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Experimental Investigation into the Consequences of Release of Liquified Hydrogen onto and under Water

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Large-scale experiments have been performed to investigate the possible consequences of realistic amounts of liquified hydrogen (LH_2) encountering water. The experiments aimed at simulating an accidental release of LH_2 onto water, for instance during the fuelling of a ship. For liquified natural gas (LNG), it has been demonstrated that physical explosions may occur when it is spilled onto water. These phenomena are referred as rapid phase transitions (RPTs). It cannot be excluded that RPTs are also possible in the case of LH_2. The tests were performed at the Test Site Technical Safety of the Bundesanstalt für Materialforschung und –prüfung (BAM) in Horstwalde, Germany. The tests were performed in a 10 m x 10 x 1.5 m basin filled with water. LH_2 releases of up to about 1 kg/s were established releasing directly from a trailer carrying LH_2. The releases occurred from a height of 50 cm above the water surface pointing downwards, 30 cm under the water surface pointing downwards and 30 cm under the water surface pointed along the water surface. All release configurations resulted in a very chaotic LH_2-water mixing zone, causing considerable evaporation and resulting in minor over pressures. No RPTs were observed. The main phenomenon to be observed is, however, an ignition of the released gas cloud resulting in significant blast wave overpressures and heat radiation to the surroundings. The ignition occurred in all under-water releases and in about 90 % of the releases above the water surface.

1. Introduction

In industries where liquids of widely differing temperatures and boiling points are handled, a safety concern is the possibility of rapid phase transitions (RPTs) if low and high-boiling point fluids accidentally come in contact. RPTs are strong physical explosion that can damage plant and structural items as seen in the metal-casting industry when water comes into contact with liquid metal (Zielinski et al, 2011), or in the liquified natural gas (LNG) industry if LNG is accidentally released onto water where several accidents have been reported (Cleaver et al, 1998). For LNG RPTs one differs between *early RPT* and *late RPT*, signifying whether the RPT occurs in the LNG-water mixing zone (early) or away from the mixing zone where a pool has formed on top of the water surface (late) (Ustolin et al, 2020; Lervåg et al, 2021). In this work the possibility and consequences of early LH_2 RPTs are studied.

RPTs have been pointed out as a possible hazard when handling LH_2 particularly for the maritime sector for ships fuelled by or transporting LH_2. A failure of a system used for transferring LH_2 from and towards land-based storage systems or a trailer could lead to a spill onto or under water. LH_2 RPTs have received little attention, and experiments are limited to a study by Verfondern and Dienhart (2007) where the result of a low-impact spill was investigated and by Atkinson (2020) where a spray of water was applied to LH_2. None of these experiments resulted in RPTs. A theoretical study reported by Odsæter et al. (2021) concluded that late LH_2 RPTs are very unlikely, and that early RPT is less likely to occur for LH_2 than for LNG. The conclusions are based on the understanding of the phenomenon of RPTs occurring when LNG comes into contact with water and is especially

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related to the low Leidenfrost temperature of LH_2 preventing a collapse of a vapour film separating LH_2 and water. Moreover, Odsæter et al. (2021) demonstrated that if RPTs occur when LH_2 is brought into contact with water overpressures generated will be considerably lower than for LNG.

The current paper presents a series of experiments performed to investigate the possibility and potential consequences of RPTs when releasing LH_2 onto or under water. The experiments aimed at simulating realistic conditions during LH_2 filling operations. The release rate was varied between 0.25 kg/ and 0.8 kg/s.

2. Experimental set-up

The 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, where the Blast Area 2 was used.

A 10 m x 10 x 1.5 m basin was created next to test pad. To contain the water the basin was lined with tarpaulin. Figure 1 shows the basin (on the left), the trailer carrying LH_2 positioned behind a concrete wall for protection and a container for logging equipment (also protected by a concrete wall). Onto the basin a bridge construction was erected for fixing the release mechanism/point and instrumentation.

Figure 1: View of the test set-up to study the release of LH2 onto and under water. The picture shows the basin on the left with a bridge structure for holding the release mechanism and instrumentation. On the right the trailer, 1, carrying the LH2 and the cabin, 2, used for logging equipment.

The LH_2 is released directly from the trailer carrying the LH_2 via an approximately 46 m long flexible double vacuum insulated transfer line (inner diameter 39 mm). The release mechanism allows for an initial phase to release flashed LH_2. A thermocouple inserted near the nozzle is used to indicate the presence of LH_2 at the nozzle. The nozzle could be moved up and downwards relative to the water surface and also moved into the water. The release system has been provided with an emergency release point as well and was purged with helium before starting a release (Figure 2). A mouthpiece at the end of the release line as well as a manually operated valve at the trailer were used to vary the release rate.

3. Test program

More than 80 single releases were performed at release rates of approximately 0.25 kg/s, 0.5 kg/s and 0.8 kg/s. The point of release and release orientation was approximately 50 cm over the water surface oriented vertically downwards, approximately 30 cm under the water surface oriented vertically downward and approximately 30 cm below the water surface oriented horizontally parallel to the water surface.

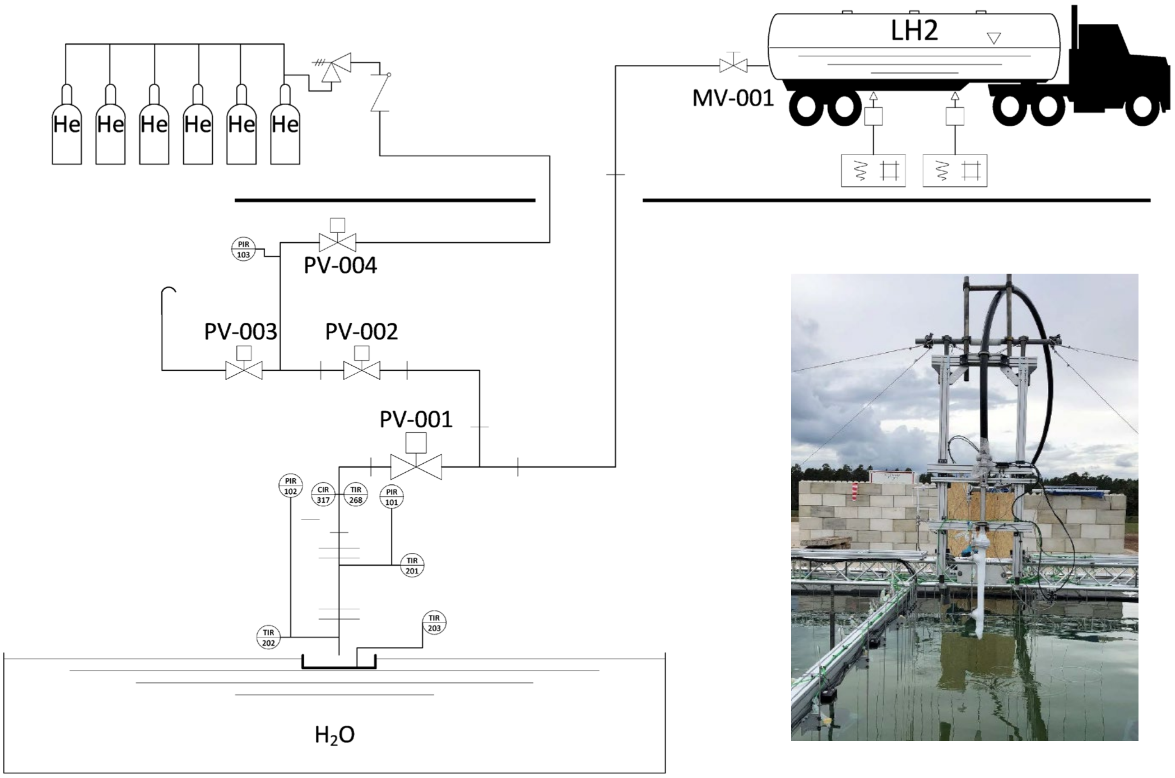

Figure 2: Schematic showing the LH2 supply system. The system consists of double vacuum insulated hoses with valves designed for use with LH2. A special T-piece can be used as a safety system in case of freezing of the nozzle (due to contact with water) as well as for releasing flashed LH2 during the initial phases of a release. The system can be purged with helium before releasing LH2. The insert shows the release mechanism shortly after a release of LH2, 50 cm above the water level pointing downwards.

4. Instrumentation

The temperature of the water (just underneath the water surface) and the air (just above the water) was measured at multiple locations. The temperature of the air was also measured at H_2 concentration probe locations. In total 63 thermocouples (type K) were used for this purpose. In addition, the temperature in the filling line was measured (1 at the outlet and 1 further down into the filling line). The pressure in the filling line was also measured at 3 locations, one located at the outlet. The release rate is determined based on the weight loss rate of the road tanker which was placed on load cells. Special blast pressure sensors were used to measure the shock waves generated by the RPTs or other phenomena both in the water (Piezotronics, type PCB 138A01 underwater blast transducer) and in the air. At several locations (10) the gas concentration development in time was measured (using H_2 concentration sensors with a response time of approximately 1 s). Heat radiation was measured at distances of 70 m, 90 m and 110 m from the point of release. High speed, infrared (IR) and normal cameras were used to record possible RPT development and to follow the gas cloud behaviour in time. This includes cameras mounted on a drone and an underwater camera. Two weather stations were used to measure wind speed, wind direction, temperature and humidity during all tests performed.

5. Results

The results presented in the following are from one single trial with 4 separate releases above the water surface with release rate approximately 0.8 kg/s. The observations are however similar for all other trials. The majority of the tests were performed with a relatively high vapour pressure in the trailer, typically 9-10 bar. When released into atmospheric conditions, a significant degree of flashing occur. As a result, a relatively high-momentum multiphase jet was generated which penetrated deep into the basin as could be observed from the underwater camera (Figure 3). Massive evaporation is observed, but no sudden bursts are detected. The camera recordings reveal a very chaotic mixing zone that seem to pulsate due to the interplay between volume production from evaporation, insulating bubbles, buoyancy, and the continuously incoming jet.

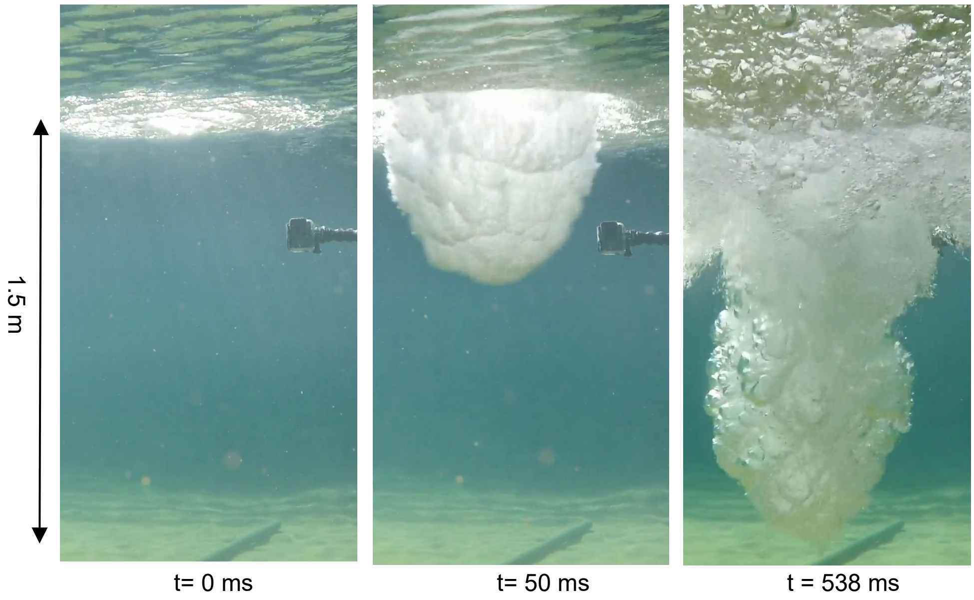

Figure 3: Multiphase jet penetrating the water (release rate 0.8 kg/s, release location 50 cm above the water pointing downwards). At t=0 ms the jet touches the water surface. At t= 50 ms the jet has penetrated about 0.5 m into the water. At t=538 ms the jet has almost reached the bottom of the basin at 1.5 m depth.

The larger bubbles only form on the sides of the impact zone and the vapour layers between LH_2 and water and the bubbles themselves are disintegrated due to what seems to be Taylor instabilities. The evaporation is not homogeneous and frequent Geysir-like jets propel out of the water. This Geysir-phenomenon is not associated with a large overpressure.

Pressures that are generated by the evaporation process described above are limited. Pressures measured in air at a distance of 3 m never exceeded 30 mbar, and at 10 m distance never exceeded 15 mbar. H_2 concentrations during the 0.8 kg/s release are shown in Figure 5. The concentrations measured above the point of release reach flammable concentrations more or less continuously during the release with some periods where the concentration is at or even above the stoichiometric concentration of 29.5 % (the minimum ignition energy of hydrogen is found at a concentration of about 33 % in air (Hankinson et al, 2009)).

Although RPTs did not occur the gas clouds generated by the evaporation of LH_2 ignited in nearly all experiments. The underwater releases (horizontally and vertically downwards) resulted in an ignition in all cases whereas the releases from 50 cm above the water resulted in clouds getting ignited in 90% of the cases.

Furthermore, it could be observed that with a low pressure in the trailer resulting in a lower momentum release, ignition did not occur, indicating that the observed ignition is dependent on the momentum of the release.

The ignitions resulted in very strong blast waves in the near field of the release location. Blast pressures of up to 0.4 bar were measured in air. Under water pressures of several bars were seen when ignition occurred. Flame speeds are in the order of 200 m/s indicating a very turbulent cloud. The blast effects, flame speeds and size of the flammable cloud are dependent on the release rate.

The ignition source is unknown. Tests were performed with all electronic and electrical equipment at the basin switched off. The instrumentation bridge itself was duly grounded. Only far field camera recordings were done. In every of these releases ignition was observed. Using the IR-cameras it could be confirmed that the ignition location was at some distance from the instrumentation bridge and any instrumentation (Figure 6).

Shock waves and shock-wave reflections as an explanation of “spontaneous ignition” in vent lines cannot have been the source of ignition here since RPTs did not occur and the pressure waves generated by the observed fast evaporation of LH_2 are too weak. Electrostatic discharges and especially corona discharges at ice crystals (Petersen et al, 2015) evolving from the release/evaporation process may be an alternative explanation provided a sufficiently strong electric field is generated by e.g., the freezing of water particles in the air generated by the sudden evaporation of LH_2. Further analysis of the experimental results is needed to investigate the mechanisms further.

Incident heat radiation measurements were performed at distances of 70m, 90m and 110m. At 70 m heat radiation peak values of 0.1 kW/m^2 were measured. Figure 7 shows the heat radiation profiles seen during the 4 ignitions in a test where 4 releases of 0.8 kg/s were established.

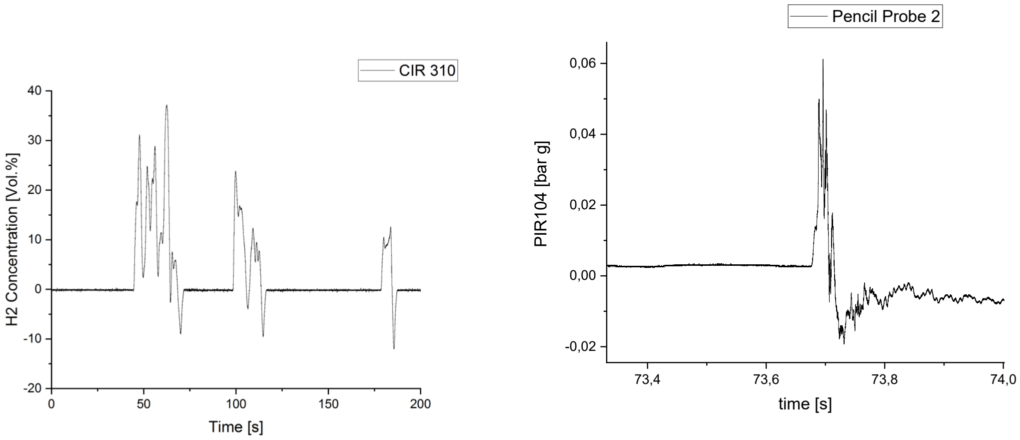

Figure 5: left: Hydrogen concentration profiles measured above the point of release (release rate 0.8 kg/s), right: pressure reading in air at a distance of ~10 m from release position for test 2 of trial 021

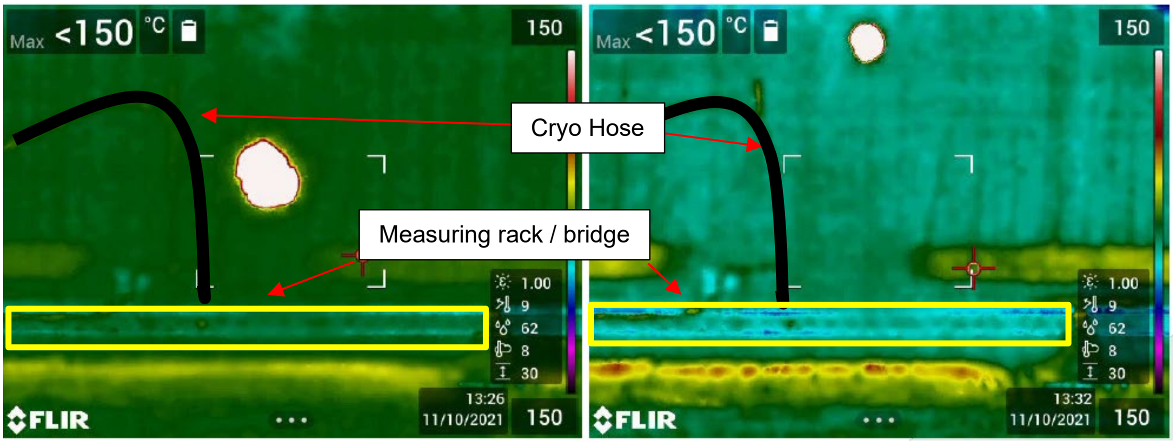

Figure 6: Moment of initial flame propagation in hydrogen-air clouds ("white spots") generated by releases of LH2 onto and under water. The ignition location appears to be somewhere in the cloud at a distance from any physical object. The locations of the release point (cryo hose) and measuring rack/bridge have been indicated.

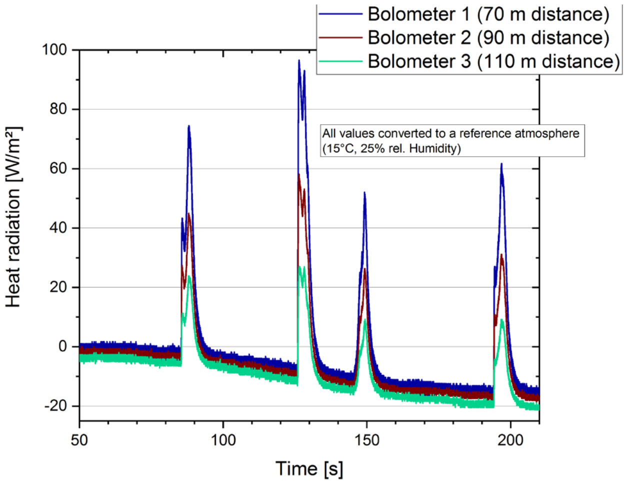

Figure 7: Heat radiation measurements during a test where 4 releases of 0.8 kg/s were established.

6. Conclusions

An experimental investigation performed at large-scale releasing 0.25 kg/s to 0.8 kg/s of LH_2 onto and under water showed that RPTs, as seen when releasing LNG onto water, do not occur. A violent and fast evaporation of LH_2 does occur upon injection into water. Pressure waves due to the impact and the evaporation process are in the mbar range, and are not dangerous and will not cause any damage or risk to personnel.

A flammable cloud is generated above the water surface which in almost all release scenarios investigated ignited. The ignition occurs in free air, and no ignition source has yet been identified. The ignition of the cloud caused considerable blast pressure both above and under water which can cause significant damage in the near field. Further analysis of the experimental results will be performed to draw more conclusions of the experimental campaign.

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