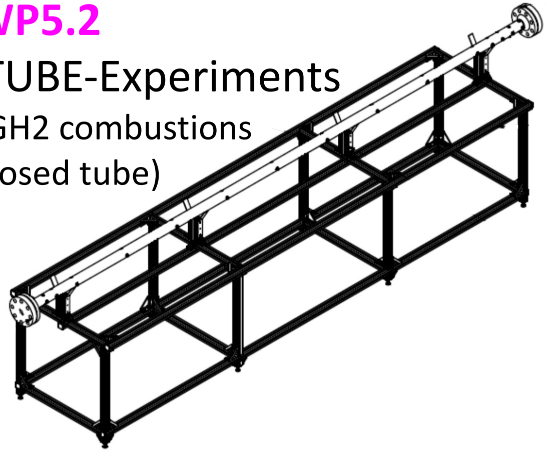
(cryogenic LH2 releases)



WP5.2

Ignited CRYOTUBE-Experiments

(cryogenic GH2 combustions in a closed tube)

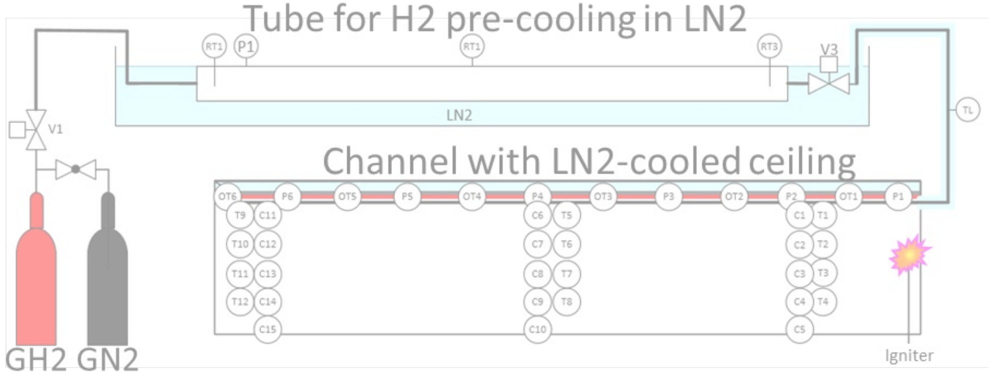


Will be omitted due to time constraints

WP5.3

Unignited & Ignited COLDCHANNEL-Experiments

(cryogenic semiconfined GH2 combustions)



WP4.2

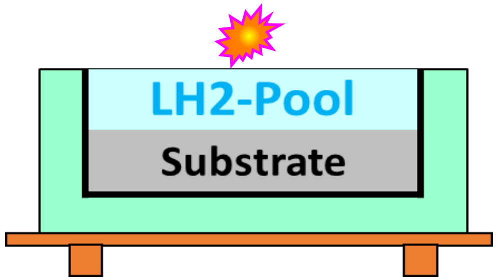
Electrostatic Field Measurements

(cryogenic GH2 & LH2 releases)

WP3.4 & WP4.4

Unignited & Ignited POOL-Experiments

(LH2-pool formation, evaporation and ignition)



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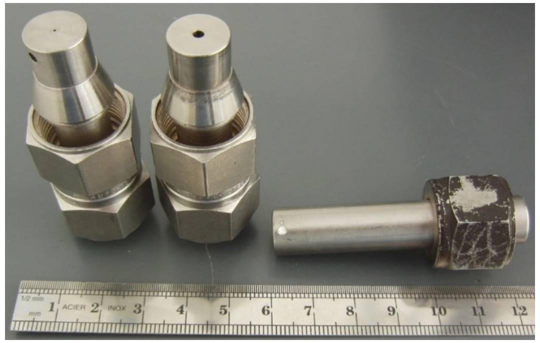
DISCHA-Experiments

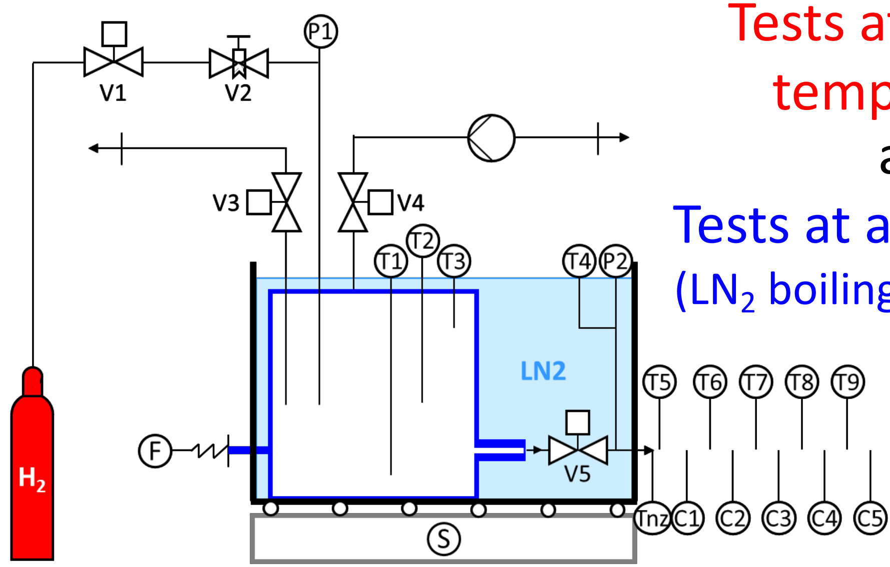
Main features of the DISCHA pressure vessel

- Designed for investigation of blow-down behavior of cryogenic hydrogen stored at elevated pressure and its dispersion in surrounding air,
- stainless steel vessel (Di = 160 mm, Hi = 140 mm, V = 2.81 dm^3)
- designed for gaseous releases (p up to 200 bar, T down to 80 K).
- Circumference equipped with:
  - 2 nozzle ports (di = 12 mm, only lower port used),
  - 1 rod opposite to nozzle ports for connection with force sensor.
- Nozzle Properties (release line: di = 10 mm):
  - 4 Nozzles with circular apertures d_i = 0.5, 1, 2 and 4 mm.



DISCHA-Experiments

DISCHA-Facility Instrumentation (UNignited experiments)



Tests at ambient temperature
and
Tests at approx. 80 K
(LN_2 boiling temperature)

DISCHA-facility (in tent behind KIT-HYKA) equipped with:

- 1 static pressure sensor in vessel and 1 dynamic pressure sensor close to nozzle
- 3 thermocouples in vessel, 1 close to nozzle and 5 downstream the nozzle,
- 5 sampling positions for H2-concentration measurements downstream the nozzle,
- 1 scale and 1 force sensor

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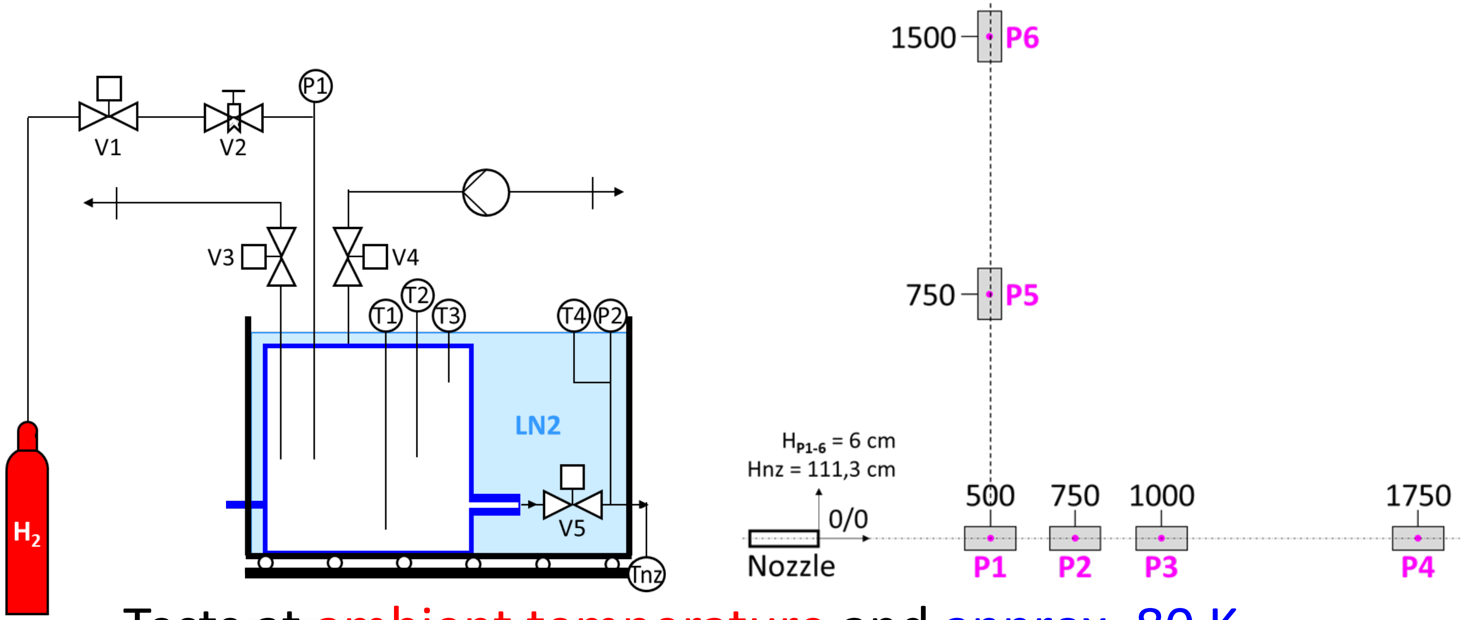
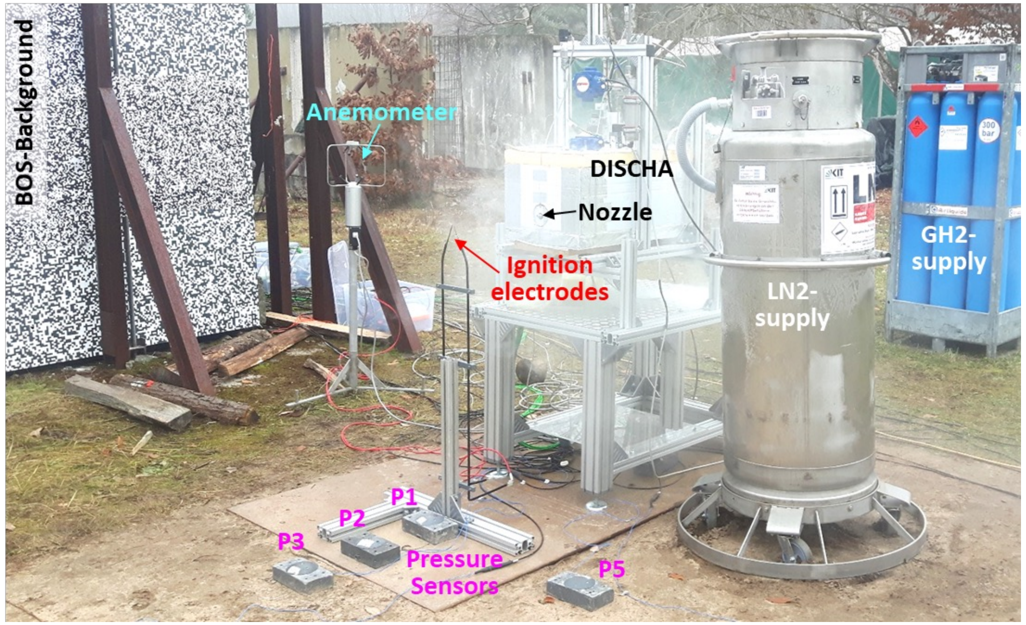
DISCHA-Experiments

DISCHA-Facility Instrumentation (ignited experiments)





Tests at ambient temperature and approx. 80 K

DISCHA-facility (on free field test site) equipped with:

- 1 static pressure sensor in vessel and 1 dynamic pressure sensor close to nozzle
- 3 thermocouples in vessel, 1 close to nozzle,
- Neither temperature nor H2-concentration measurements downstream the nozzle,
- Ignition electrodes and 6 fast dynamic pressure sensors on ground,
- Neither scale nor force sensor.

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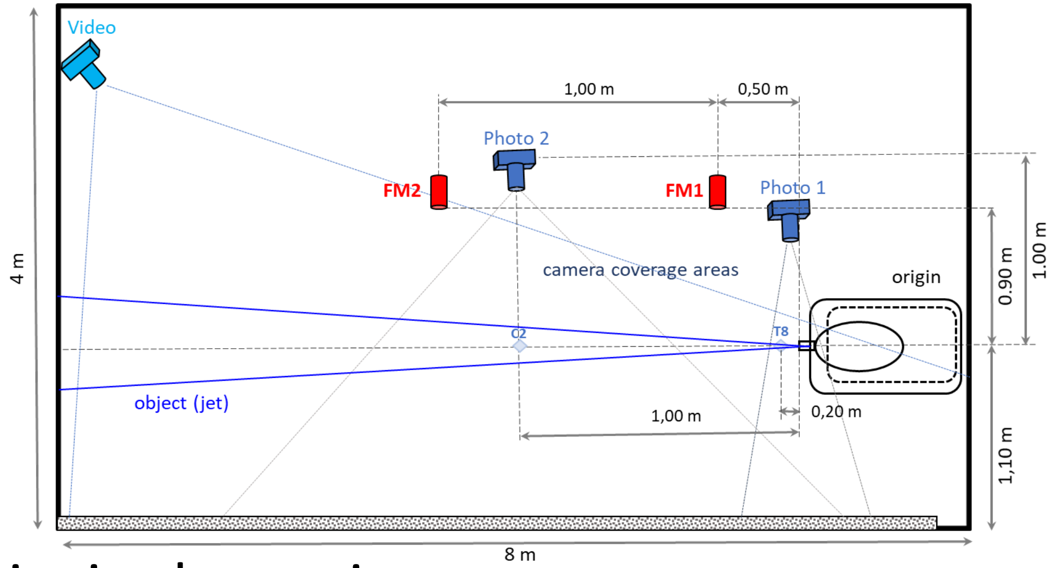
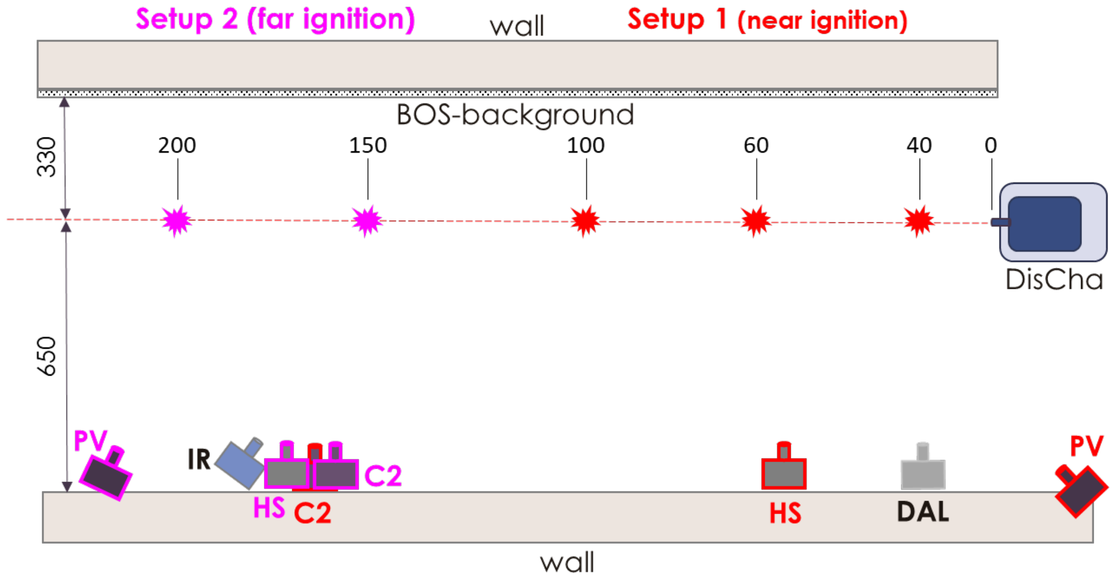
DISCHA-Experiments

DISCHA-Facility Optical and additional equipment

Photos/Videos processed using different BOS-procedures optimized for different jet-regions.





Unignited experiments:

- 2 Photo-cameras (Canon EOS5D Mark I & II)
- 1 Panasonic video camera
- 2 Field mills (FM, electrostatic field),

Ignited experiments:

- **HS**: PHOTRON FastCAM SA 1.1 (≤ 5.000 fps)
- **DAL**: DALSA video camera (70 fps)
- **PV:** Panasonic video camera (24 fps)
- **C2**: CANON EOS5D Mark II
- **IR**: Thermocamera FLIR T450 (IR)

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DISCHA-Experiments

Test matrix Unignited Experiments

- Test matrix for unignited DISCHA-experiments: 7 initial pressure stages x 4 nozzle diameters x 2 initial temperatures = 56 cases, all cases tested at least once,
- Up to 7 repetitions to check reproducibility (facility improved several times),
- In total > 200 experiments performed.

		Nozzle diameter [mm]			
		0.5	1	2	4
Pini [bar]	5	A/C	A/C	A/C	A/C
	10	A/C	A/C	A/C	A/C
	20	A/C	A/C	A/C	A/C
	50	A/C	A/C	A/C	A/C
	100	A/C	A/C	A/C	A/C
	150	A/C	A/C	A/C	A/C
	200	A/C	A/C	A/C	A/C

A: ambient temperature (290 K) C: cryogenic temperature (80 K)

Theoretical Utilization of Experimental Data

- Data of unignited DISCHA-experiments used by PRESLHY-Partners for validation of models on blowdown behavior of cryogenic GH2.

(1) S. Giannissi, A. Venetsanos et al.: Cold hydrogen blowdown release: an inter-comparison study; International Conference on Hydrogen Safety - Online, Edinburgh, United Kingdom, Sept. 21-24 2021

(2) Cirrone, D., Molkov, V. et al.: Modelling the non-adiabatic blowdown of pressurised cryogenic hydrogen storage tank; International Conference on Hydrogen Safety 2023 (ICHS2023), Quebec, Kanada, 19.–21.09.2023

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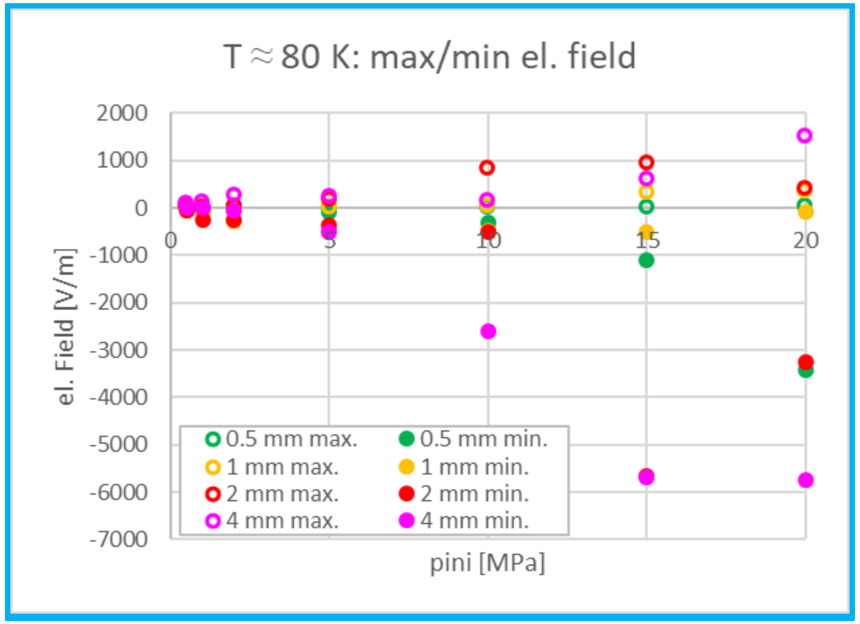
DISCHA-Experiments

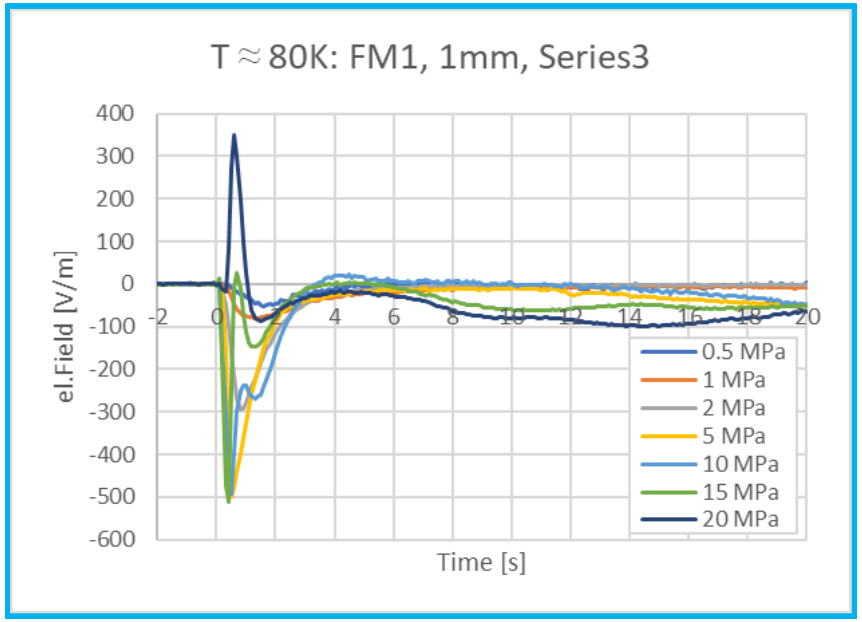
Unignited Experiments: Electrostatic field measurements (WP4.2)

- No ignition due to electrostatic discharge observed in complete experimental program,
- Highest positive and lowest negative electric field values measured for **T ≈ 80 K:**



- Max. field values >> 1000 V/m measured,
- Most extremal values measured for largest d_{noz} (4 mm) and highest p_{ini} (20 MPa),

➔ **Assumption:**
Electrostatic field built-up during release mainly connected with ice crystals due to frozen humidity at cold nozzle prior to release.



Reproducibility

- Extremal field values within a series mostly consistent,
- Extremal field values always at t < 1 s,
- Within few hours positive **and** negative values measured.

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DISCHA-Experiments

Test Matrix Ignited Experiments

- Test matrix of main ignited DISCHA-experiments: 4 initial pressures x 3 nozzle diameters x 5 ignition distances x 2 initial temperatures = 120 cases, Experiments on almost complete test matrix performed for both initial temperatures,
- Variation of ignition delay time in initial test series: ➔ Main series with ignition delay time of 120 ms.

Theoretical Utilization of Experimental Data

- Ignited DISCHA-experimental data used by PRESLHY-Partners for model validation ignited cryogenic H2.

Z. Ren, J. Wen et al.: The evolution and structure of ignited high-pressure cryogenic hydrogen jets; Int J Hydrogen Energy (2022) Volume 47, Issue 50, pp. 21596-21611

p_{ini} [bar]	d_{ign} [cm]	Nozzle diam. [mm]		
		1	2	4
5	39.5	A/C	A/C	A/C
	62.5	A/C	A/C	A/C
	106.5	A/C	A/C	A/C
	150	-/-	-/C	A/C
	200	-/-	-/C	A/C
50	39.5	A/C	A/C	A/C
	62.5	A/C	A/C	A/C
	106.5	A/C	A/C	A/C
	150	A/C	A/C	A/C
	200	-/C	A/C	A/C
100	39.5	A/C	A/C	A/C
	62.5	A/C	A/C	A/C
	106.5	A/C	A/C	A/C
	150	A/C	A/C	A/C
	200	A/C	A/C	A/C
200	39.5	A/C*	A/C	A/C
	62.5	A/C*	A/C	A/C
	106.5	A/C*	A/C	A/C
	150	A/C	A/C	A/C
	200	A/C	A/-*	A/C

A: ambient temperature (290 K) C: cryogenic temperature (80 K)
* Omitted or pressure slightly below 200 bar due to lack of pressure in H_2-bundle

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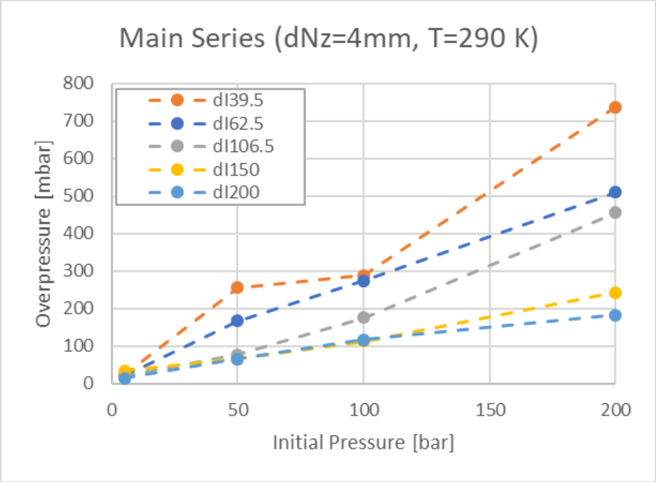
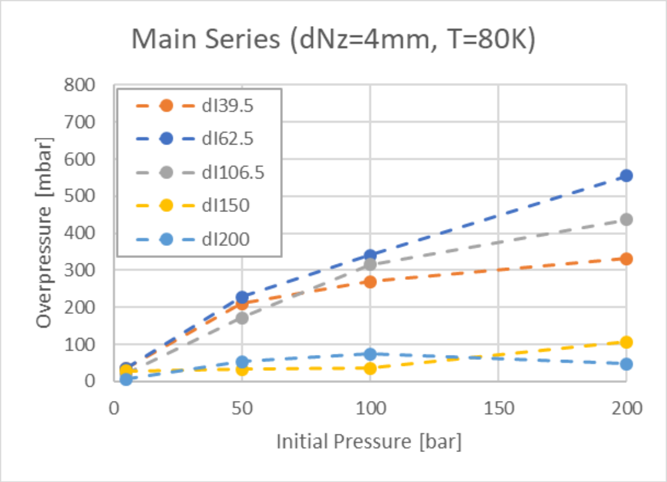
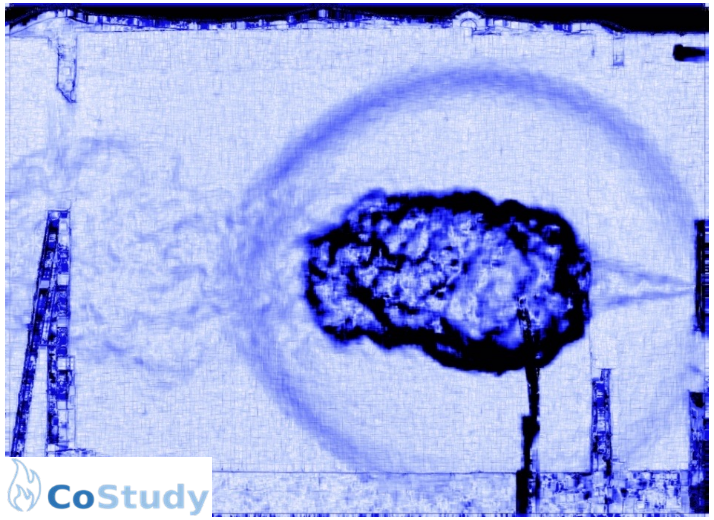
DISCHA-Experiments

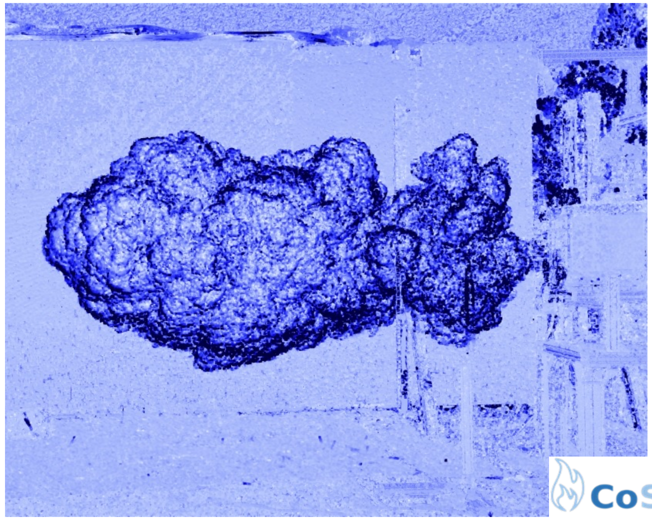
Test Matrix Ignited Experiments

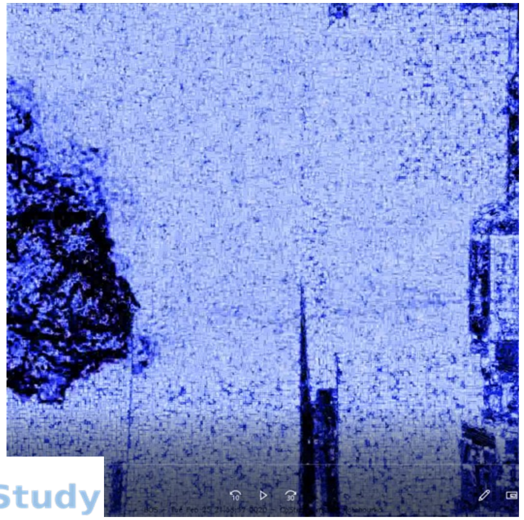
- Warm/cold experiments differ concerning influence of ignition distance on maximum combustion overpressures.
- After ignition flame can either burn back to nozzle or not, determining whether the flame continues to burn when ignition is turned off.
- Pressure waves generated by the ignition could be visualized using the BOS method.











Cryogenic GH2 combustions in tubes

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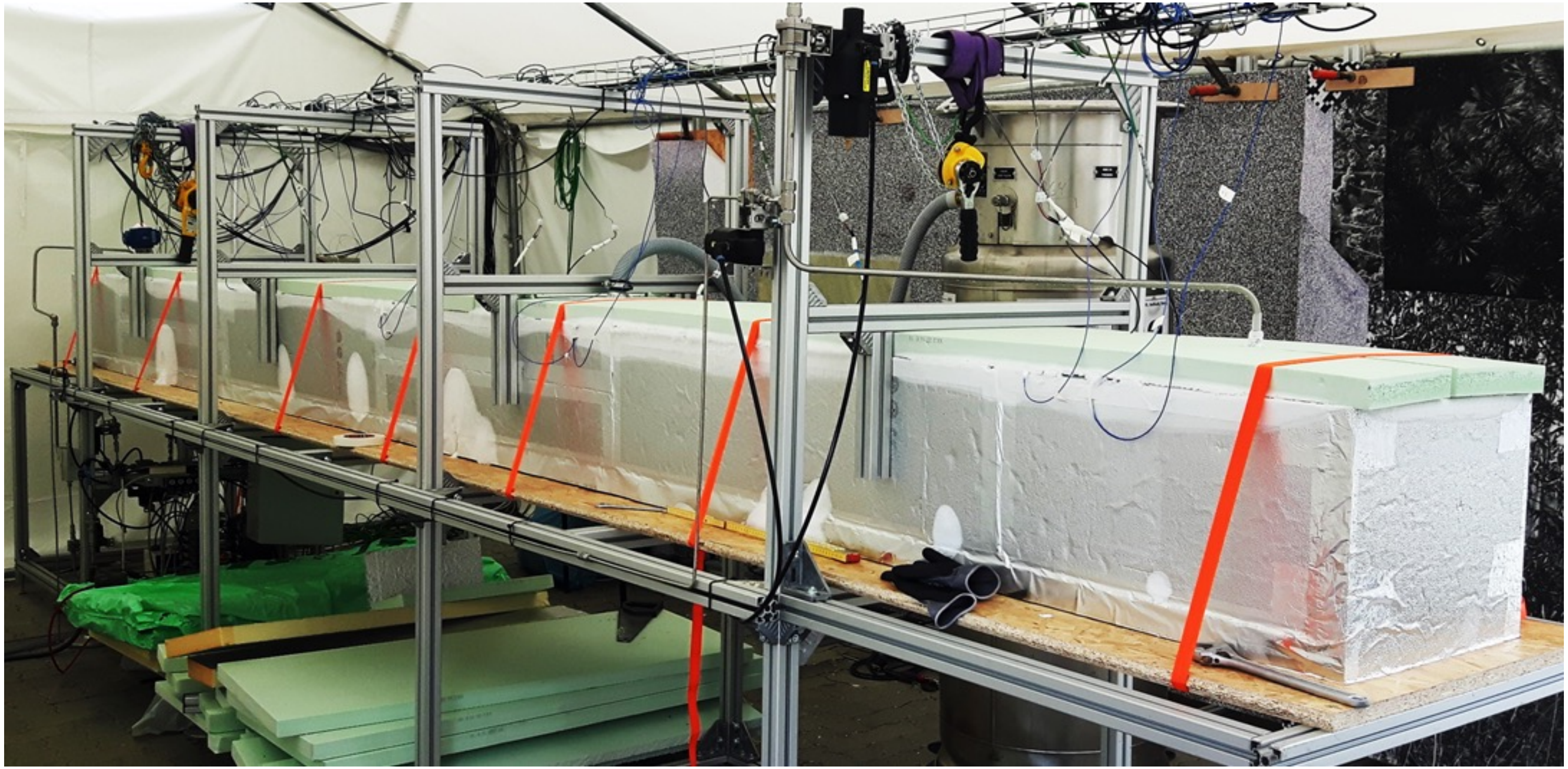

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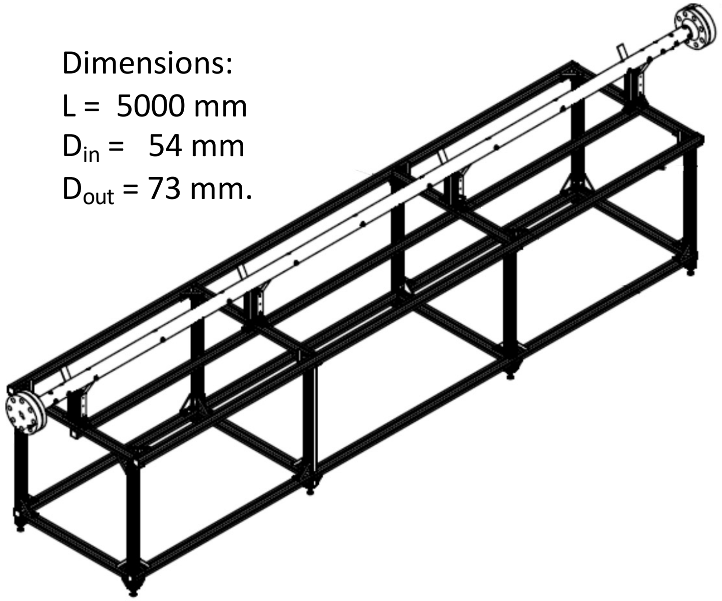
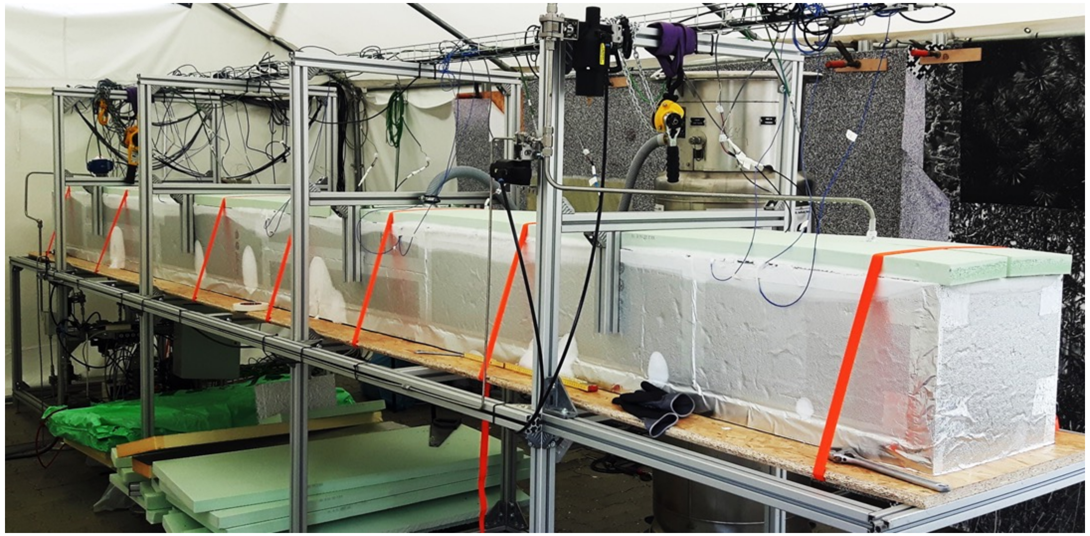
Cryogenic GH2 combustions in tubes

Combustion-Tube

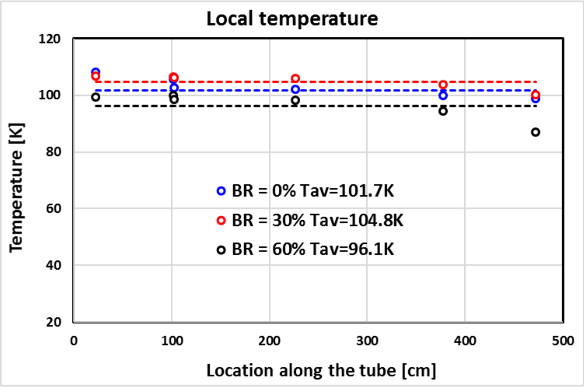
- Combustion of H2-air-mixtures in an obstructed tube at cryogenic temperatures

Dimensions:
L = 5000 mm
D_{in} = 54 mm
D_{out} = 73 mm.

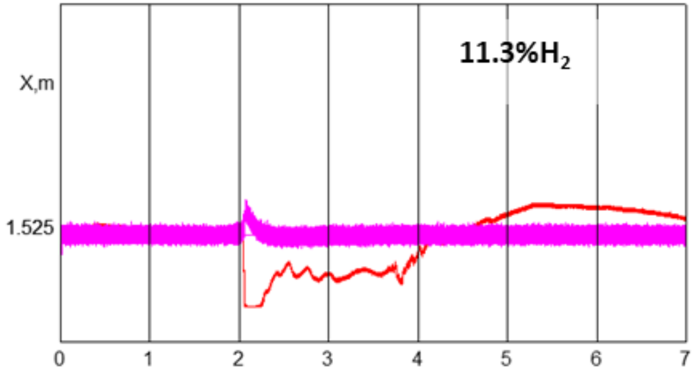




Temperature uniformity



- Tube placed in basin filled with LN2 (77K) to cool it down for cryogenic experiments, uniformity of temperature checked with an array of 6 calibrated thermocouples,
- In experiments flame position detected by:
  - 13 Pressure Sensors (with/without thermal compensation),
  - 15 Phototransistors (InGaAs)



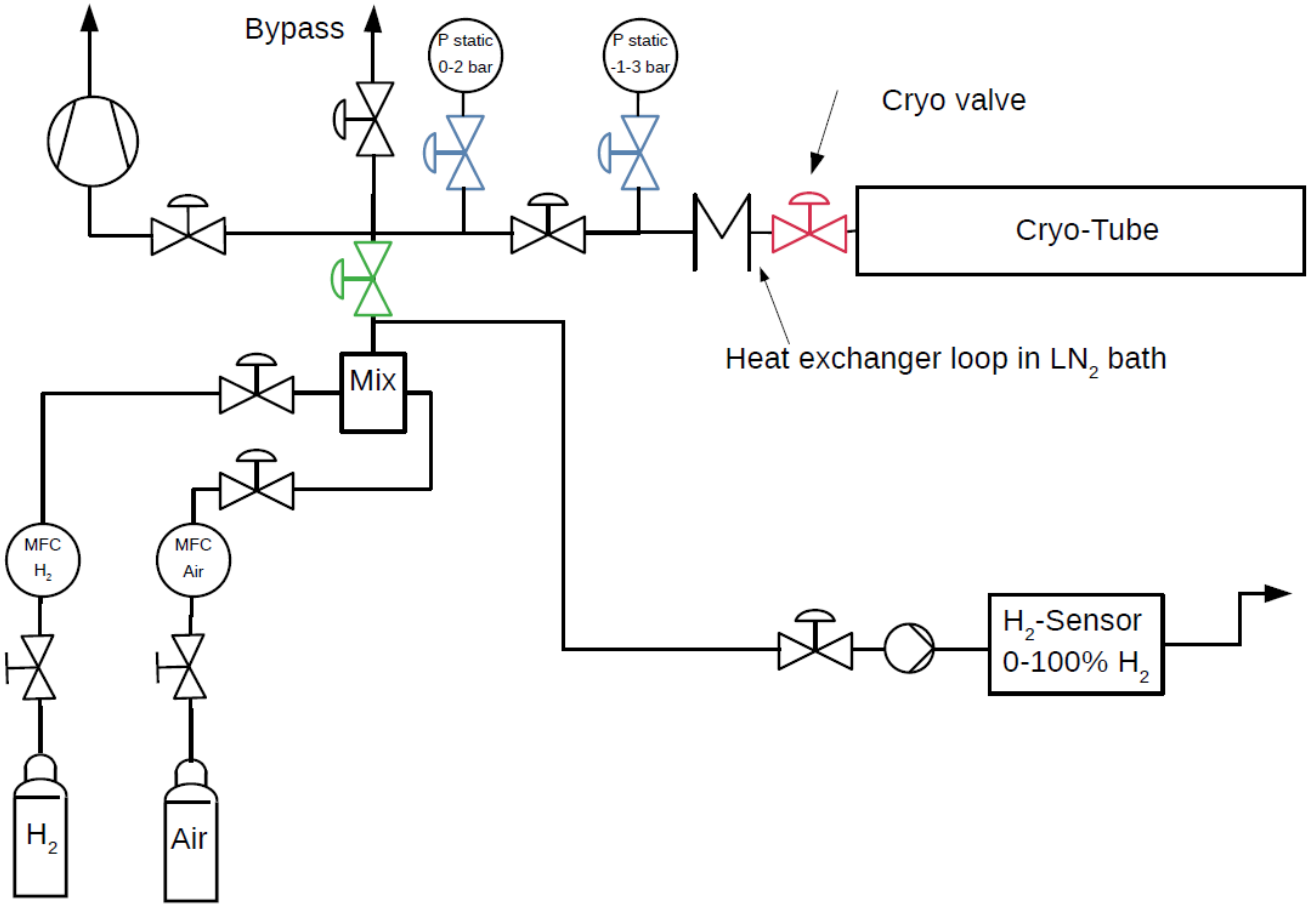
Cryogenic GH2 combustions in tubes

Combustion-Tube: Test Matrix

- Temperatures: ambient (293 K), above LN2-temperature (90-130 K)
- Blockage ratios: 0%, 30% and 60%
- H2-concentrations: 8 to 60 Vol% H2

- Higher hydrogen concentration in mixture leads to lower condensation temperature, mainly for air components

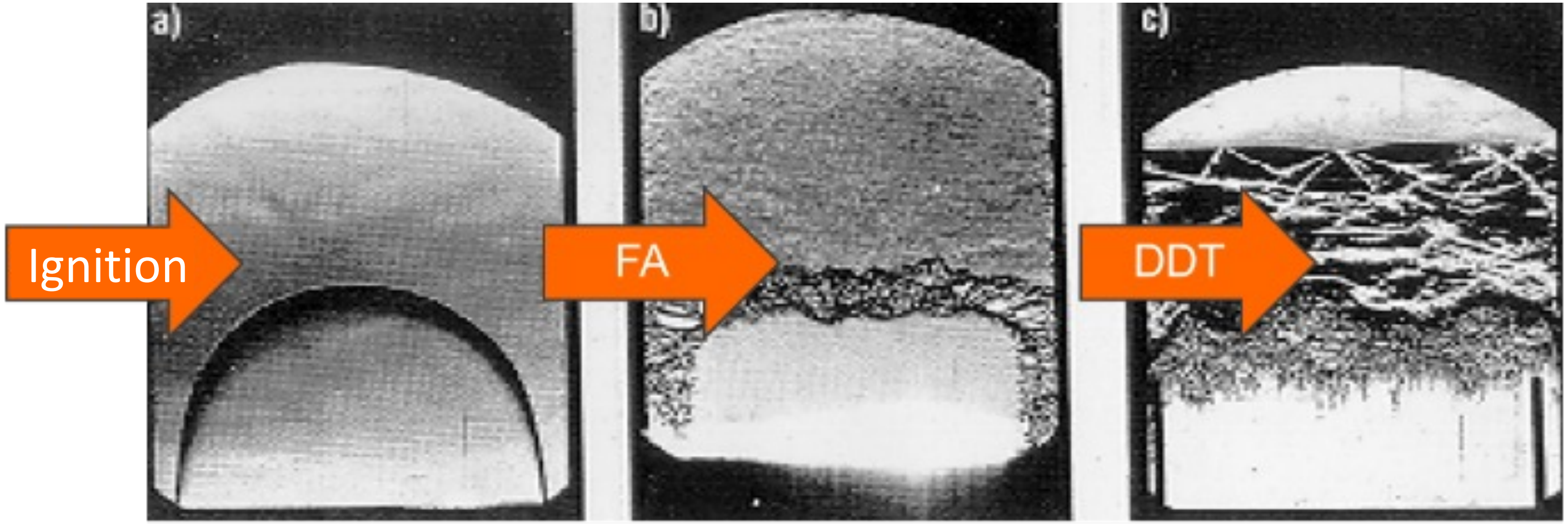
- To cover flammable range, lowest initial temperature should be higher than 80 K to avoid condensation.



Cryogenic GH2 combustions in tubes

Hydrogen Combustion regimes

- For gaseous hydrogen combustions three main combustion regimes are distinguished:

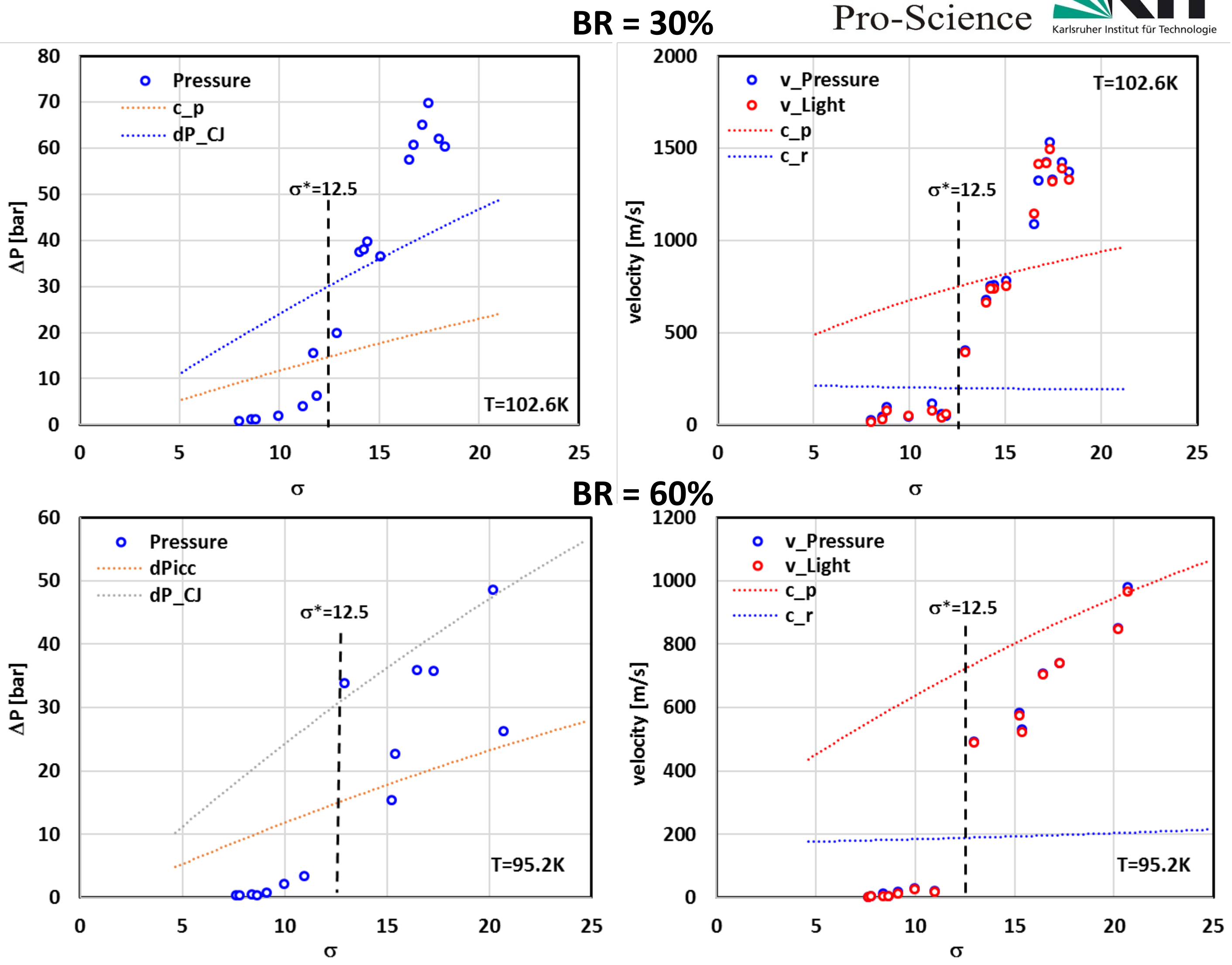


Slow Deflagration (laminar flame)	Fast Deflagration (turbulent flame)	Detonation
v ≈ 1 m/s (Ma << 1), dp ≈ 3 – 5 p_0	v ≈ 300 m/s (Ma ≈ 1), dp ≈ 6 – 9 p_0	v > 1000 m/s (Ma > 1), dp ≈ 15 – 20 p_0

Cryogenic GH2 combustions in tubes

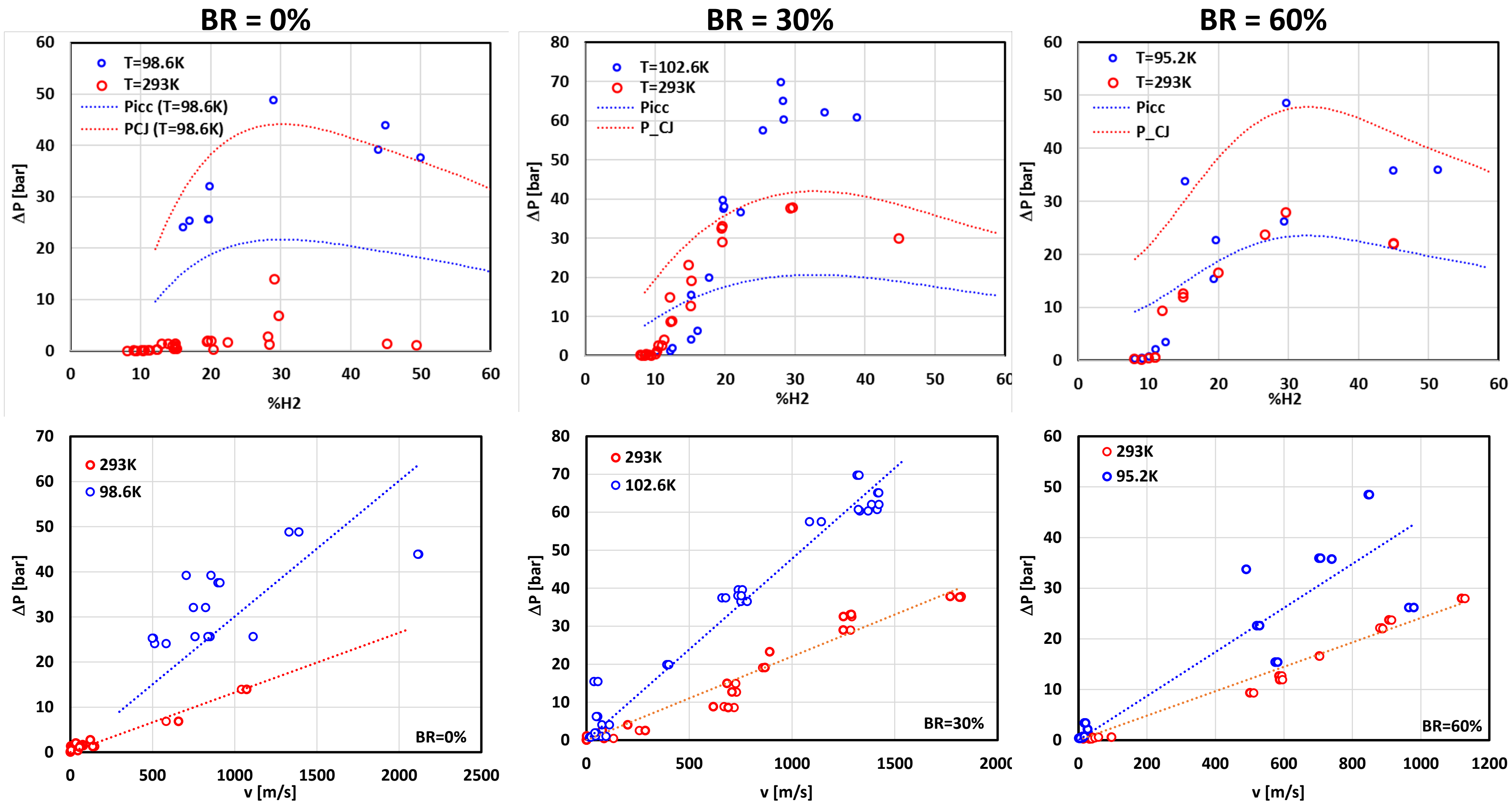
Critical expansion ratio for effective flame acceleration in cold experiments (T = 90 – 130 K)

- For cryogenic temperature T ≈ 100 K critical expansion ratio is σ* = 12.5 (corresponds to 16% H2)
- Detonation achieved when flame speed becomes larger than speed of sound in products (c_p) and approaches theoretical detonation velocity (D_{CJ}).



Cryogenic GH2 combustions in tubes

Comparison of cryogenic combustion with ambient conditions



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Cryogenic GH2 combustions in tubes

Conclusions

- Three typical flame propagation regimes were experimentally observed:
  (1) slow subsonic deflagration, (2) fast sonic deflagration, and (3) detonation.
- Critical conditions for FA evaluated as a function of T_{ini} within range (T_{ini} = >90 - 650 K).
- Detonation cell sizes at cryogenic temperature T = 100 K were evaluated on the basis of existing criteria for detonation onset in smooth and obstructed tubes,
- Maximum combustion pressure at cryogenic temperatures found to be 2-3 times higher than for ambient conditions, resulting in much higher hazard potential of cryogenic combustions, compared to combustions at ambient conditions.
- Run-up distance to detonation at cryogenic temperatures found to be 2 times shorter than at ambient temperature,
- Further information see:

M. Kuznetsov, T. Jordan et al.: Shock tube experiments on flame propagation regimes and critical conditions for flame acceleration and detonation transition for hydrogen-air mixtures at cryogenic temperatures; International Conference on Hydrogen Safety - Online, Edinburgh, United Kingdom, Sept. 21-24 2021

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POOL-Experiments

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POOL-Experiments

Motivation

- Leakages or failures during LH2 transport and refueling lead to LH2-releases that will produce large clouds of GH2 and might even form LH2-pools.
- Pool evaporation and mixing of GH2 with air leads to generation of flammable H2/air clouds that can produce huge temperature and pressure loads in case of ignition.
- Evaporation rates of LH2 from pools above different substrates are of fundamental interest for safety assessments of LH2 applications, but only limited data are available.
- Most data concentrate on free spills above flat grounds and water surfaces, where mostly expansion and shrinking of puddle is investigated and computational models are proposed.
- Only few data is available for confining basins, in which LH2-pools of considerable depth might form and where evaporation is governed by heat transfer from ground material.

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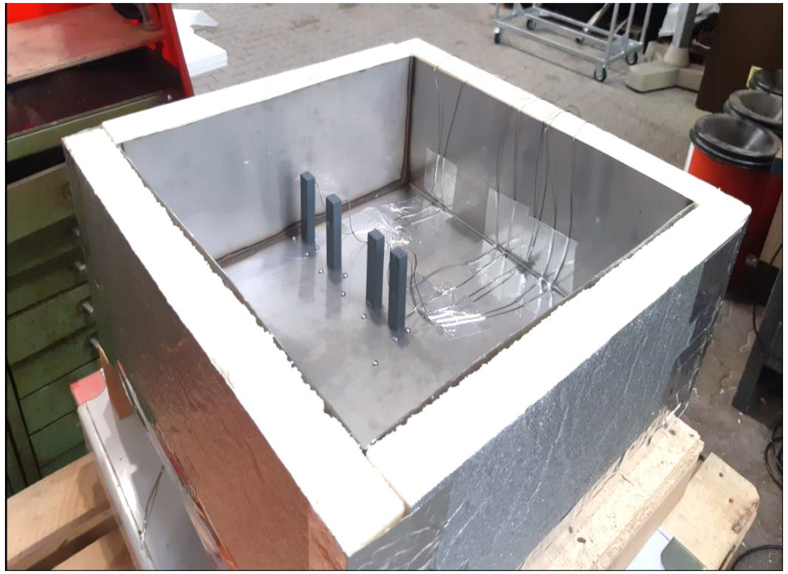
POOL-Facility, test procedure and test matrix

Pool properties

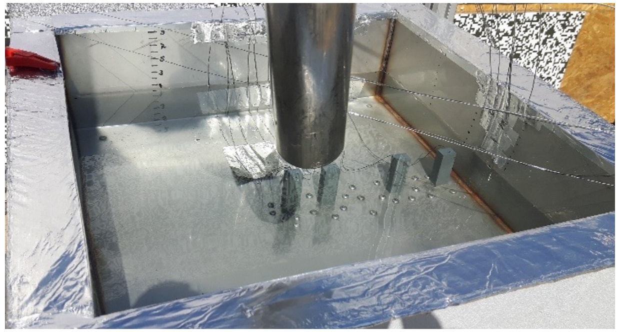
- Box-material: stainless steel
- Inner dimensions: 50 x 50 x 20 cm (L x W x H),
- Insulated with styrofoam plates on bottom and sides,
- In-substrate instrumentation positioned with holders,
- 3 Pools filled up to half the height (10 cm) with different substrates



Concrete
(prepared > 1 month prior to 1st experiment)

Sand
(equipped with baffle plate)

Gravel
(gravel removed for tests with water)



Water
(water removed for tests with gravel)

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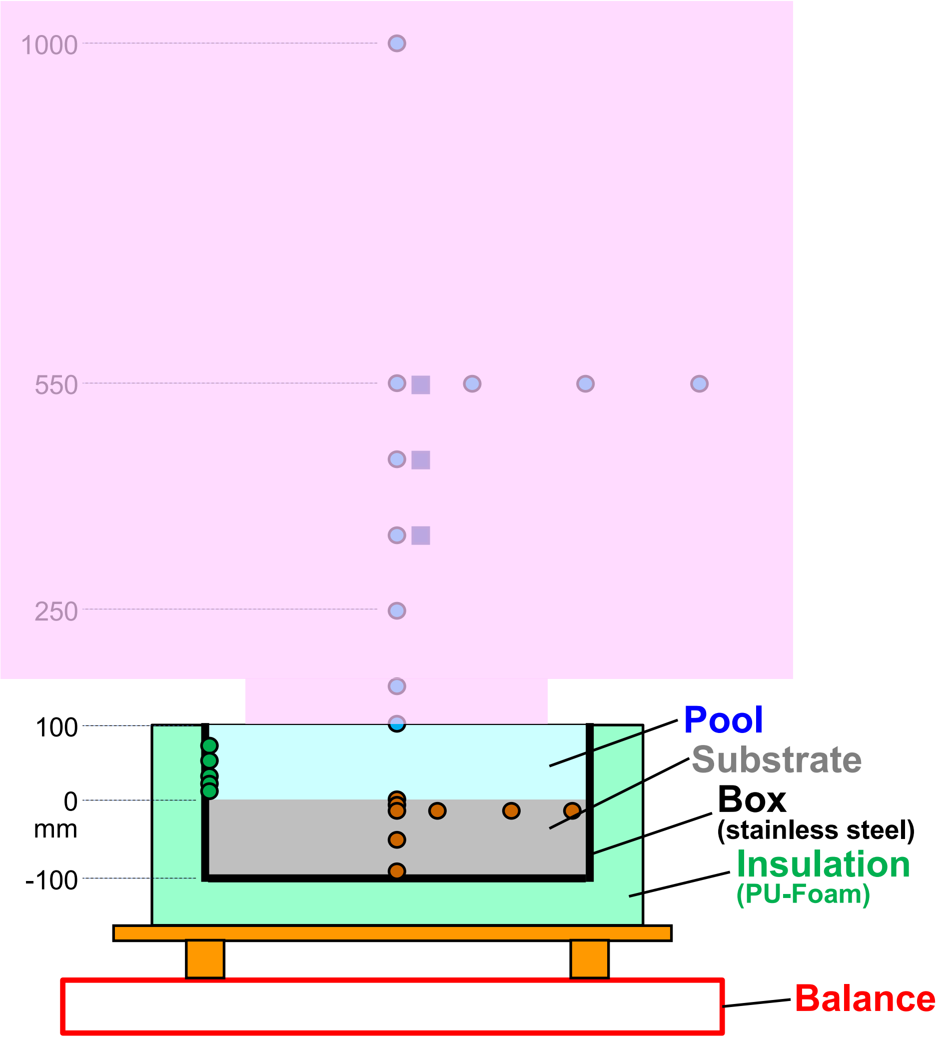
POOL-Facility, test procedure and test matrix

Instrumentation

Every pool is equipped with:

- Balance for weight measurement of LH_2-pool,
- 8 Thermocouples in substrate,
- 6 Thermocouples in pool,
- 10 Thermocouples above pool,
- 3 H_2-concentration measurement positions above pool,
- Experiments observed with up to 5 cameras,
- Wind conditions recorded with anemometer
- In ignited tests no sensors (T, cH_2) above pool, but additional fast pressure sensors on ground around facility.

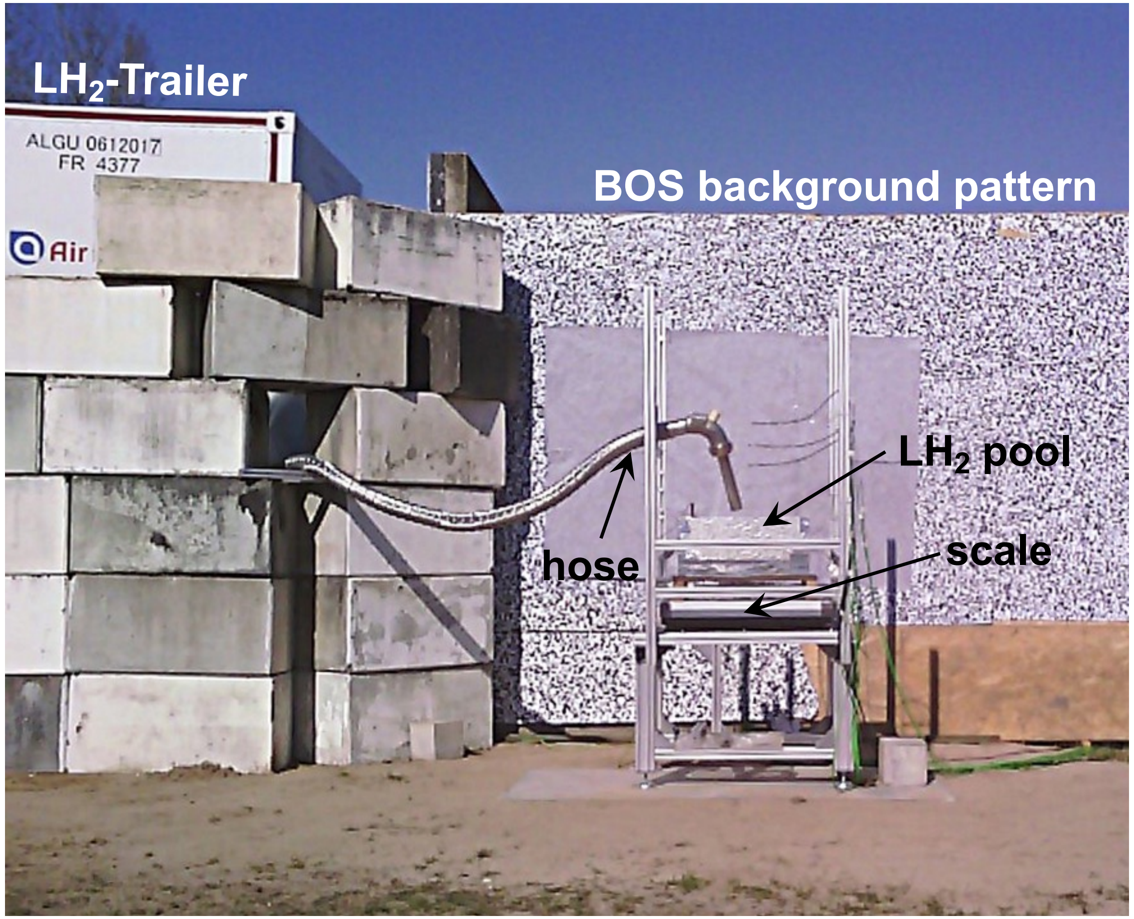


POOL-Facility, test procedure and test matrix

Test procedure

- Hose positioned and fixed above pool,
- Data acquisition started manually and then controlled remotely from shelter,
- Cameras started manually,
- LH2-release started manually at trailer (same valve opening) & stopped remotely,
- After pool evaporation following release again started manually (after safety check with H2-sensor) and stopped remotely,

- **Unignited experiments**:
  Pool usually filled 3x in one experiment,
- **Ignited experiments**:
  Ignition during evaporation after 2nd filling



POOL-Facility, test procedure and test matrix

Test matrix unignited experiments

- In total 10 unignited experiments performed with pool-facility,
- Experiments performed with all 4 substrates (concrete, sand, gravel, water),
- 4 Experiments performed with "artificial side wind" of known velocity and direction.

Date	Substrate	Procedure	Conditions	Comments
20.03.2020	**Concrete01**	2 Fillings	**Natural**	No scales data (Not used)
24.03.2020	**Concrete02**	4 Fillings	**Natural**	
08.04.2020	**Gravel01**	3 Fillings	**Natural**	
09.04.2020	**Sand01**	3 Fillings	**Natural**	
15.04.2020	**Sand02**	3 Fillings	**Wind**	No natural wind data
16.04.2020	**Sand03**	3 Fillings	**Wind**	
17.04.2020	**Concrete03**	3 Fillings	**Wind**	
22.04.2020	**Gravel02**	3 Fillings	**Natural**	Gas-Samples
23.04.2020	**Gravel03**	3 Fillings	**Wind**	Gas-Samples
23.04.2020	**Water01**	3 Fillings	**Natural**	

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POOL-Facility, test procedure and test matrix

Test matrix ignited experiments

- In total 14 ignited experiments were performed with the pool-facility,
- Experiments performed with all 4 substrates (concrete, sand, gravel, water),
- Main variable apart from substrate was ignition height.

Date	Substrate	Procedure	Ignition Height [cm]	Comments
24.04.2020	**Sand04**	2 Fillings	25	
24.04.2020	**Sand05**	2 Fillings	25	T100 moved near ignition
24.04.2020	**Sand06**	2 Fillings	15	
27.04.2020	**Sand07**	2 Fillings	45	No ignition
27.04.2020	**Sand08**	2 Fillings	40	
27.04.2020	**Sand09**	2 Fillings	35	
27.04.2020	**Sand10**	2 Fillings	8	
27.04.2020	**Sand11**	2 Fillings	45	Repetition of Sand 07
27.04.2020	**Concrete04**	2 Fillings	45	
27.04.2020	**Concrete04**	2 Fillings	25	
27.04.2020	**Concrete04**	2 Fillings	15	
27.04.2020	**Concrete04**	2 Fillings	8	Ignition in 3rd attempt
27.04.2020	**Water02**	2 Fillings	25	
04.05.2020	**Gravel04**	2 Fillings	25	

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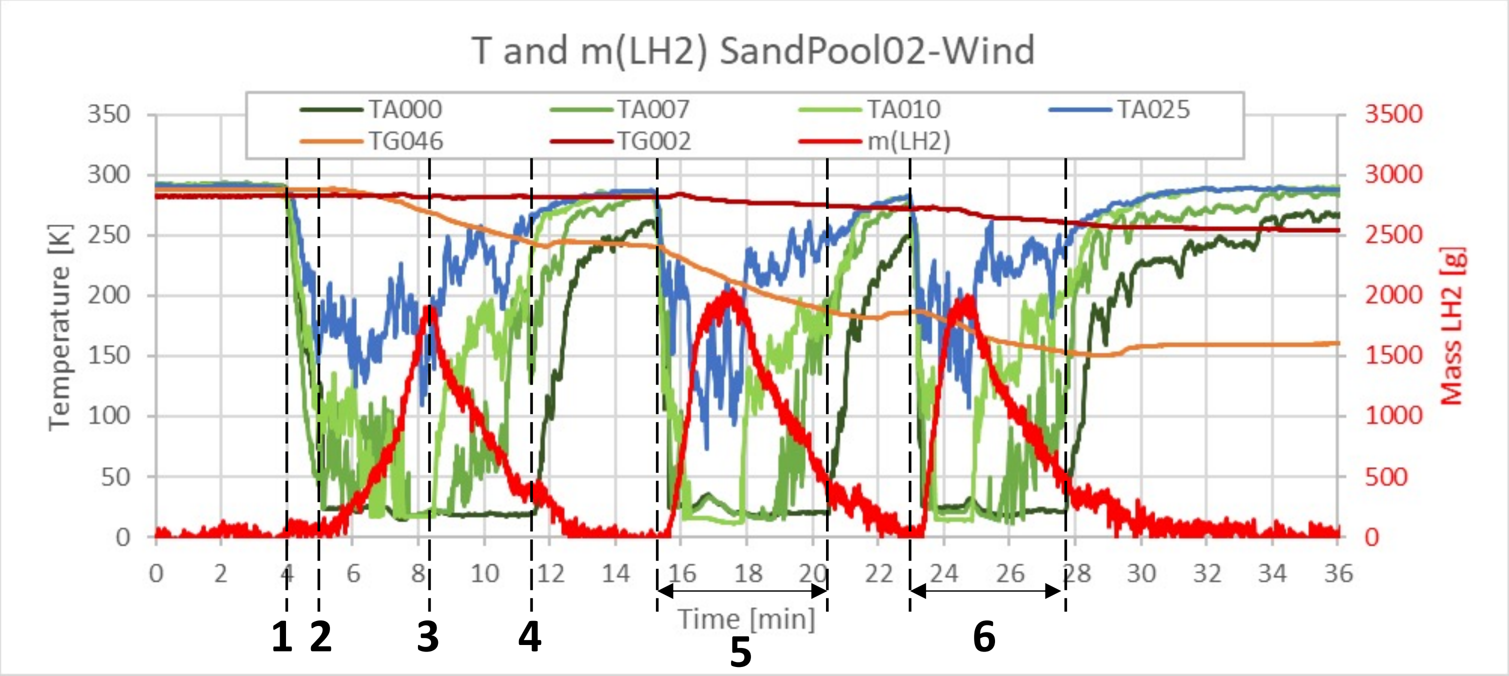
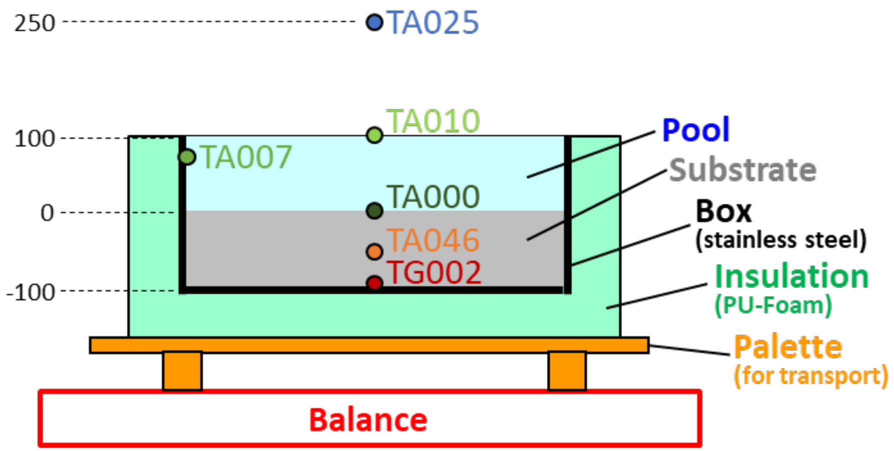
Unignited Experiments with the POOL-Facility

LH2-Evaporation above sand and concrete (Example SandPool02)





1. Beginning LH2-release
2. Beginning (1st) pool-formation
3. End (1st) release, beginning (1st) evaporation
4. End (1st) evaporation
5. 2nd release and evaporation
6. 3rd release and evaporation

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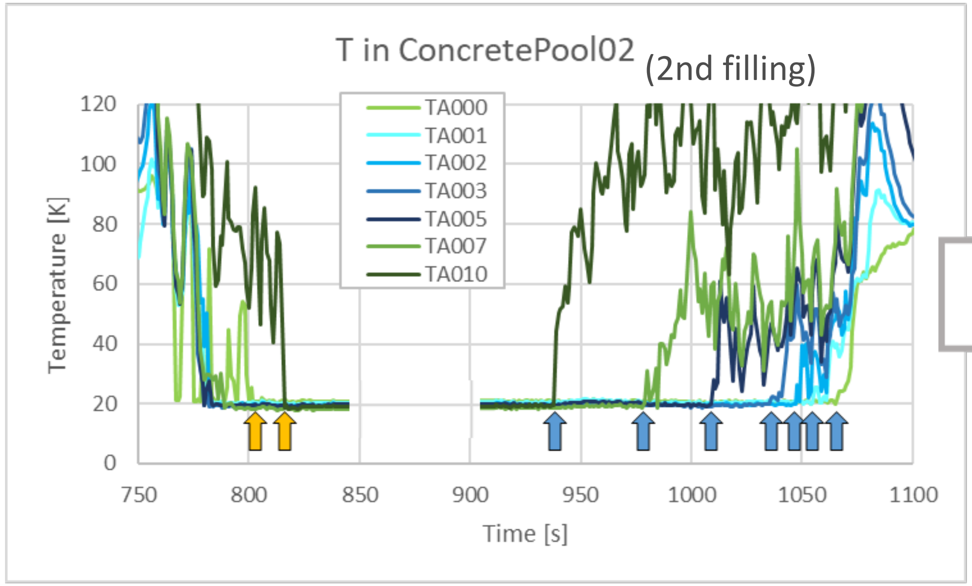
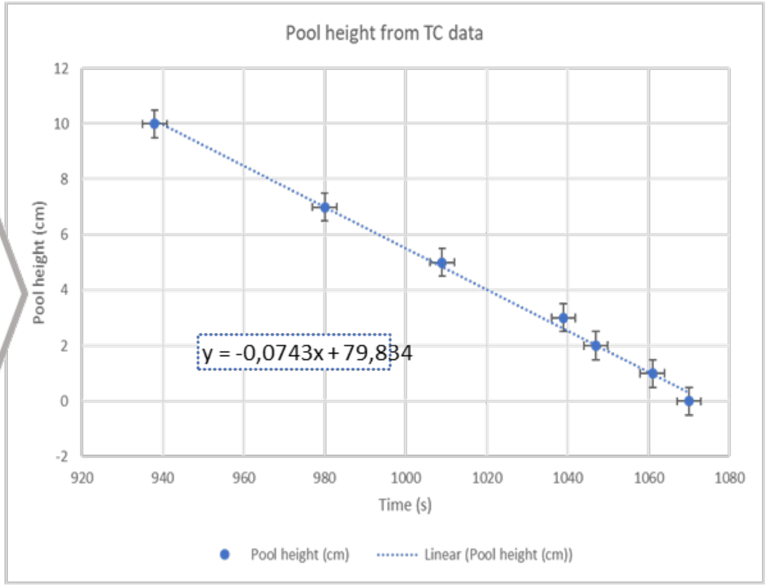
Unignited Experiments with the POOL-Facility

LH2-Evaporation above sand and concrete (Example ConcretePool02)





- For filling periods (yellow arrows in left graph) no clear order of TCs reaching $T_b(LH2)$ in positions above substrate can be determined ➔ no detailed analysis of pool formation.
- For evaporating pool, passing-times of LH2 level for pool-TCs can be clearly identified and when plotted over time, vaporization velocity of boiling LH2 pool in form of a height reduction velocity can be determined from slope,
- Further evaluation yields mass reduction velocity and heat transfer from substrate to LH2.

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Unignited Experiments with the POOL-Facility

LH2-Evaporation above sand and concrete (Example ConcretePool02)

- In similar manner, analysis of evaporation behavior in all other experiments with concrete and sand as substrate was performed.
- Evaporation of cryogenic fluids is governed by heat conduction from ground into liquid.
- Phenomena might be described by one-dimensional heat conduction equation, whose solution gives LH2 evaporation rate in kg/s:

$$dm_{LH2}/dt = L^2\, k\, \Delta T \,/\, [\Delta h_{fg}\, (\pi\, \alpha\, t)^{1/2}], \qquad (8)$$

where L – side length of square pool ground face, m; k – thermal conductivity of substrate, W/mK; ΔT – temperature difference between boiling temperature of liquid and environment, K; Δh_{fg} – heat of LH2 vaporization, J/g; α –thermal diffusivity of substrate, m^2/s; t – time after coverage of ground with liquid pool.

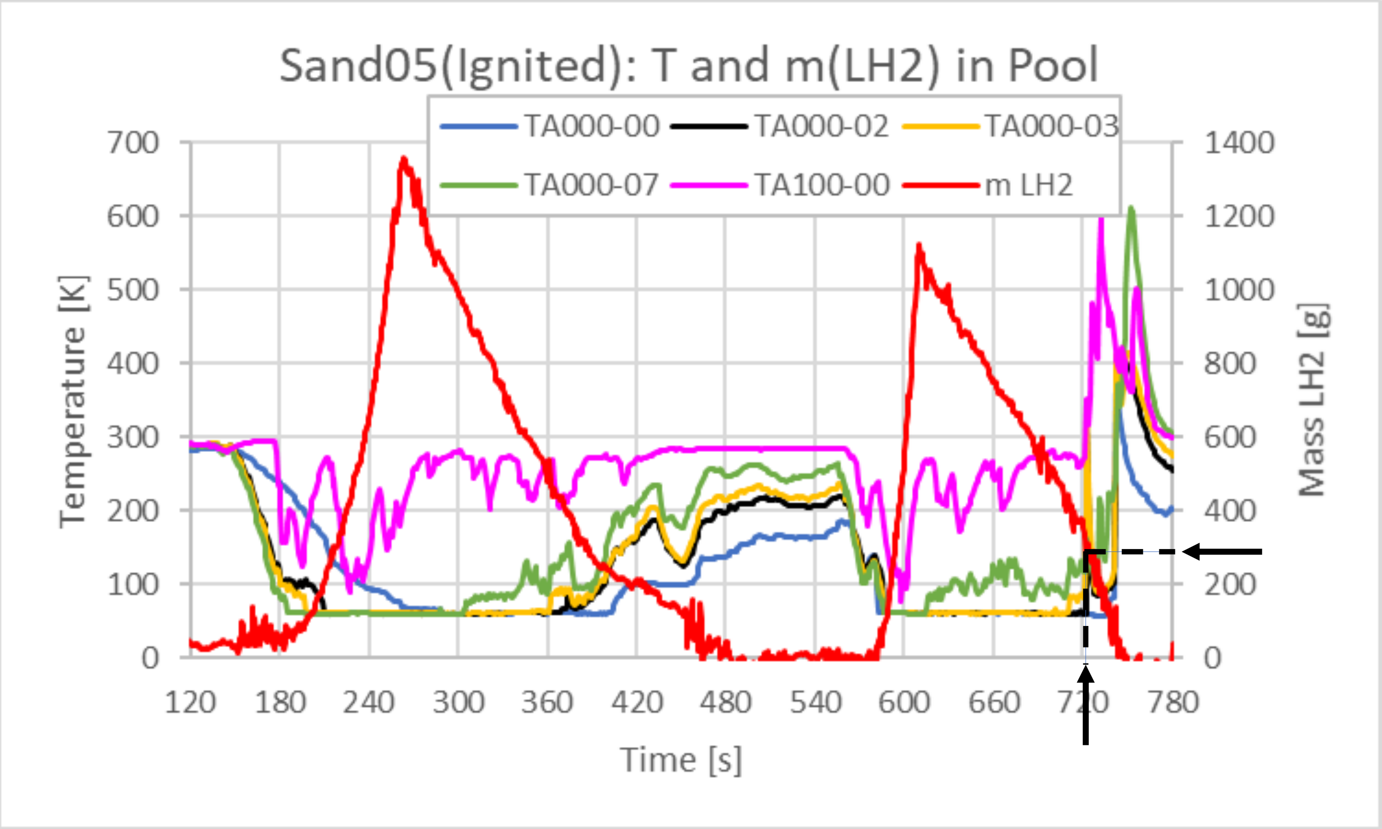
- Derivation and further results presented in:

Friedrich, A., Breitung, W. et al.: Liquid hydrogen pool evaporation above four different substrates; International Conference on Hydrogen Safety 2023 (ICHS2023), Quebec, Kanada, 19.–21.09.2023

Ignited Experiments with the POOL-Facility

Test procedure - Ignited Pool Experiment Sand05

- After second filling LH2-level in pool was closely monitored,
- Increase in temperatures indicates that respective thermocouple is no longer covered by LH2,
- At filling level 3 cm (increase in **T03**) ignition was prepared,
- Ignition was activated at filling level of 2 cm (increase in **T02**),
- Thermocouple **TA100** positioned close to electrodes to record moment of ignition,
- According to graph:
  in experiment Sand05
  approx. 300 g LH2 was in pool
  in moment of ignition.



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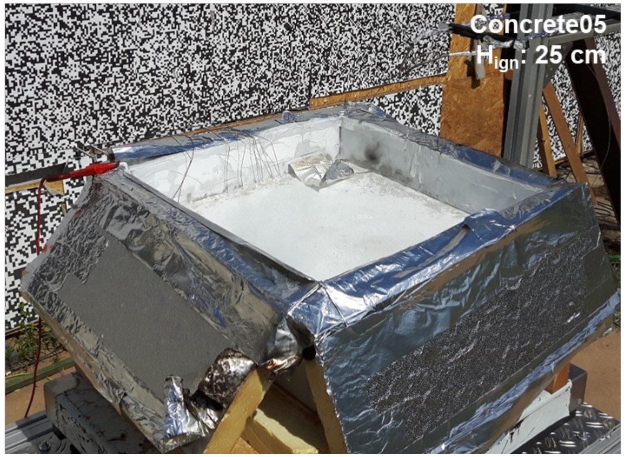
Ignited Experiments with the POOL-Facility

Degree of damage in Ignited Pool Experiment

- Almost undamaged: minor burns (e.g.: Water02),
- More severe damage: torn off insulation (e.g.: Sand11, Concrete05),



- Complete destruction of facility with substrate gravel.

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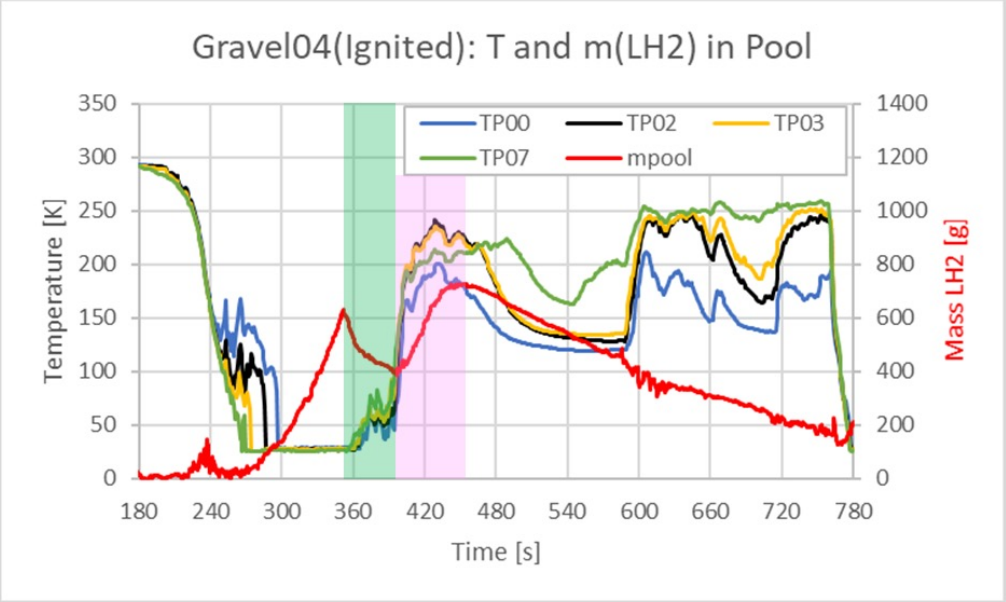
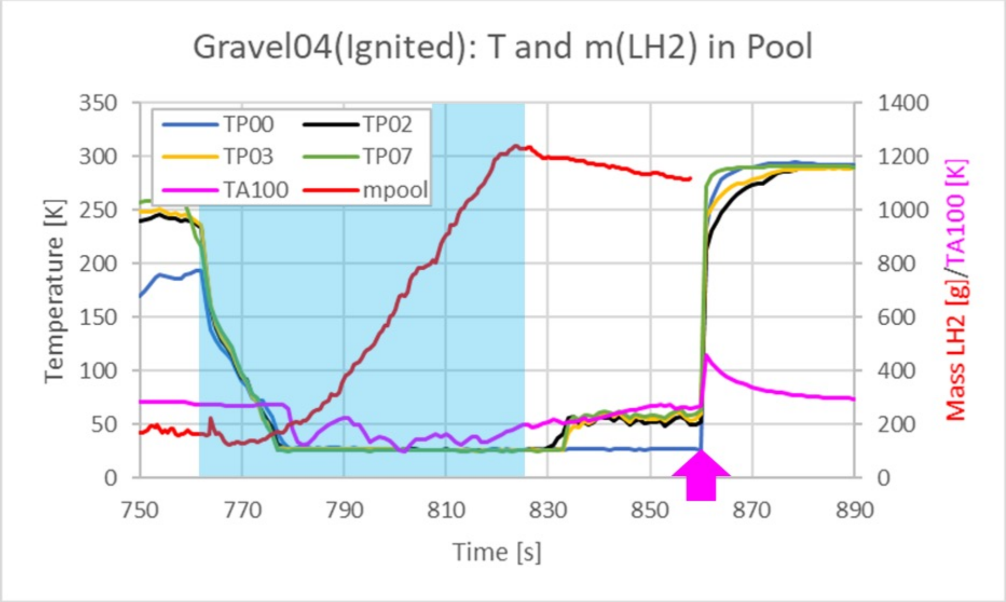
Ignited Experiments with the POOL-Facility

Ignited Pool Experiment Gravel04

Possible explanation for different behavior of experiment Gravel04:

- Main difference to other ignited experiments is phase of mass increase after 1st evaporation of pool above substrate (t ≈ 390 - 450 s),
- Mass increase most likely due to condensation/solidification of air,
- When ignition was activated after 2nd filling (t ≈ 859 s) additional mass in pool was about 1100 g,
- Complete LH2-inventory consumed in only one combustion event.





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Ignited Experiments with the POOL-Facility

Ignited Pool Experiment Gravel04

Video observation (PHOTRON High-Speed Camera, 2000 fps)

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Experimental Data available from: https://publikationen.bibliothek.kit.edu/1000145885

PRESLHY

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Thank you for your attention

andreas.friedrich@kit.edu

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European Commission | Horizon 2020 European Union funding for Research & Innovation

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ELVHYS project No. 101101381 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).

The PRESLHY project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking under the European Union's Horizon 2020 research and innovation program under the grant agreement No 779613.