

LIQUID HYDROGEN POOL EVAPORATION ABOVE FOUR DIFFERENT SUBSTRATES

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Outline

- Motivation
- Pool-facility set-up, test procedure and test matrix
- LH₂-Pool behavior above different substrates
- LH₂-Evaporation above sand and concrete
- Summary

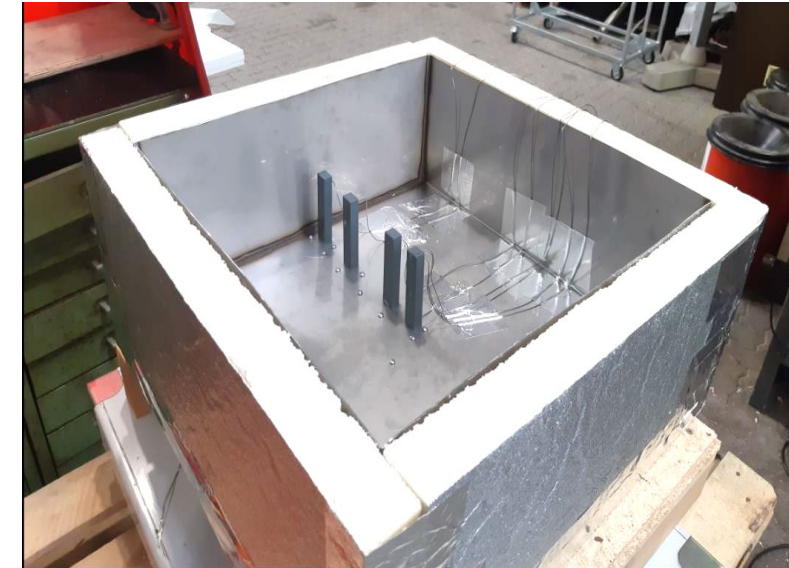
Motivation

- In safety considerations on liquid hydrogen (LH₂) transport and refueling, leakages or failures may lead to LH₂-releases to the environment.
- Such spills will produce large clouds of gaseous hydrogen (GH₂) and might form pools, depending on amount of LH₂ and nature of ground (or substrate) that is exposed to LH₂.
- Pool evaporation and mixing of GH₂ with air is first step in an accident scenario leading to generation of flammable cloud of H₂/air mixture that might produce huge temperature and pressure loads in case of ignition.
- So 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.

Pool-facility set-up, 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)



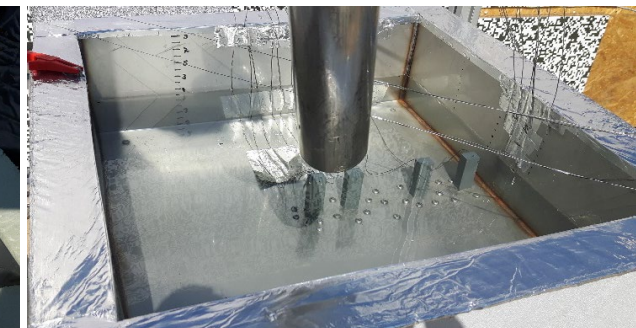
Sand

(equipped with baffle plate)



Gravel

(gravel removed for tests with water)

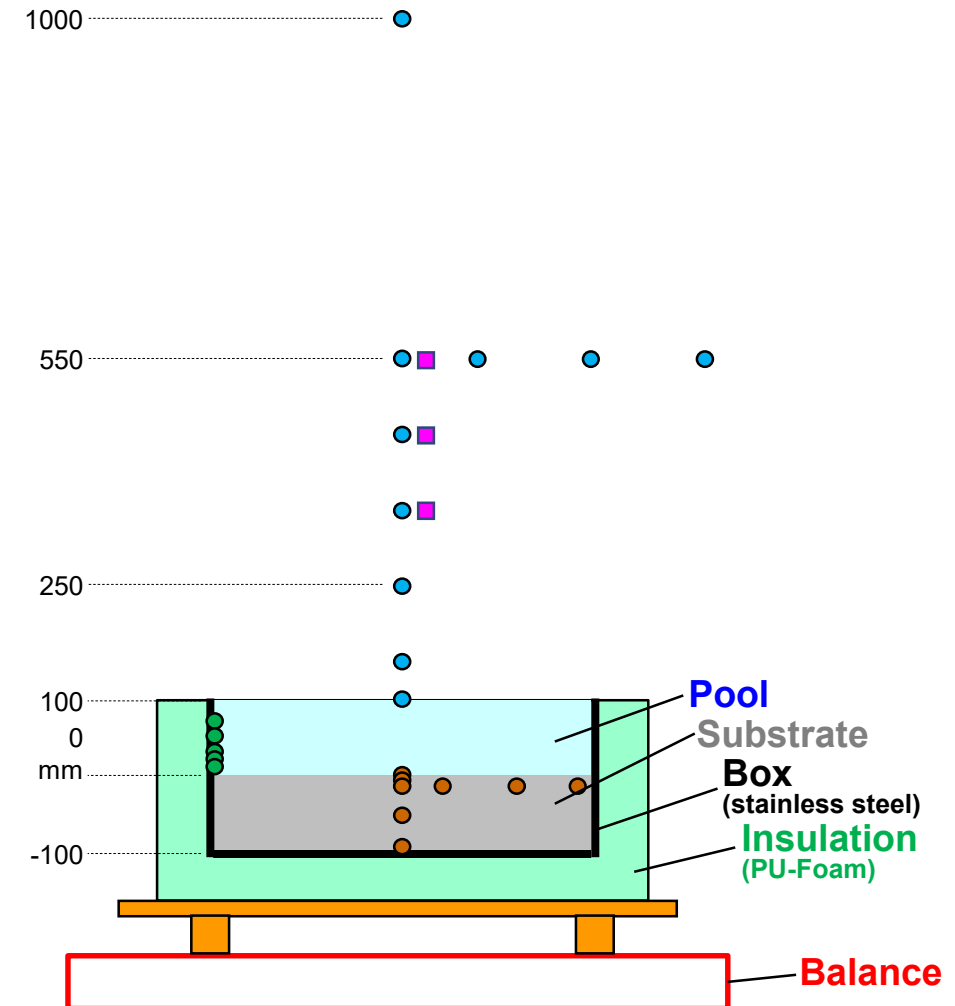


Water

(water removed for tests with gravel)

Pool-facility set-up, test procedure and test matrix

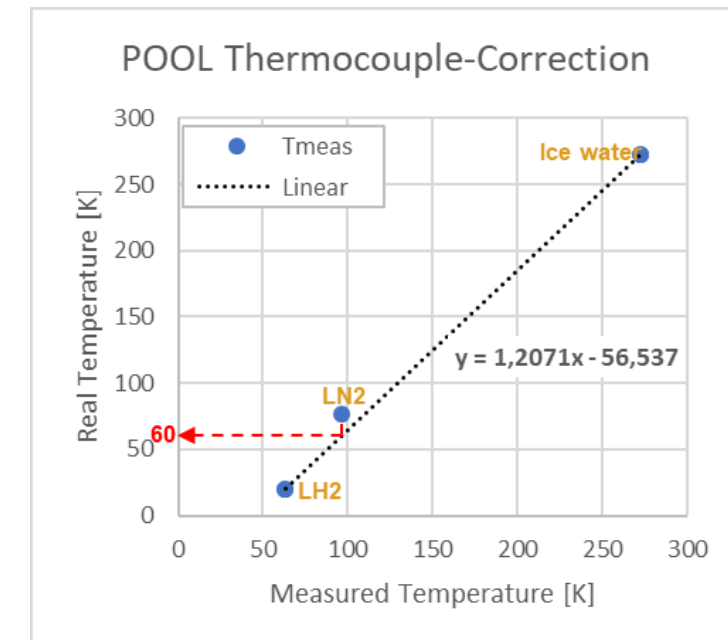
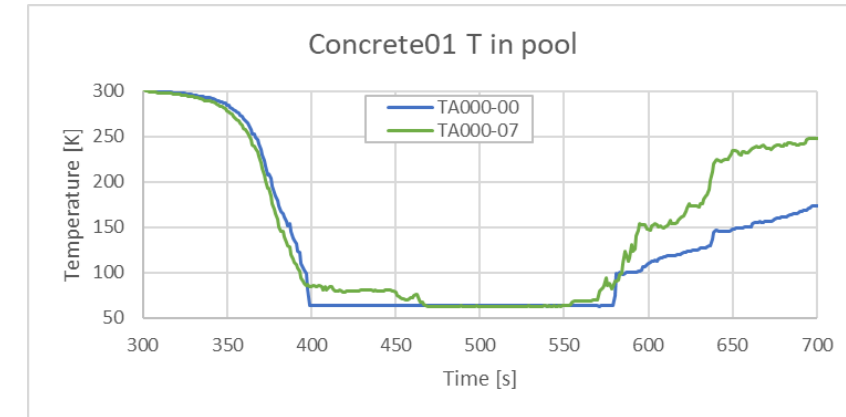
- **Instrumentation** Every pool is equipped with:
 - Balance for weight measurement of LH₂-pool,
 - 8 Thermocouples in substrate,
 - 6 Thermocouples in pool,
 - 10 Thermocouples above pool,
 - 3 H₂-concentration measurement positions above pool,
 - Experiments observed with up to 5 cameras,
 - Ambient wind conditions recorded with anemometer.



Pool-facility set-up, test procedure and test matrix

■ Thermocouple (TC) measurements

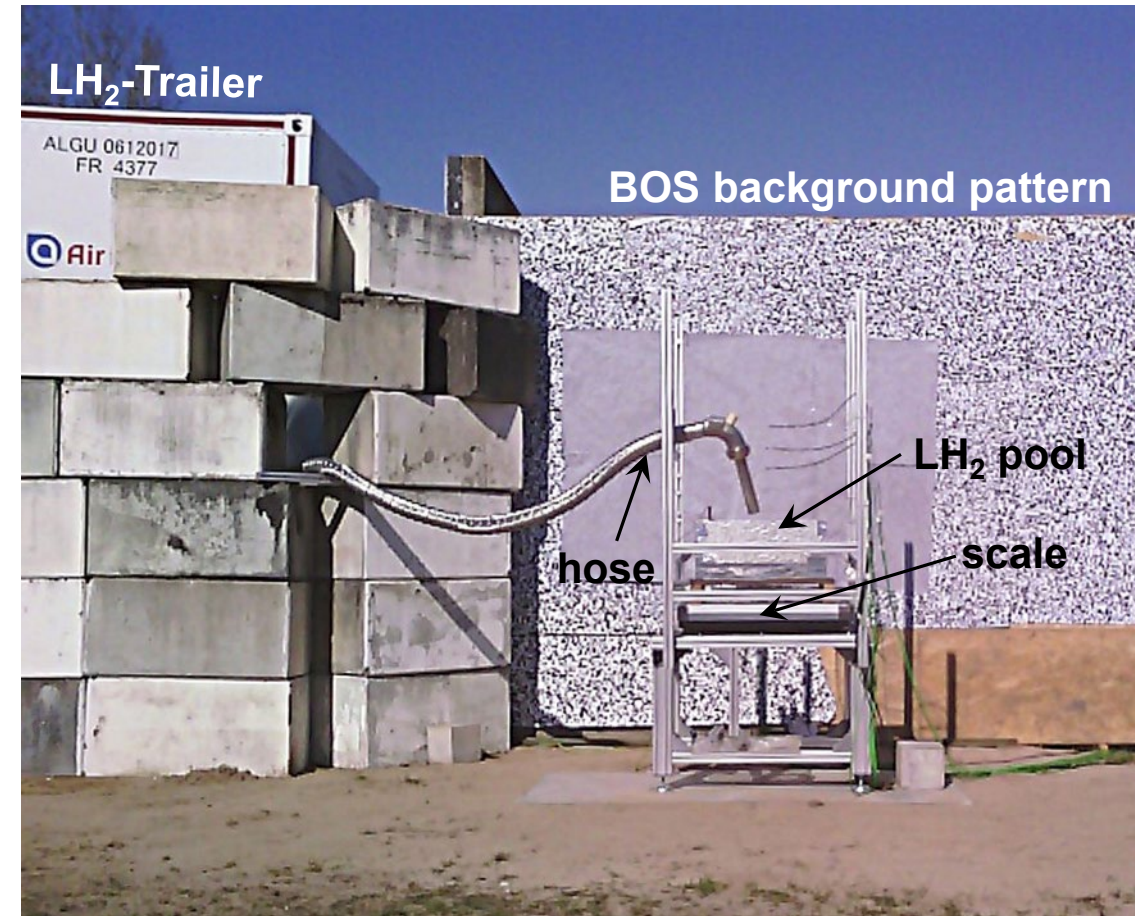
- Type K thermocouples not suitable for cryogenic temperatures, but main aim of measurements is **NOT** precise temperature measurement, **BUT** detection of liquid phase!
- TC measurements show straight horizontal lines as long as covered with liquid,
- When no longer covered with liquid, fast temperature increases and fluctuations occur,
- Same behavior observed in LN_2 and LH_2 .
- To facilitate interpretation, all temperature values in following plots are “corrected” using a linear fit, that yields reasonable values for LH_2 -temperature,
- LN_2 -temperature is calculated to be 20 K colder (60 K).



Pool-facility set-up, test procedure and test matrix

■ Test procedure

- Hose positioned and fixed above pool,
- Data acquisition in tent started manually and then controlled remotely from shelter until end of experiment,
- Cameras started manually,
- LH₂-release started manually at trailer (always approx. same degree of valve opening) but stopped remotely,
- After pool evaporation following release is again started manually (after safety check with hand held H₂-sensor) and again stopped remotely,
- Pool usually filled 3x in one experiment.



Pool-facility set-up, test procedure and test matrix

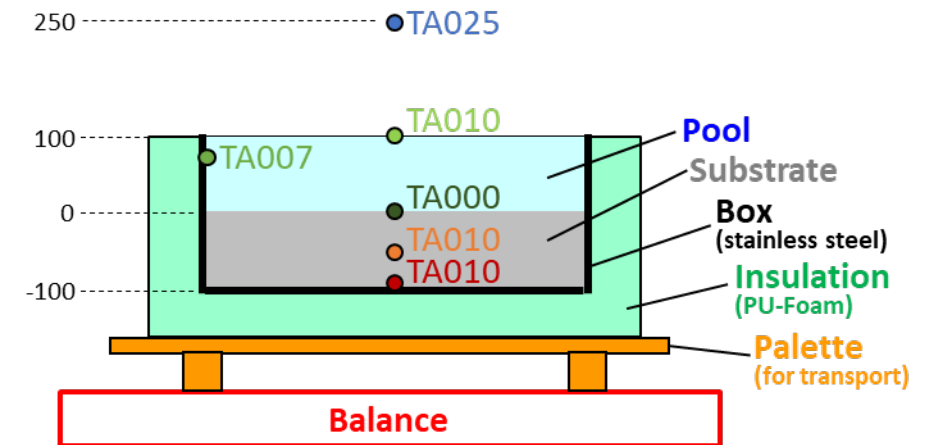
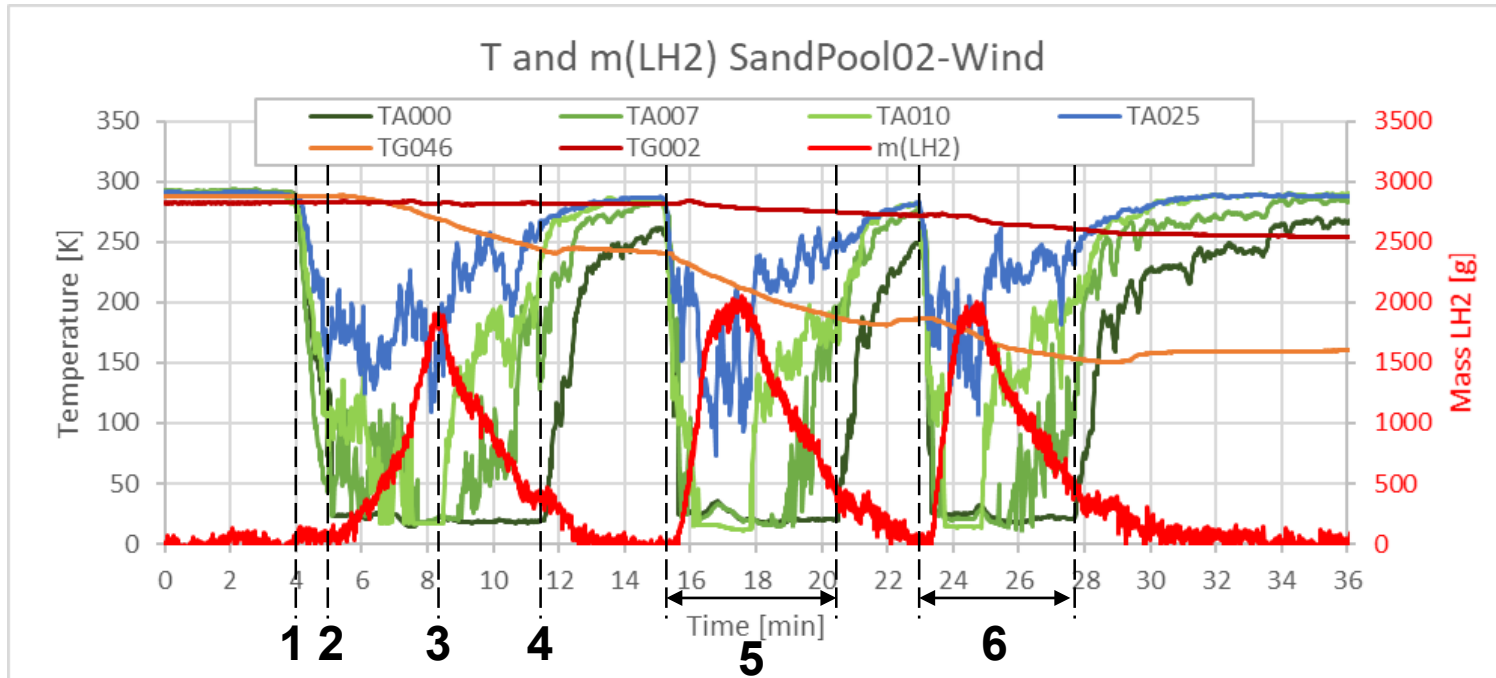
■ Test matrix

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

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

LH₂-Pool behavior above different substrates

- Example SandPool02 (behavior above concrete similar)



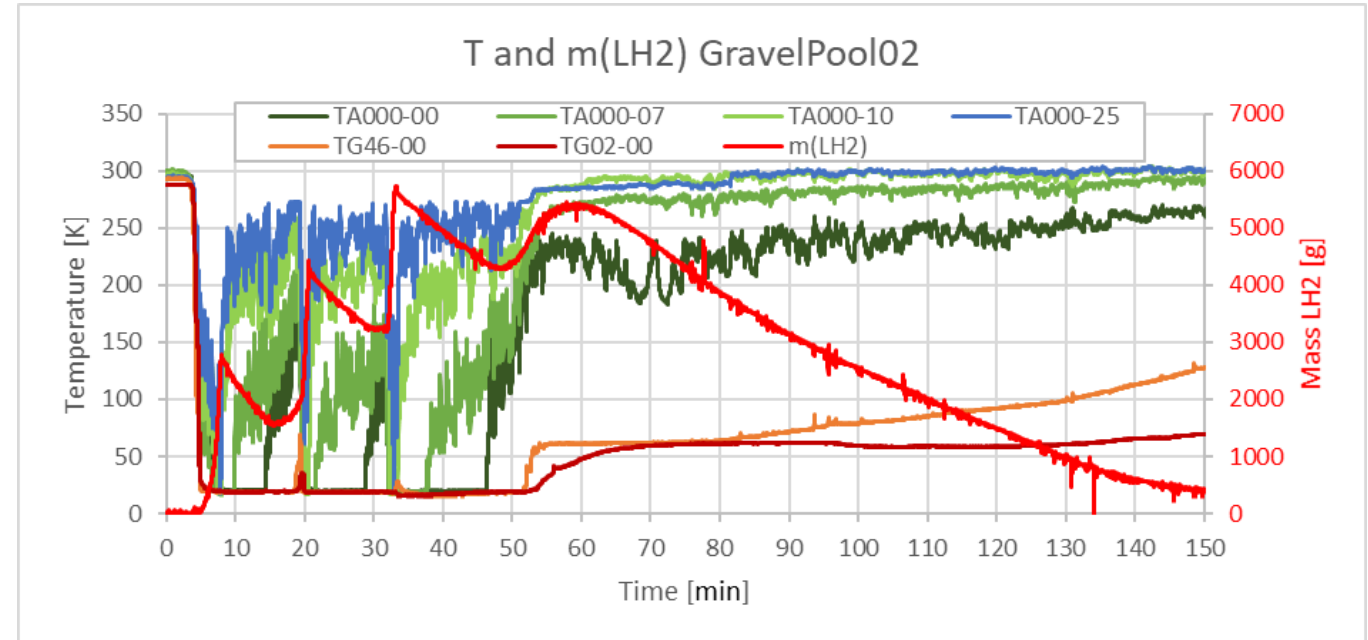
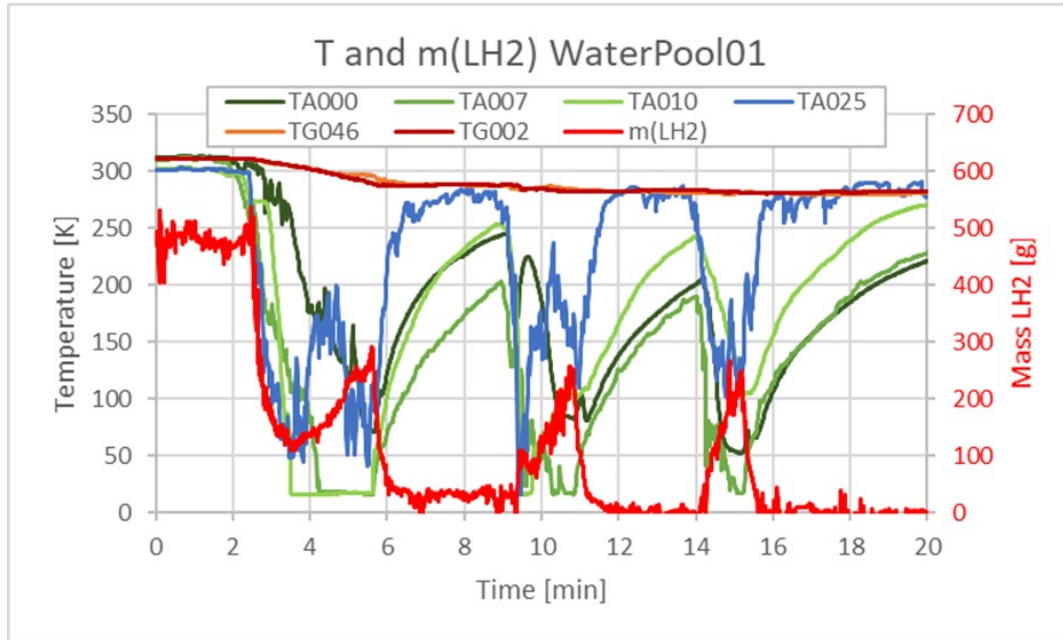
1. Beginning LH₂-release
2. Beginning (1st) pool-formation
3. End (1st) release, beginning (1st) evaporation

4. End (1st) evaporation
5. 2nd release and evaporation
6. 3rd release and evaporation

LH₂-Pool behavior above different substrates

■ Examples WaterPool01

GravelPool02

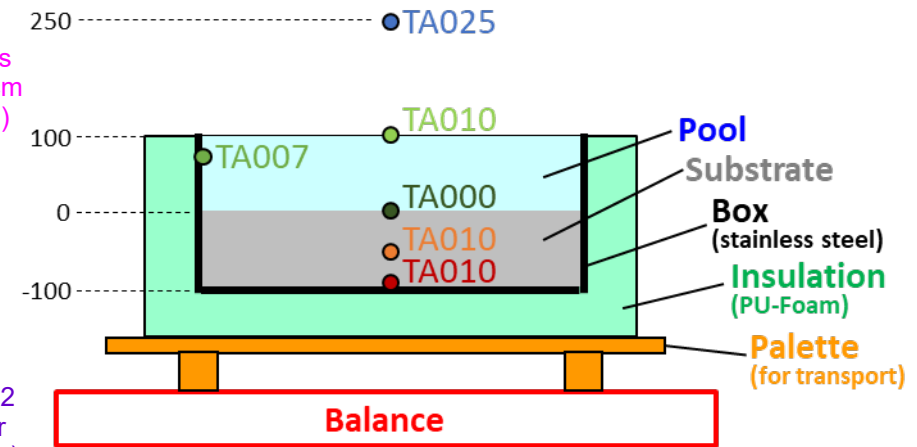
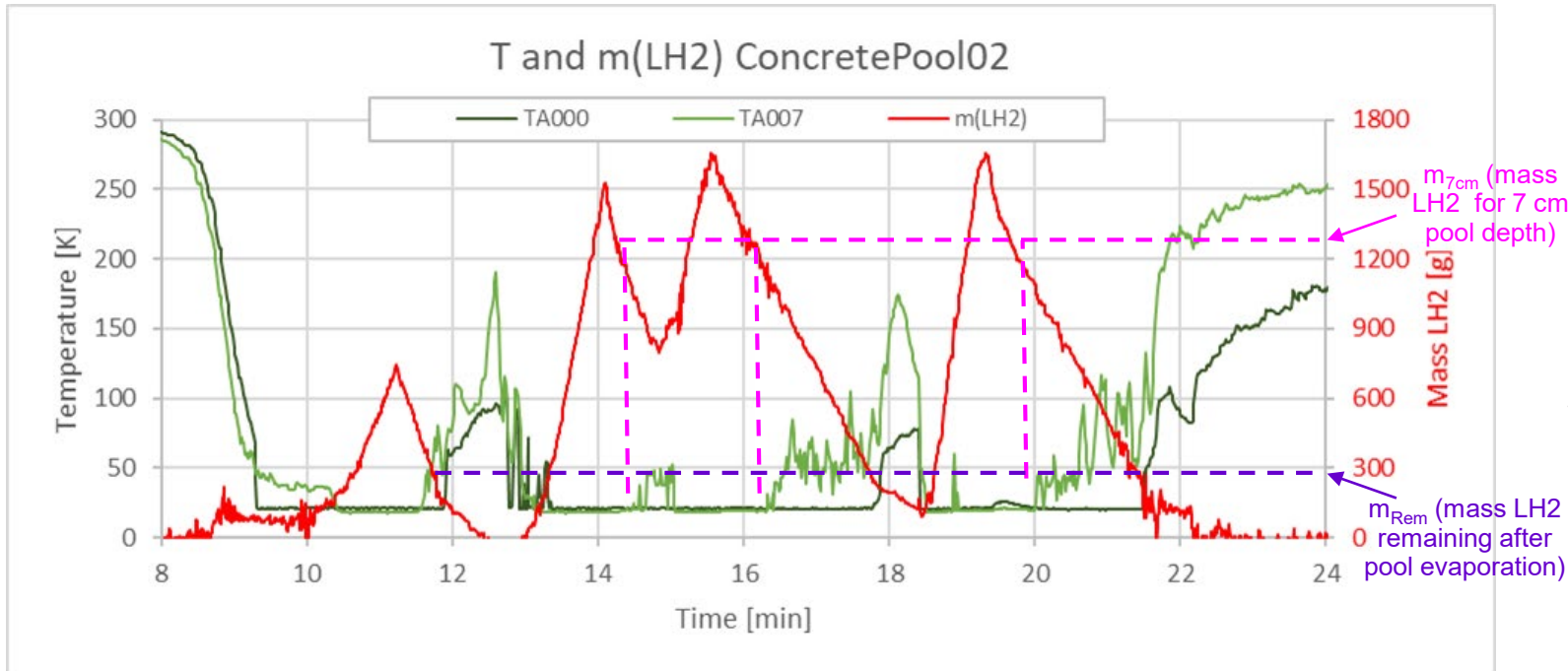


- Mass initially decreases (water blown out),
- Stable T(LH₂) at higher TCs before pool forms on water surface (ice formation on TCs)
- No reliable signals of most important sensors → experiment stopped.

- Much longer pool formation time and much higher LH₂ mass in pool (porous substrate),
- Accumulation of mass in pool (air-condensation),
- Evaluation of processes much more complex → gravel experiments not further discussed here.

LH₂-Evaporation above sand and concrete

■ Example ConcretePool02



- Increase in TA007 indicates LH₂-level falling below 7 cm height;
- For 3 points in time in example, mass of $m_{7\text{cm}} \approx 1240$ g in pool is obtained,
- When complete LH₂-pool has evaporated (increase TA000 at substrate surface), remaining mass of $m_{\text{Rem}} = 300$ g due to LH₂ in gaps or frozen air components.

LH₂-Evaporation above sand and concrete

■ Example ConcretePool02

- Mass of LH₂ in pool at point in time when filling level decreases below 7 cm:

$$m_{\text{LH}_2@7\text{cm}} = m_{7\text{cm}} - m_{\text{Rem}} = 1.240 \text{ kg} - 0.300 \text{ kg} = 0.940 \text{ kg} \quad (1)$$

with $m_{\text{LH}_2@7\text{cm}}$ - mass of hydrogen in pool at filling level 7 cm, kg; $m_{7\text{cm}}$ - measured mass for pool height 7 cm, kg; m_{Rem} - remaining additional mass after evaporation, kg.

- Volume of pool with height 7 cm above square base area with side length 0.5 m:

$$V_{\text{Pool}@7\text{cm}} = L^2 \cdot h = 0.0175 \text{ m}^3 \quad (2)$$

with $V_{\text{Pool}@7\text{cm}}$ - pool volume for 7 cm height, m³; L - side length of square pool ground face, m; h - height of pool, m.

- Density of LH₂ in pool:

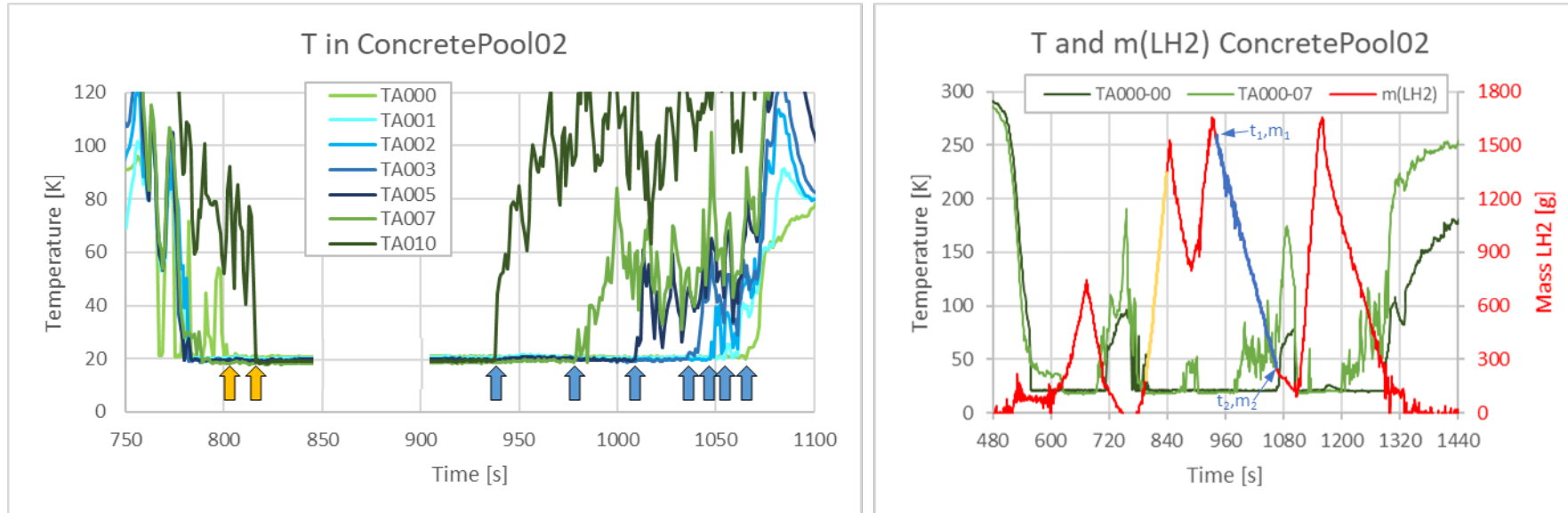
$$\rho_{\text{LH}_2\text{pool}} = m_{\text{LH}_2@7\text{cm}} / V_{\text{Pool}@7\text{cm}} = 53.7 \text{ kg/m}^3 \quad (3)$$

with $\rho_{\text{LH}_2\text{pool}}$ - density of LH₂ in pool, kg/m³; $m_{\text{LH}_2@7\text{cm}}$ - LH₂ mass in pool of 7 cm height, kg; $V_{\text{Pool}@7\text{cm}}$ - volume of pool of 7 cm height, m³.

- Value is low compared to $\rho_{\text{LH}_2} \approx 70.8 \text{ kg/m}^3$ from literature,
- Indicates that pool contains approx. 76% LH₂ and 24% void.

LH₂-Evaporation above sand and concrete

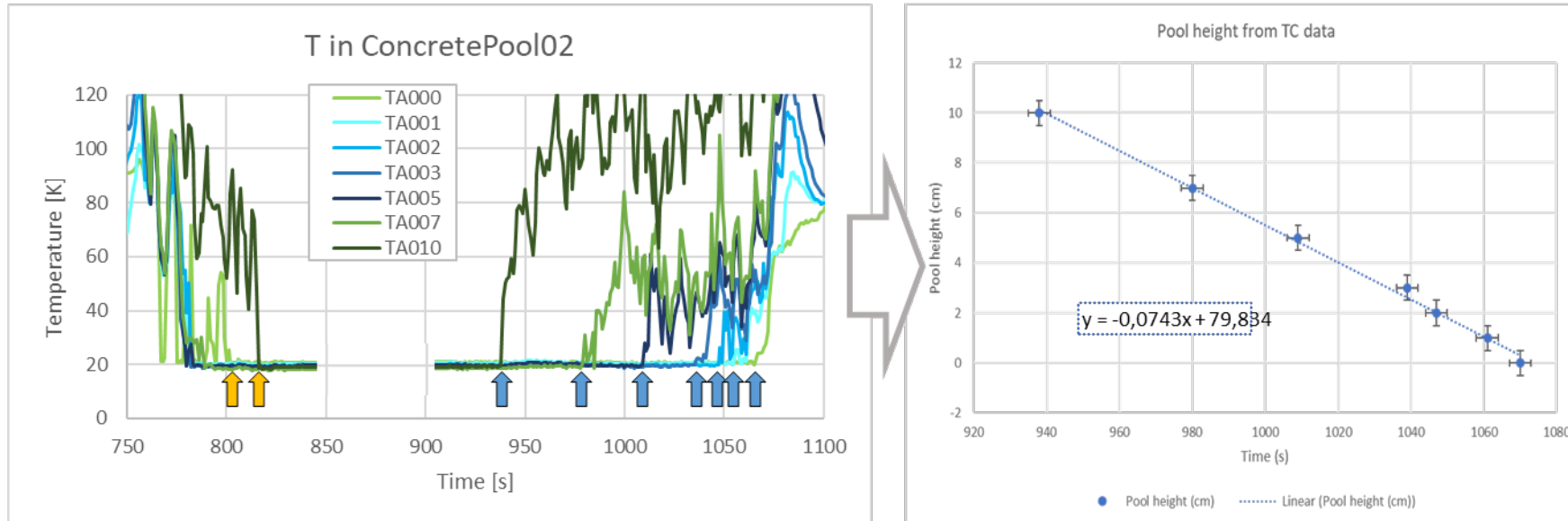
■ Example ConcretePool02



- Left graph shows details of pool-TC signals for **2nd filling** and **3rd evaporation** period (highlighted in respective color in right overall plot),
- For **2nd filling** period (yellow arrows in left graph) no clear order of TCs reaching LH₂-temperature in positions above substrate surface can be determined,
- Pool is vigorously boiling despite pre-cooling during 1st (incomplete) filling. So TC signals cannot be used for a detailed analysis of pool formation.

LH₂-Evaporation above sand and concrete

■ Example ConcretePool02



- After 3rd filling period ($t \approx 890$ to 935 s) pool is completely filled with LH₂ ($h = 10$ cm),
- As soon as LH₂ level passes a TC position, its temperature jumps to a higher gas temperature, as highlighted by blue arrows in left graph.
- For evaporating pool, passing-times of LH₂ level for pool-TCs can be clearly identified.
- When plotted over time, vaporization velocity of boiling LH₂ pool in form of a height reduction velocity $(dh/dt)_{\text{boil}} = 0.0743$ cm/s can be determined from slope of curve.

LH₂-Evaporation above sand and concrete

■ Example ConcretePool02

- Weight loss velocity can be determined using values for beginning (index 1) and end (index 2) of blue line:

$$dm_{H_2}/dt = (m_1 - m_2)/(t_2 - t_1) = 0.0105 \text{ kg/s}, \quad (4)$$

where dm_{H_2}/dt – weight loss velocity, kg/s; m_1, m_2 – weight of pool at beginning/end of time span under consideration, kg;

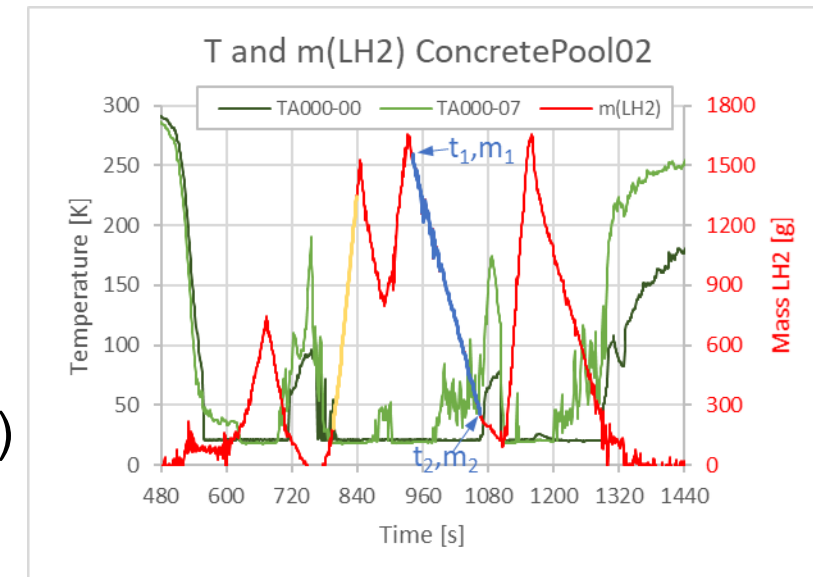
t_1, t_2 – beginning/end of time span under consideration, s.

- Using $dm_{H_2}/dt = \rho_{\text{boil}} \cdot L^2 \cdot (dh/dt)_{\text{boil}}$ (5a)
boiling pool density can be estimated:

$$\rho_{\text{boil}} = dm_{H_2}/dt / [L^2 \cdot (dh/dt)_{\text{boil}}], \quad (5)$$

where ρ_{boil} – density of boiling pool, kg/m³, dm_{H_2}/dt – measured weight loss rate of pool from Eq. (4), kg/s; L – side length of square pool ground face, m; $(dh/dt)_{\text{boil}}$ – recession velocity of pool surface determined graphically on previous slide; m/s.

- Eq. (5) yields $\rho_{\text{boil}} = 56.5 \text{ kg/m}^3$, corresponding to 80% LH₂ and 20% GH₂ void fraction, which is close to estimated value of 24% void determined before.



LH₂-Evaporation above sand and concrete

■ Example ConcretePool02

- Heat flow from concrete into the LH₂ pool is estimated as

$$Q_{\text{pool}} = (dm_{\text{H}_2}/dt) \cdot \Delta h_{\text{fg}} = 4725 \text{ W} \quad (6)$$

where Q_{pool} – heat flow from concrete into LH₂ pool, W; dm_{H_2}/dt – measured weight loss rate of pool from Eq. (4), kg/s; Δh_{fg} – heat of LH₂ vaporization (450 kJ/kg [1]), J/kg.

- Heat flux density from concrete into LH₂ can be calculated as follows:

$$q_{\text{pool}} = Q_{\text{pool}} / L^2 = 18.7 \text{ kW/m}^2 \quad (7)$$

where q_{pool} – heat flux density from concrete into LH₂, W/m²; Q_{pool} – heat flow from concrete into LH₂, W; L – side length of square pool ground face, m.

- Evaporation rate (dm_{H_2}/dt) and corresponding heat flow from concrete into LH₂ pool decreases with increasing time due to decreasing temperature gradient in concrete.

[1] Zhang, Y. et. al., Corrected Values for Boiling Points and Enthalpies of Vaporization of Elements in Handbooks, J. Chem. Eng. Data, 56, 2011, pp. 328–337.

LH₂-Evaporation above sand and concrete

■ Example ConcretePool02

- 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:

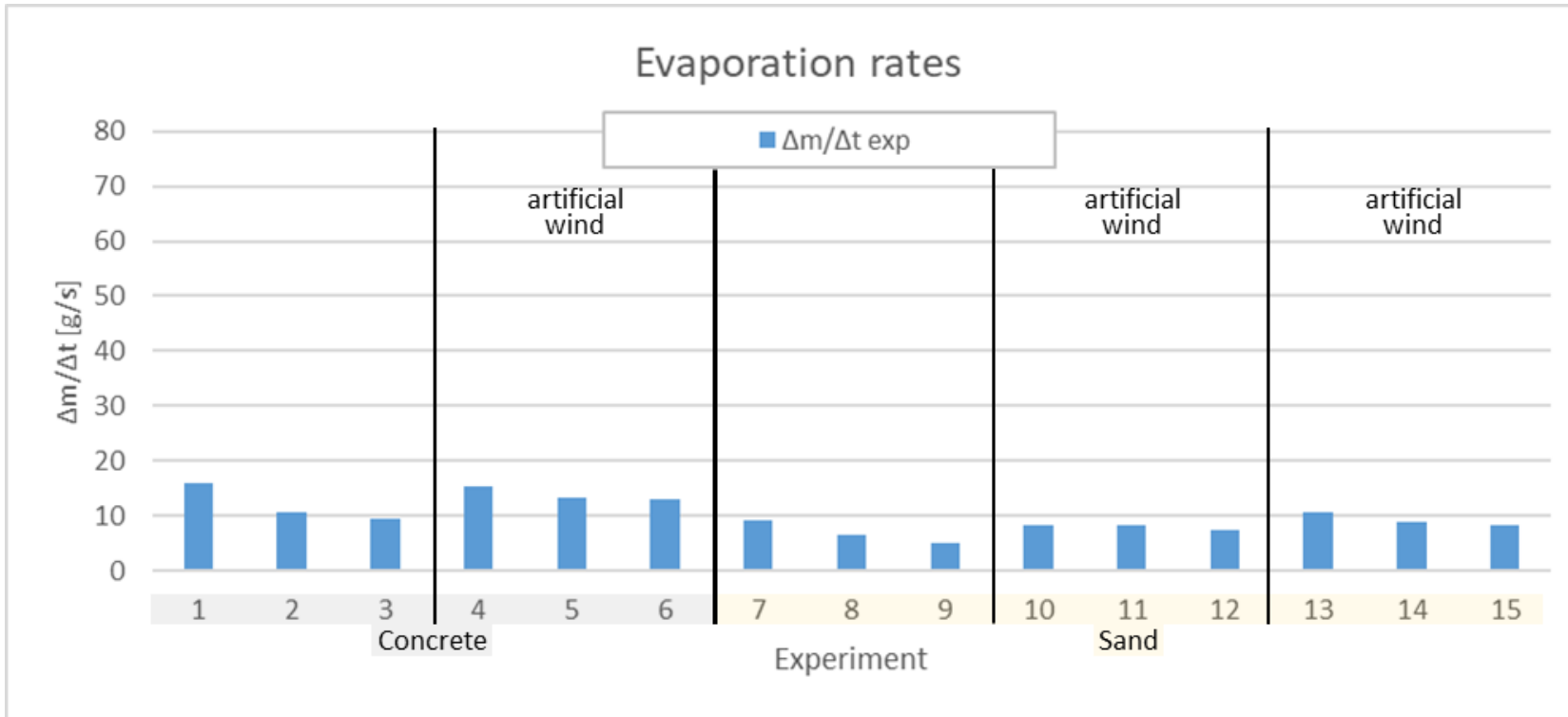
$$dm_{\text{LH}_2}/dt = L^2 k \Delta T / [\Delta h_{\text{fg}} (\pi \alpha t)^{1/2}], \quad (8)$$

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, m²/s; t – time after coverage of ground with liquid pool.

- In same way, analysis of evaporation behavior for remaining evaporation phases in experiment Concrete02 and all other experiments with concrete and sand as substrate was performed.

LH₂-Evaporation above sand and concrete

■ Collected observations

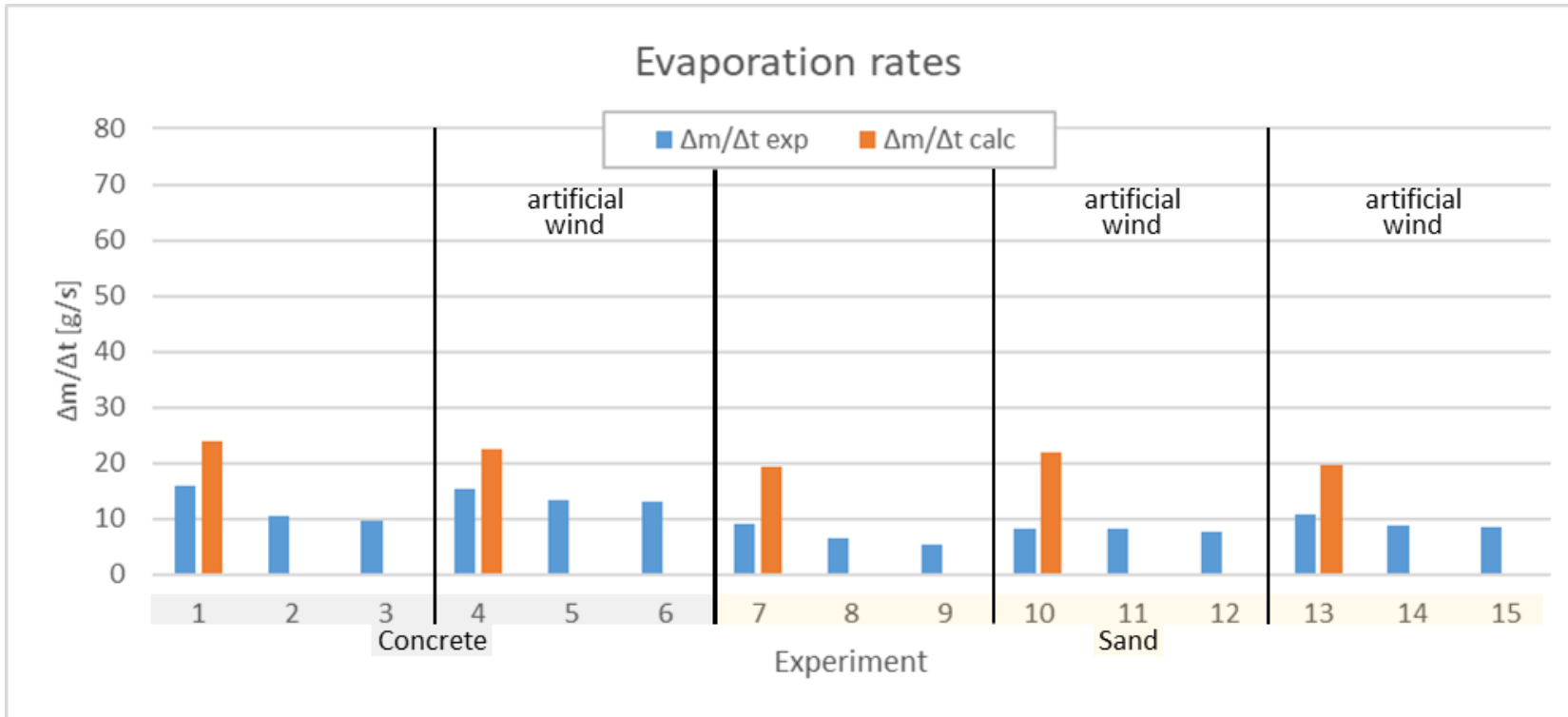


Experimental evaporation rates show similar tendencies in all experiments:

- Evaporation rates for concrete higher than for sand,
 - During 1st evaporation phase always highest evaporation rate of an experiment, since substrate initially has ambient temperature,
- In subsequent fillings, pool is generated above pre-cooled substrate, so driving force for evaporation (temperature difference between liquid and substrate), is smaller.

LH₂-Evaporation above sand and concrete

■ Collected observations



Calculation of evaporation rates (Eq. (8)) only applied to 1st filling of a series.

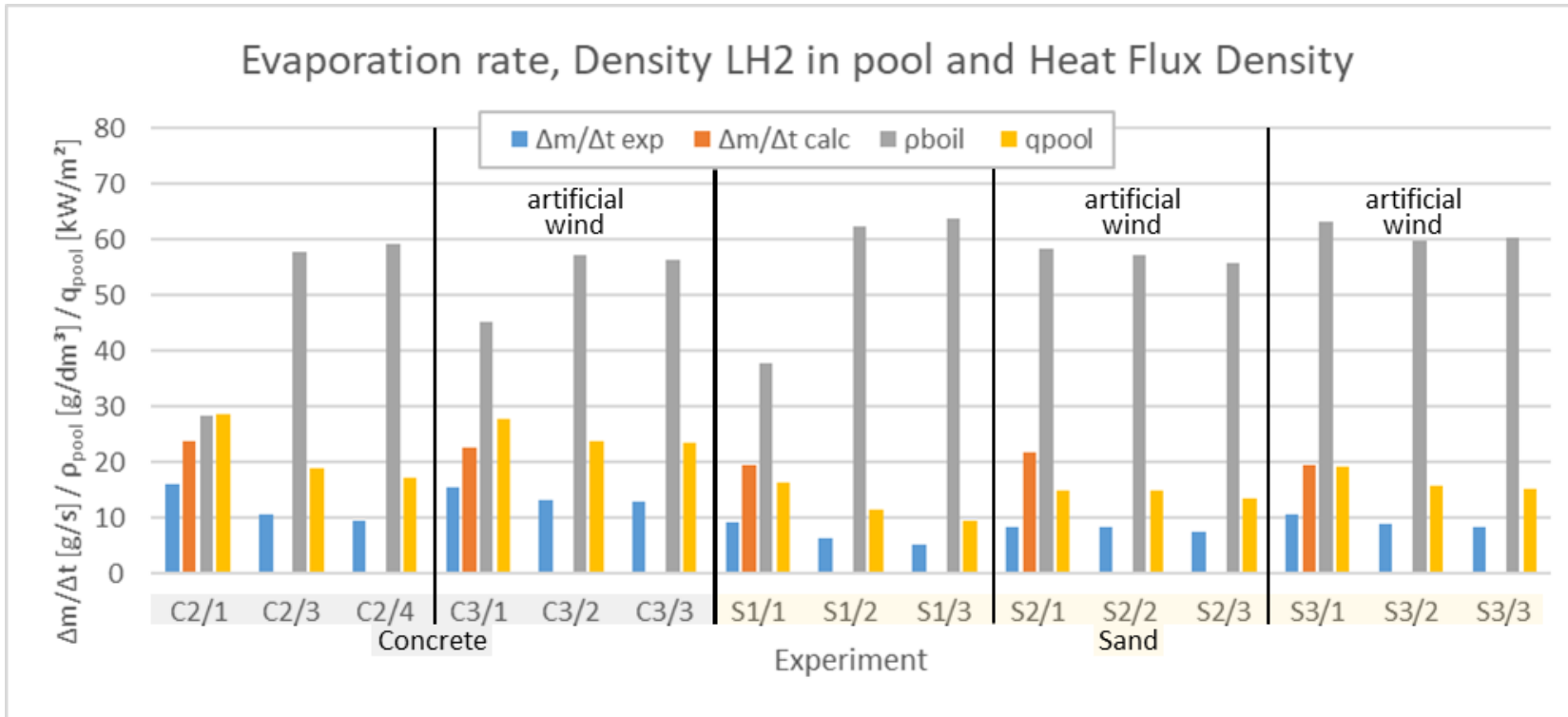
All following fillings started at pre-cooled surface with temperature far below T_{amb} , where TC measurements are inaccurate, so ΔT in Eq. (8) cannot be determined accurately.

Good agreement for experimental and calculated evaporation rates, problems due to

- values for thermal properties of substrates k and α (Eq. (8), taken from internet),
- uncertainties on beginning of time interval (Eq. (4)) and initial temperature for determination of ΔT (Eq. (8)).

LH₂-Evaporation above sand and concrete

■ Collected observations



- Most vigorous boiling in 1st evaporation phase, so density of evaporating pool is found to be lowest,
- Later less vigorous boiling above pre-cooled substrate, so density increases.
- Heat flux density is proportional to measured evaporation rate, thus behavior of both values is similar.

- With strong “artificial” side wind, differences between first and subsequent evaporation rates become smaller due to longer duration of first filling procedure that allows more effective cooling of substrate prior to first evaporation phase.

Summary

- Current work concentrates on evaporation phases of experiments with concrete and sand as substrate, where evaporation rates were determined for 15 evaporation phases of 5 experiments.
- Experiment with water as substrate was omitted due to incomplete data records,
- Experiments with gravel were omitted due to complicated underlying processes in connection with frozen air compounds inside LH₂ pool.
- Using scale and TC records, evaporation rates above substrates concrete and sand were determined for initial ambient and subsequent pre-cooled conditions of substrate. Values determined during the evaluation showed good consistency.
- Equation for estimation of evaporation rate of LH₂ over non-porous solid surfaces was proposed that yielded good agreement with experimental values.

Thank you for your attention!

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