Experiments to investigate the effects of releasing liquified hydrogen onto or under water

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RPT (Rapid Phase Transition)

“Definition”

Process that takes place when a liquid rapidly changes phase to vapour, whereby the large increase in volume (due to the vapour generation) causes a localized pressure increase which can give rise to an air or waterborne blast wave.

Discussion

RPT is a complex phenomenon where the main mechanism causing direct contact between the hot and cold liquid is collapse of the insulating vapour film between the fluids. Upon collapse of the vapour film a chain reaction of rapid superheating of the cold liquid, homogeneous nucleation and explosive expansion is occurring.

Due to the large temperature difference between the hydrogen and the water this phenomenon may not be possible.

RPTs of LH2: previous work

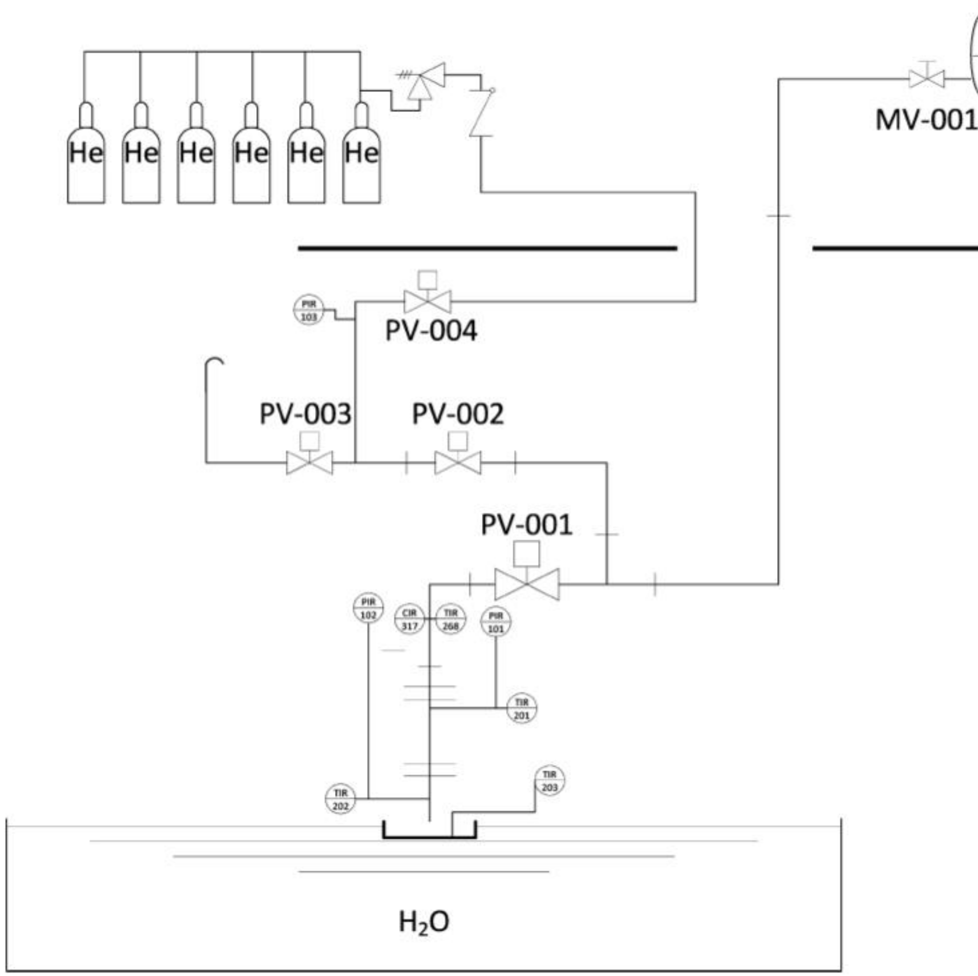
- Releases of LH2 onto water were performed by Verfondern (2007) studying the result of a low-impulse spill. These authors tried to avoid RPTs
- Atkinson (2020) investigated the effect of spraying water onto a pool of LH2. No RPT phenomenon was seen in these experiments either

Experimental set-up

- Experiments were performed at the Test Site Technical Safety (TTS) of the Bundesanstalt für Materialforschung und –prüfung (BAM) in Horstwalde, approximately 50 km south of Berlin, Germany
- To simulate realistic conditions, a 10 m x 10 x 1.5 m basin lined with tarpaulin was created at a 400 m diameter flat circular area next to an 80 m x 80 m concrete pad in the centre of the circular area
- An observation bunker at about 200 m distance from the centre of the test pad is used for controlling and monitoring the tests from a safe distance
- LH2 was supplied from a road tanker via a 46 m long flexible double vacuum insulated transfer line (inner diameter 39 mm) connected to a remotely operated vacuum insulated valve. From there an approximately 10 m long flexible double vacuum insulated transfer line (inner diameter 39 mm) lead to the release nozzle
- The nozzle could be moved up and downwards, enabling releases over and under the water surface
- A part of the flexible hose was inerted using helium before the performance of tests
- Release conditions were monitored by pressure transducers and thermocouples in the release system
- The hydrogen release rate was monitored by load cells onto which the road tanker was placed
- The release rate was varied using the main outlet valve at the road tanker

Experimental set-up

Release system



Measurements

Item/Sensor	Number	Description
Gas sensor for H2	10	NEOHYSENSE NEO974A
Heat radiation sensor	each in 70 m, 90 m and 110 m	Medtherm, Model 64-XX-14
Underwater pressure	2	Piezotronics, type PCB 138A01
Thermocouple	96	Type K, 1.5 mm with Inconel mantle
UAV	1	DJI M300 RTK, optical and IR (DJI Zenmuse H20T)
IR-Camera	1	FLIR E 95
Highspeed camera	1	Redlake Motion PRO X4
Load cells	4	MTS VC 3500
Blast sensors	2	Kistler Pencil Probe, type 6233A
Action cams	Up to 5	GoPro, 4K
Ultasonic anemometers	2	METEK USA-1 scientific

Test programme

- Variation of release rate (3 different rates)
- Variation of release point and direction
  - 50 cm over water surface pointing downwards
  - 30 cm under water surface pointing downwards
  - 30 cm under water surface pointing along water surface

Test programme

Trial	Type of Release	Number of successful releases	Number of rotations of the main valve (max. possible: 16)	Released mass flow (range)
RPT 001	A	1	10	**4 kg/s
RPT 002	A	8	10	0,3 – 1 kg/s
RPT 003	A	1	10	**0,1 kg/s
RPT 004	U	3	10	0,35 – 0,85 kg/s
RPT 005	A	2	10	**0,25 kg/s
RPT 006	U	4	10	0,5 – 1,1 kg/s
RPT 007	U	5	10	0,35 – 0,65 kg/s
RPT 008	U	3	10	0,55 – 0,62 kg/s
RPT 009	U	3	16	0,35 – 0,7 kg/s
RPT 010	U	3	16	0,35 – 0,45 kg/s
RPT 011	A	3	16	0,45 – 1,1 kg/s
RPT 012	A	3	16	0,32 – 0,58 kg/s
RPT 013	A	3	5	0,25 – 0,4 kg/s
RPT 014	U	2	5	0,3 – 0,5 kg/s
RPT 015	U	3	16	0,5 – 0,75 kg/s
RPT 016	U	1	16	0,8 kg/s
RPT 017	A	5	16	0,4 – **1,4 kg/s
RPT 019	A	2	16	0,8 kg/s
RPT 020	A	3	16	1,1 kg/s
RPT 021	U	4	16	0,25 – 0,76 kg/s
RPT 022	U	3	16	0,27 – 0,37 kg/s
RPT 023	UH	3	16	0,53 – 0,78 kg/s
RPT 024	UH	3	16	0,36 - 0,55 kg/s
RPT 025	UH	4	16	0,38 – **0,93 kg/s

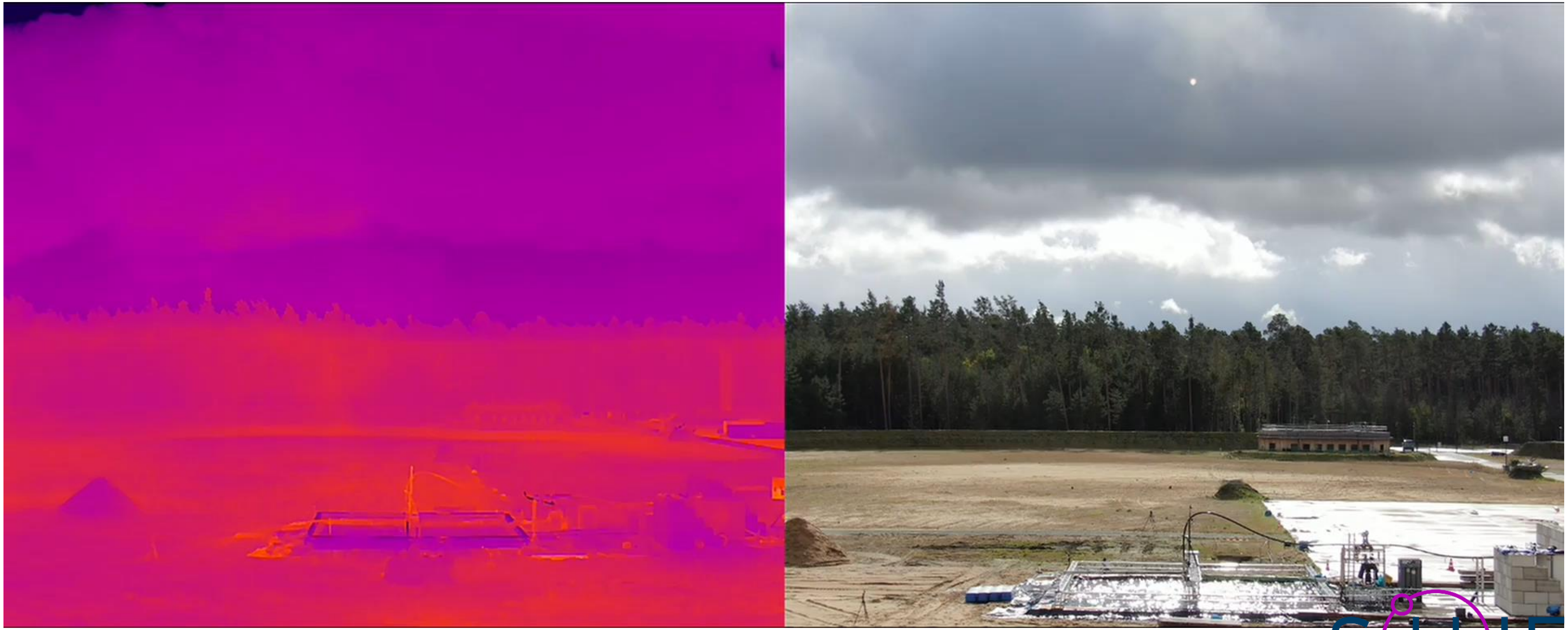
Results: overall observations

- Total of 75 releases
- High pressure in road tanker (typically 10 bar) caused high momentum releases
- LH2 jet penetrated deep into the water
- Evaporation mechanism different from seen for RPTs involving LNG and water
- Due to big difference in density break-up of large bubbles into smaller droplets occurs due to Taylor instability increasing evaporation rate
- Many of the releases resulted in a hydrogen cloud that was ignited

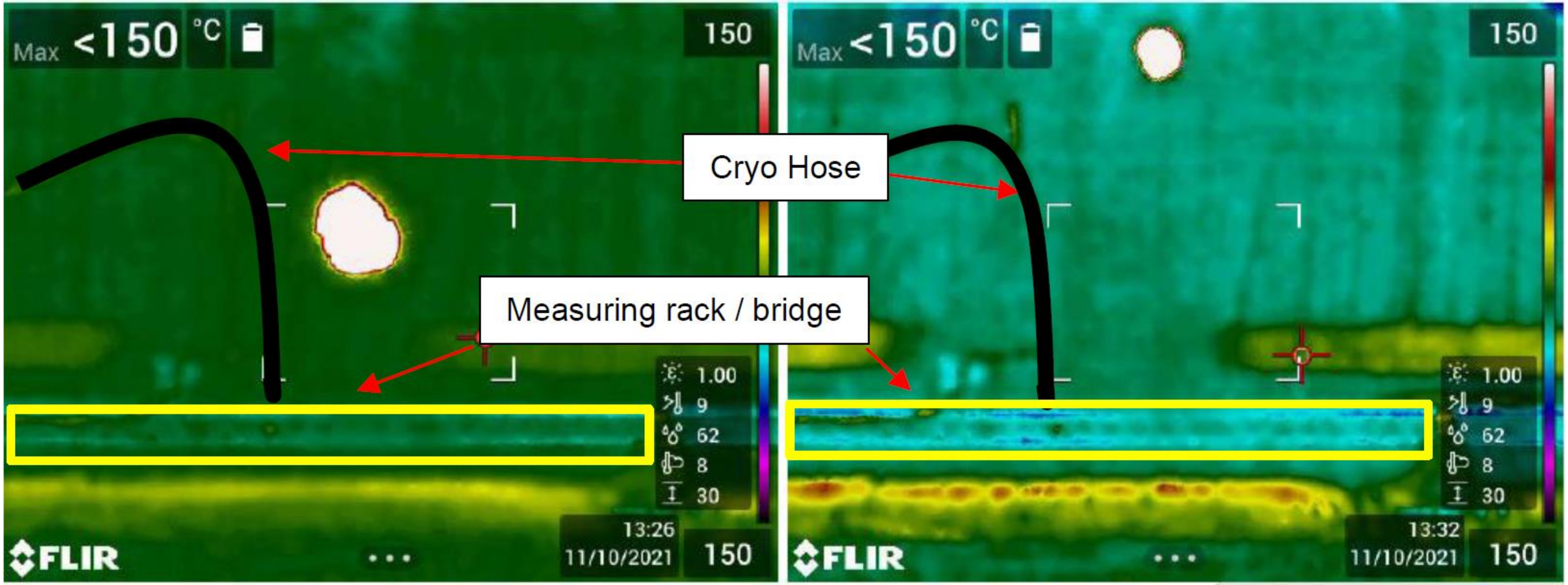
Interaction of hydrogen jet with water (RPT 001)

Interaction of hydrogen jet with water (RPT 001)

Release of liquified hydrogen onto water



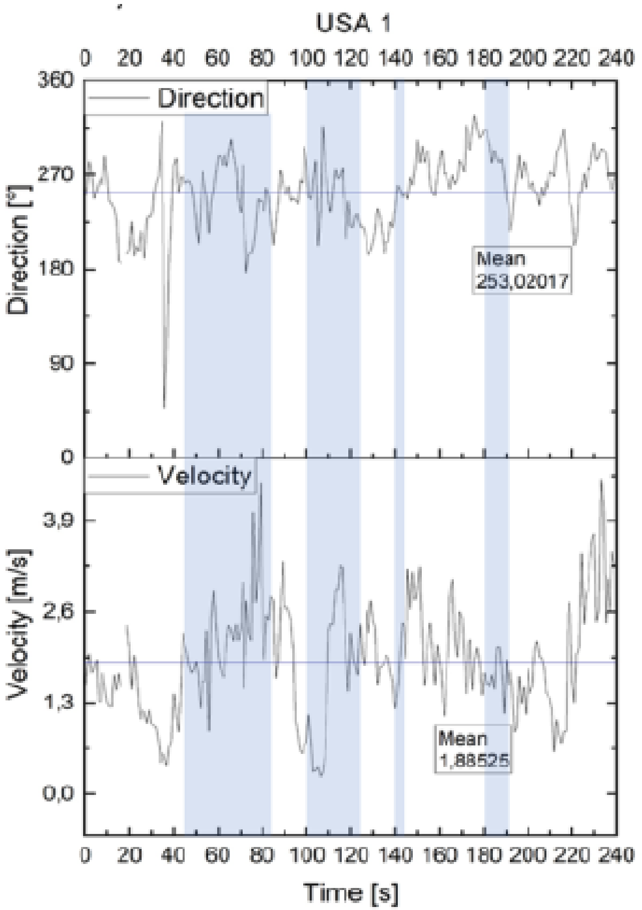
Ignition location (RPT 021)

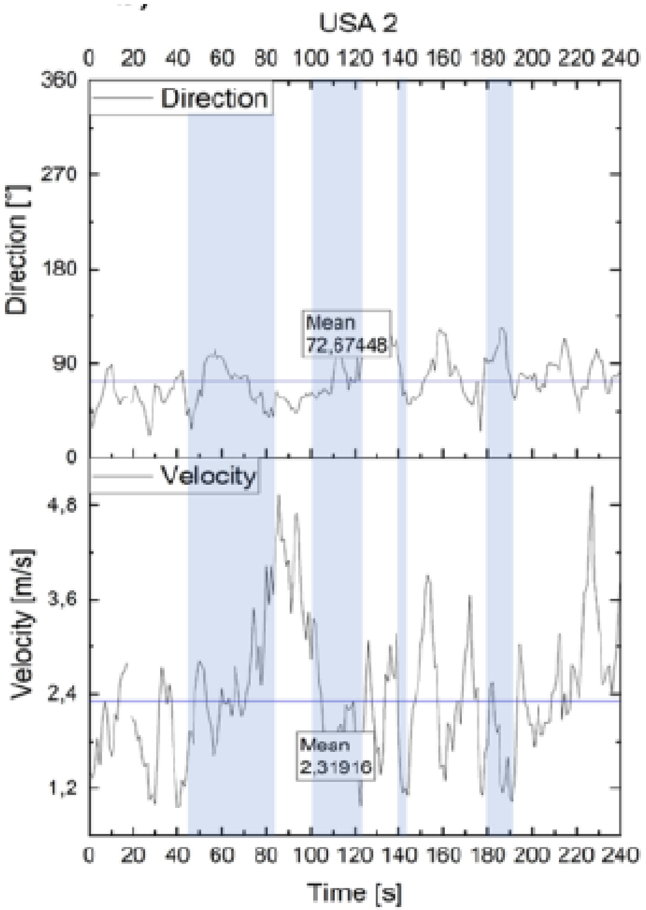


Overall cases of ignition

Type of release	Total number of releases	Total Number of observed ignitions	Percent of releases with ignition
Above water pointing downwards	31	21	68
Under water pointing downwards	34	32	94
Under water pointing horizontal	10	7	70

Hydrogen flammable cloud generation (RPT 021)





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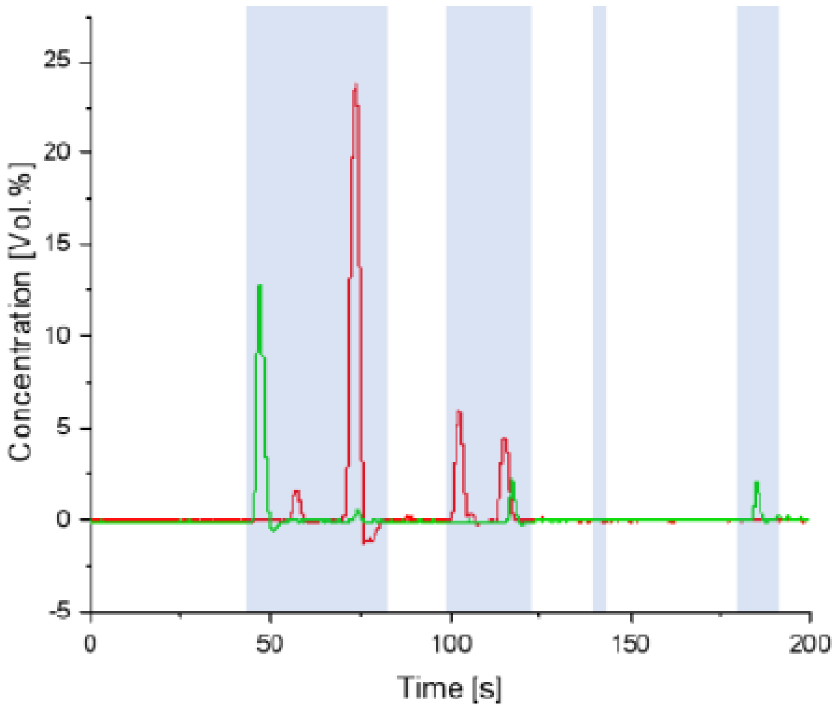
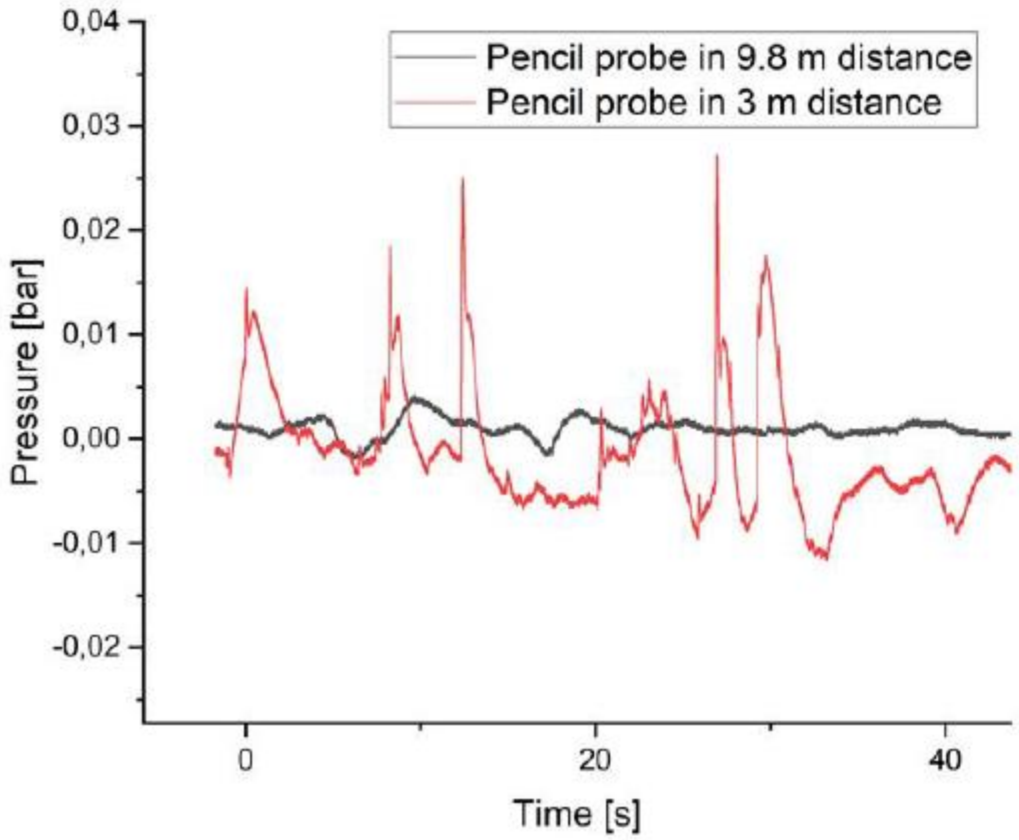
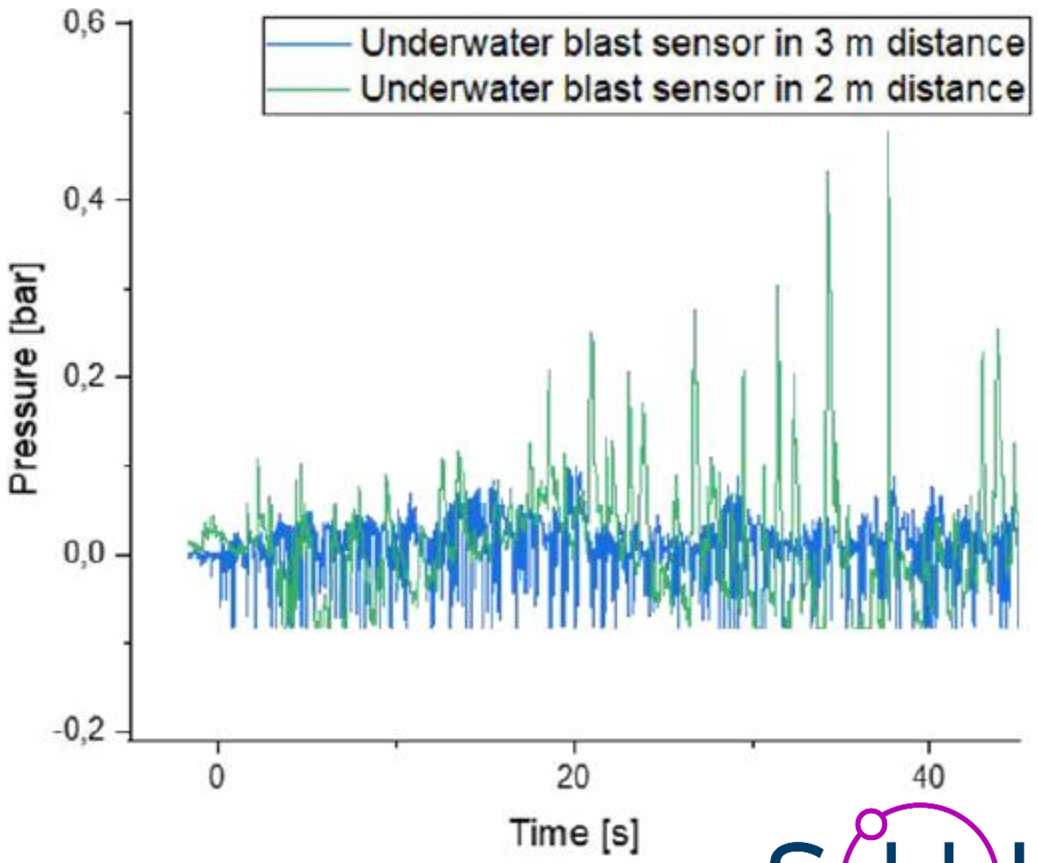
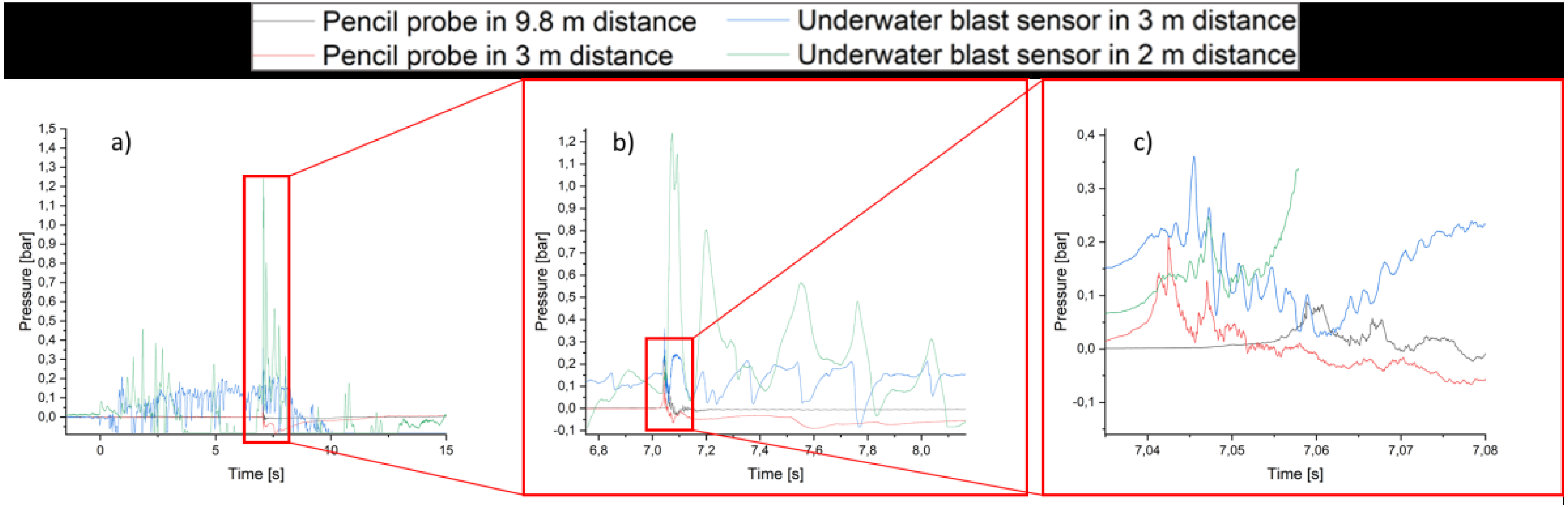


Blast overpressures in case no ignition (RPT 013)

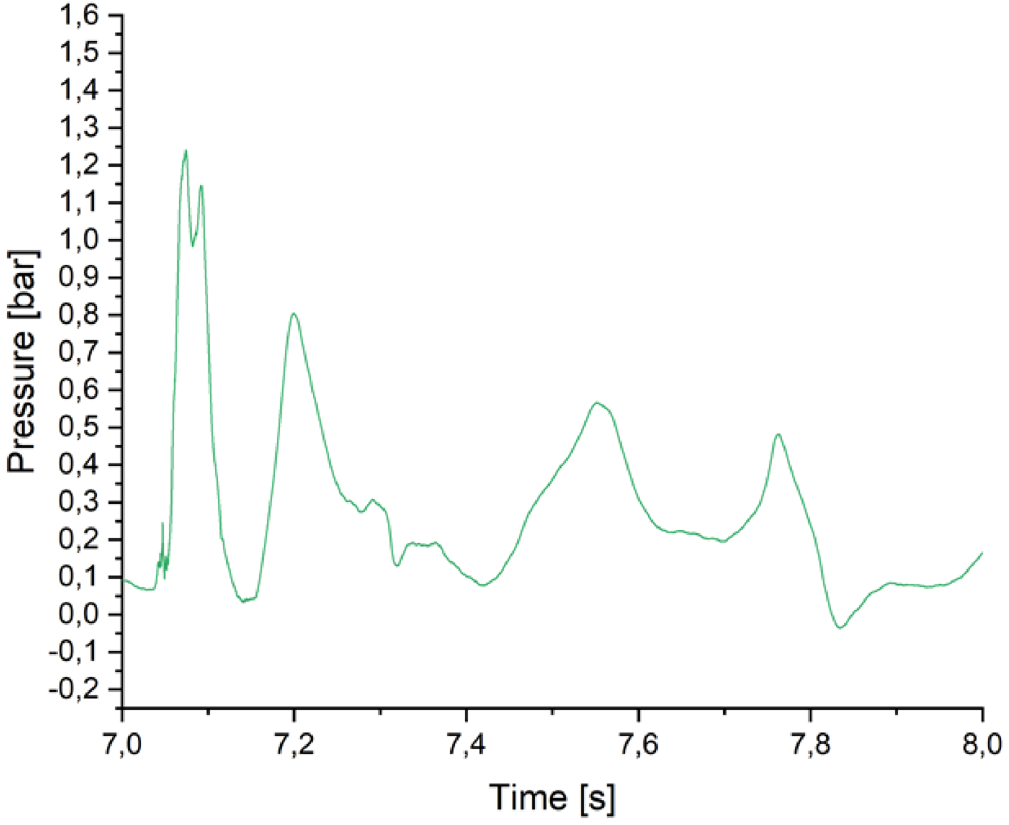




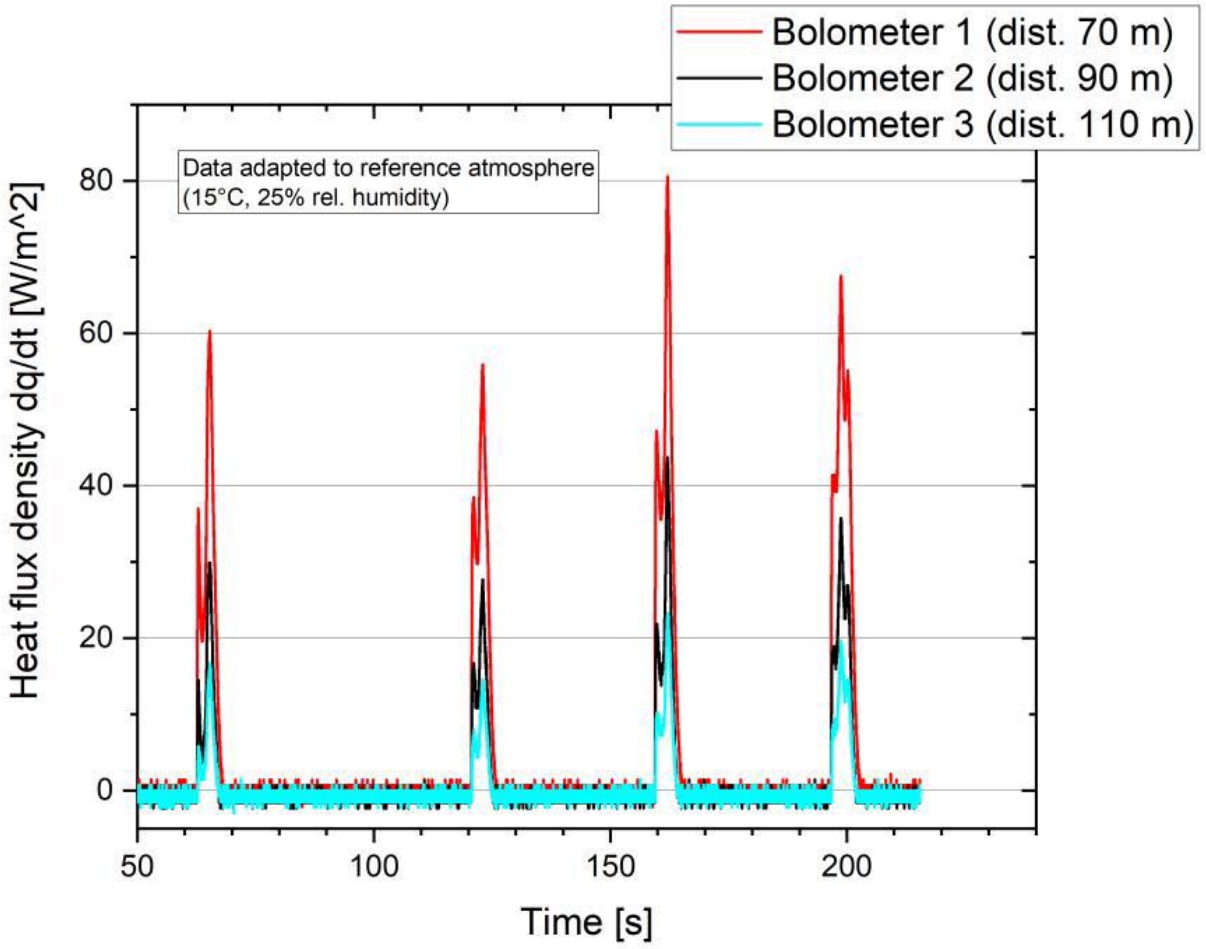
Blast overpressures in case of ignition (RPT 006)



Blast overpressures in case of ignition (RPT 006; underwater sensor



Radiation measurements (RPT 006)



Conclusions

- Pressure waves generated in air upon releasing high momentum LH2 jets into water either from a point above the water surface or under water due to the explosive evaporation are in the range of several 10 mbar
- The evaporation mechanism differs from that described for LNG and water
- The majority of the releases showed an ignition of the generated gas cloud followed by an explosion producing overpressures of up to several 100 mbar in air and up to several bars under water.
- The ignition itself took place in free air and the ignition mechanism is not identified yet.
- The reason for the high pressures under water should also be better understood

Acknowledgement

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Thank you!

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