Pre-normative REsearch for Safe use of Liquid Hydrogen (PRESLHY)

Project Deliverable

Experimental investigation of Pre-mixed Systems with Cryogenic Hydrogen

Deliverable Number:	5.3 (D20)
Work Package:	5
Version:	1.2
Author(s), Institution(s):	T. Jordan, KIT; M. Kuznetsov, KIT
Submission Date:	31 May 2021
Due Date:	31 May 2021
Report Classification:	Public

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

History		
Nr.	Date	Changes/Author
1.0	31.5.2021	Release version by T. Jordan KIT
1.1	31.10.2021	M. Kuznetsov KIT

Approvals			
Version	Name	Organisation	Date
1.2	A. Friedrich	KIT	08.12.2021

Acknowledgements

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

Disclaimer

The data management in the PRESLHY project follows the principle of data management, which shall make data Findable, Accessible, Interoperable and Re-usable (FAIR). The plan for FAIR data management as described in this document is based on the corresponding template for open research data management plan (DMP) of the European Research Council (ERC).

Despite the care that was taken while preparing this document the following disclaimer applies: The information in this document is provided as is and no guarantee or warranty is given that the information is fit for any particular purpose. The user thereof employs the information at his/her sole risk and liability.

The document reflects only the authors' views. The FCH JU and the European Union are not liable for any use that may be made of the information contained therein.

Key Words

Cryogenic, combustion, hydrogen, jet fire, flame acceleration, deflagration-to-detonation transition, confinement, congestion, pre-mixed clouds

Publishable Short Summary

WP5 of the PRESLHY project focussed on combustion phenomena of hydrogen at cryogenic conditions. This report summarises the experimental work consisting of the 4 experimental campaigns: Ignited DISCHA experiments for investigating transient jet fire pressure and heat radiation effects, CRYOTUBE experiments for analyzing the flame acceleration and DDT at cryogenic temperatures, semi-open channel experiments for simulation of flame propagation over a spill of LH2 and flame propagation in obstructed /confined cold cloud.

Table of Contents

1 Ignited DISCHA experiments (experimental series E5.1)

In these experiments the modified DISCHA facility was applied by KIT and Pro-Science to investigate the combustion behaviour of discharged cryogenic hydrogen at temperatures of approximately 80 K and pressures up to 200 bar.

1.1 General description of the DISCHA facility

Due to the expected strong pressure waves and the resulting loudness of the experiments it was not possible to conduct these tests in the premises of KIT. So, after negotiations with the Institute of Construction Engineering of KIT-Campus South their free-field test site was loaned to conduct the Ignited DisCha experiments. This test site is located in the woods approx. 2 km north of the northern end of KIT Campus North and the closest inhabited buildings have a distance of approx. 2 km to it (see Figure 1).

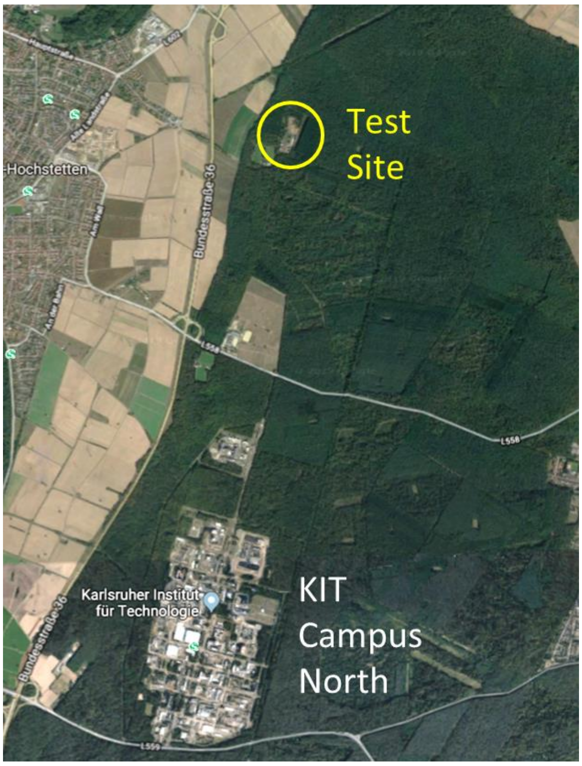

Figure 1: DisCha-facility in the free-field test site north to KIT-Campus north.

The test site is connected to the municipal electricity and water grid, but no internet is available at the test site and also no solid buildings can be utilized to house the infrastructure of the test facility. A tent was used to protect technical equipment and personnel from the weather, while the DisCha-vessel itself was assembled without any protection. A photograph of the facility is shown in Figure 2.

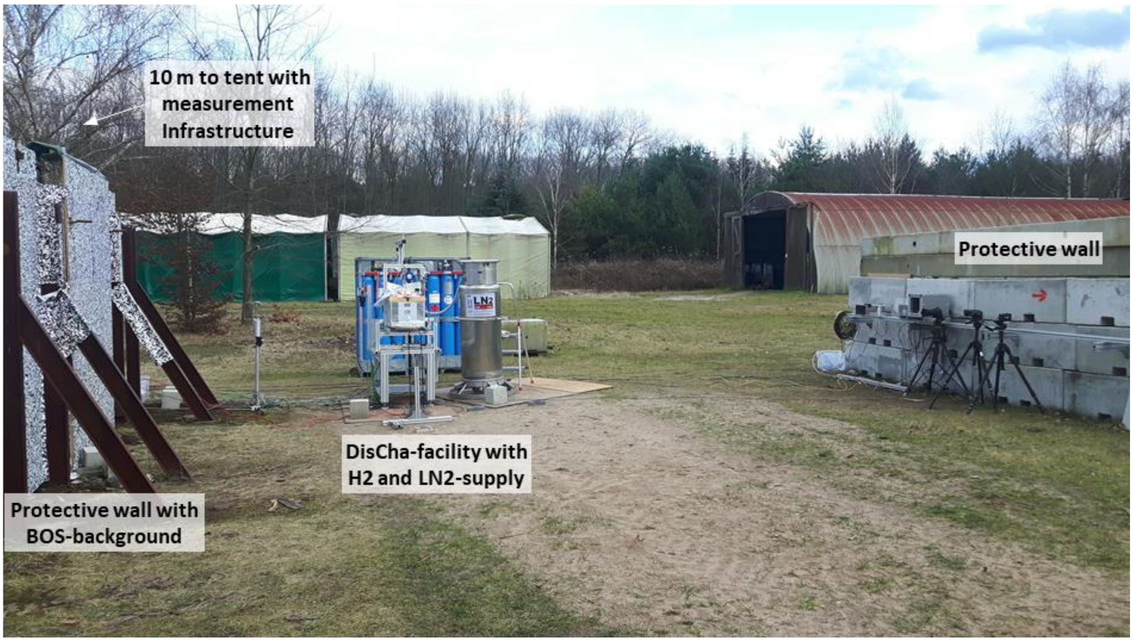

Figure 2: DisCha-facility in the free-field test site north to KIT-Campus North.

The main objectives of the tests are to close knowledge gaps and to generate data for model validation of e.g. hazard distances due to pressure and heat radiation effects during delayed ignitions of cryogenic hydrogen jets. The tests are closely related to the discharge tests of E3.1, but here the transient cryogenic hydrogen jets are ignited at different axial positions and with different time delays after nozzle opening.

The effects of the following variables on the maximum combustion pressure and the heat flux are investigated:

- initial pressure,
- nozzle diameter,
- ignition location and
- ignition delay time.

The measurements consist of pressure and temperature measurements in the DisCha-vessel, remote pressure, heat flux and temperature measurements of the ignited jet. High-speed video combined with BOS imaging is provided for visual observation of explosion phenomena.

The DisCha facility mainly consists of a stainless-steel pressure vessel with an internal volume of 2.8 dm^3 which is fastened in an insulated box for the LN2 pool cooling (Remark: the original plan to cool the DisCha facility in a pool of LH2 was discarded because of the high costs and the volatile boiling behavior expected for LH2, which, in connection with a burning jet might lead to a strong combustion event that might destroy the complete facility. Furthermore, the vessel is designed for LN2 boiling temperature as minimum operational temperature). A photograph of the naked vessel and a sketch of the facility are shown in Figure 3.

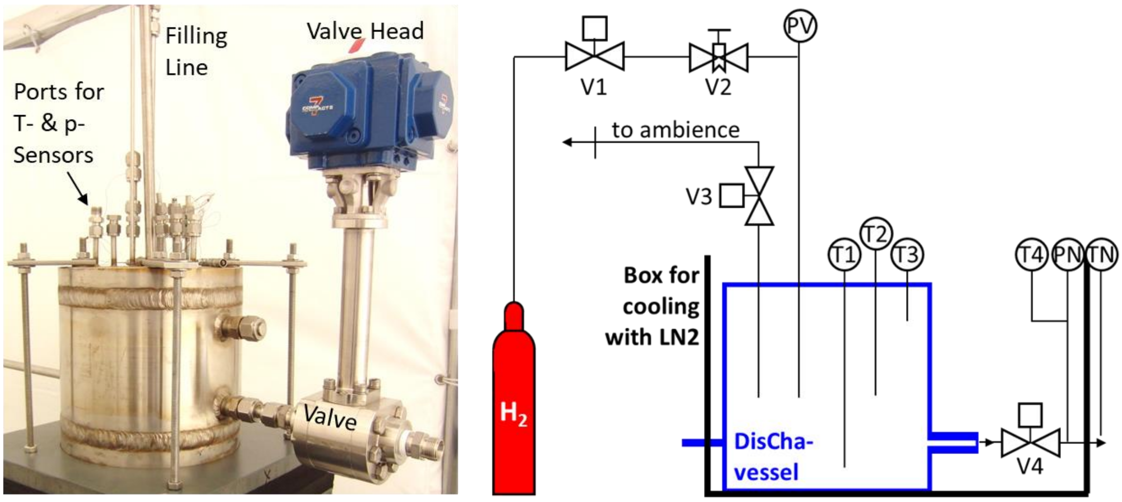

Figure 3: Photo of DisCha-vessel with valve (left) and sketch of the complete facility(right).

1.2 Instrumentation

As in the previous series of unignited DisCha experiments (PRESLHY-Deliverable Number: 3.4 (D21)) inside the test vessel and the release nozzle two pressure sensors and four thermocouples were used. But since the effusion behavior of H2 was already investigated in the previous series, neither force sensor nor balance were used in the ignited DisCha experiments. For the same reason outside the release nozzle no temperature and H2-concentration measurements were performed, but instead, to record the pressure phenomena during the combustion, a set of six fast and sensitive pressure transducers was distributed on the ground in two lines. Four cameras (two regular and one high speed video camera as well as one photo camera) were used to monitor the ignited H2-releases using the BOS-technique for the visualization of density gradients. Furthermore, an infrared camera was utilized to monitor the heat release during the combustion process.

Static pressure sensors: One static pressure sensor (PV in Figure 3) in the filling line is used to control the initial pressure inside the vessel during the filling procedure, while the second static pressure sensor (PN) measures the pressure changes in the release line. Since the second sensor is connected to the tube in between release valve and nozzle, the first increase in this signal corresponds to the actual start of the release. After the initial pressure built-up in the release line both pressure sensors capture the pressure decrease inside the vessel during the experiment.

Thermocouples (TCs): In the ignited DisCha experiments only one set of three NiCr/Ni-thermocouples (Type K, diameter 0.36 mm, T1 to T3 in Figure 3) is installed inside the vessel to record the gas temperature during the experiment in different heights. In the release line two further thermocouples of the same kind are positioned: T4 is welded into the line to measure the temperature inside it, while TN is mounted from the outside in a hole in the material of the stainless-steel nozzle aperture with no direct contact to the flowing gas (see Figure 4).

Dynamic pressure sensors: Five dynamic pressure sensors of Type PCB 112A22 and 113B28 (range 0 - 3.5 bar, open circles in Figure 4) and 113B21 (range 0 - 14 bar, solid black circles in Figure 4) were distributed on the ground in front of the release nozzle, which has a height of 111,3 mm above the ground. All sensors were mounted in cap-like adapters on the top of lead bricks to prevent them from being displaced by the pressure waves.

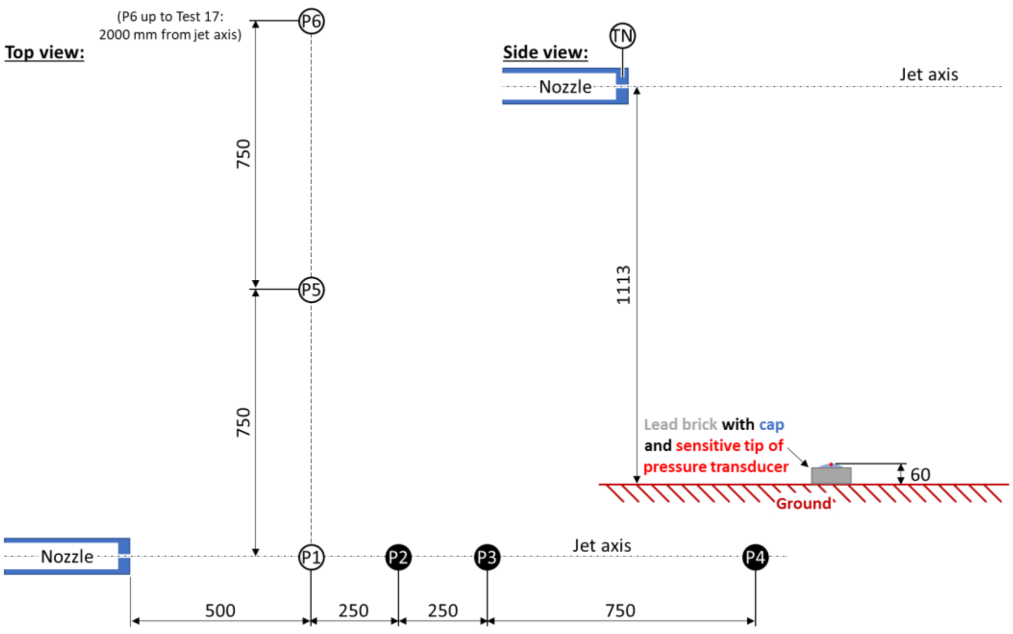

Figure 4: Sketches of the ex-vessel instrumentation of the DisCha-facility with fast pressure transducers.

Ambient conditions: An ultrasonic anemometer was utilized to record the ambient temperature and wind conditions during the experiment. It records the wind speed in three directions (N to S, E to W, and in vertical direction) and also records the temperature. It was positioned on a tripod in 1.2 m distance besides the DisCha-vessel (see Figure 4).

Ignition source: A high frequency spark igniter (60 kV, 20 kHz) was used to ignite the H2-air mixtures generated by the jet releases. It consists of two long insulated electrodes with bare sharpened tips that were mounted to a small stand of aluminum profiles, which was used to move the electrodes to the different ignition positions

Cameras: All cameras were positioned in a distance of 6 m to the left of the jet in the height of its centerline. In all experiments a fast video camera (DAL; Dalsa camera with 70 fps) and the Infrared camera (FLIR, T540, 30 fps) were positioned close to the near and the far end of the expected jet monitoring the complete section covered with BOS-background pattern (Figure 7). Due to the different ignition positions with various distances to the nozzle (40 cm to 2 m) two set-ups for the remaining three cameras were realized. In the cases with near ignition (ignition distance to nozzle up to 1 m) the high-speed camera (HS, Photron FastCAM SA 1.1, 5.4 kHz at maximum resolution) and a regular video camera (PV; Panasonic camera with 24 fps) were positioned in a way that allowed to capture the region close to the nozzle and the first 3 m of the jet release. To supervise also the region farther downstream from the nozzle a Canon Photo camera was positioned close to the Infrared camera (upper part of Figure 5). In the experiments with far ignition (distance to nozzle > 1 m) the high-speed camera and the regular video camera were also positioned in downstream positions while only the Dalsa-camera was used to monitor the jet region close to the nozzle (lower part of Figure 5).

To the right of the jet, opposite to the cameras, random black and white box background patterns with different resolution were glued to wooden walls to utilize the BOS optical method for the visualization of the cold H2-jet releases and the hot combustion processes. In the part behind the nozzle area a finer random black and white box-pattern was used, while in farther distances coarser patterns were installed.

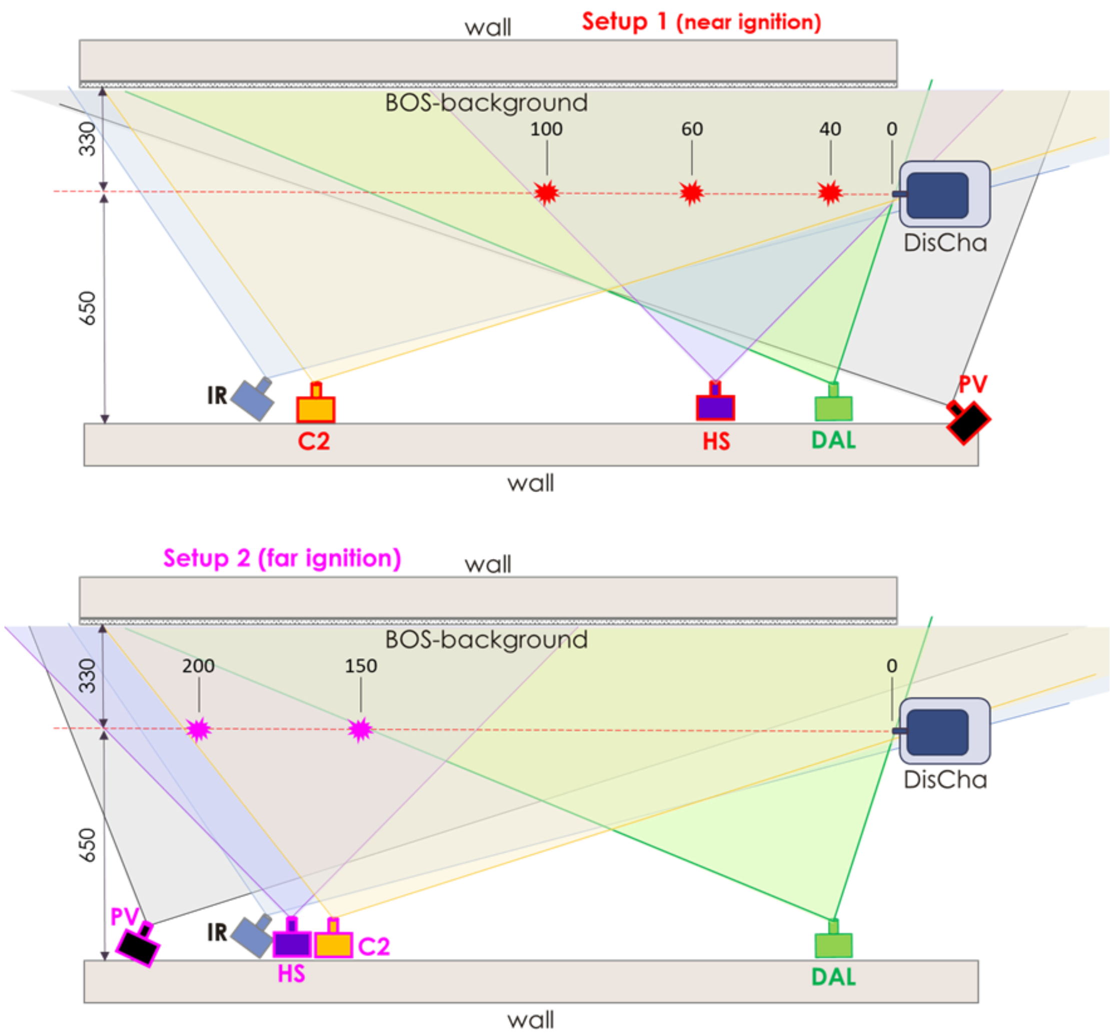

Figure 5: Sketch of positions and view field of the various cameras in the ignited DisCha-experiments

1.3 Test matrix

Possible variables to be investigated in the ignited DisCha experiments are:

- nozzle diameter
- initial gas (H2) pressure
- initial gas (H2) temperature
- ignition position
- ignition duration
- ignition delay time

To cover the influence of all the above variables an almost infinite number of tests with different settings is necessary. To reduce this number to a reasonable value it was decided to concentrate on three nozzle diameters (1, 2, 4 mm), four initial pressures (5, 50, 100, 200 bar), two initial temperatures (approx. 80 and 280 K), five ignition positions (in distances of approx. 40, 60, 100, 150 and 200 cm from the nozzle on the jet axis) and one ignition duration (1 s). Without varying the ignition delay time this would lead to a set of 120 tests which seemed to be feasible to be performed and evaluated within current project. Nevertheless, a variation of the ignition delay time also seemed promising, so in an

initial test series several parameters were randomly tested with different ignition delay times to determine the settings where maximum pressure loads are obtained.
The test matrix for the second test series comprised two temperatures (ambient temperature and temperature of boiling nitrogen (approx. 80 K)), three nozzle diameters (1, 2, 4 mm), four initial pressures (5, 50, 100 and 200 bar) and four ignition distances (39.5, 62.5, 105, 150 and 200 cm).

1.4 Experimental results

Transient cryogenic hydrogen jet fire behaviour, including scaling and radiation properties is investigated with the DISCHA facility (Figure 3). Hydrogen inventory will be changed depending on the initial pressure from 4.4 to 138 g H2 with initial pressure changes from 0.5 to 20 MPa and LN2 temperature about 80K. Similar as for the unignited discharge experiments the nozzle size was varied from 1-4 mm id. Measurements consisted of background imaging system (BOS) combined with a high speed camera, fast pressure sensors and thermocouples. Additionally a thermos-vision FLIR camera allowed monitoring the transient temperature fields. With known mass flow rate and hydrogen distribution profile as a function of initial pressure and temperature, hydrogen ignition phenomena and further flame development are investigated with respect to maximum combustion pressure, temperature and heat flux radiation for model validation and hazard distance evaluation.

Unburned cold hydrogen jet was ignited with different delay time after jet initiation at different distances from the nozzle. Then, a strong explosion with formation of a spherical shock wave might occur just after ignition (Figure 6). The over-pressure from 0.04 to 0.115 MPa corresponds to a visible shock wave velocity from 390 to 480 m/s measured by high speed BOS imaging.

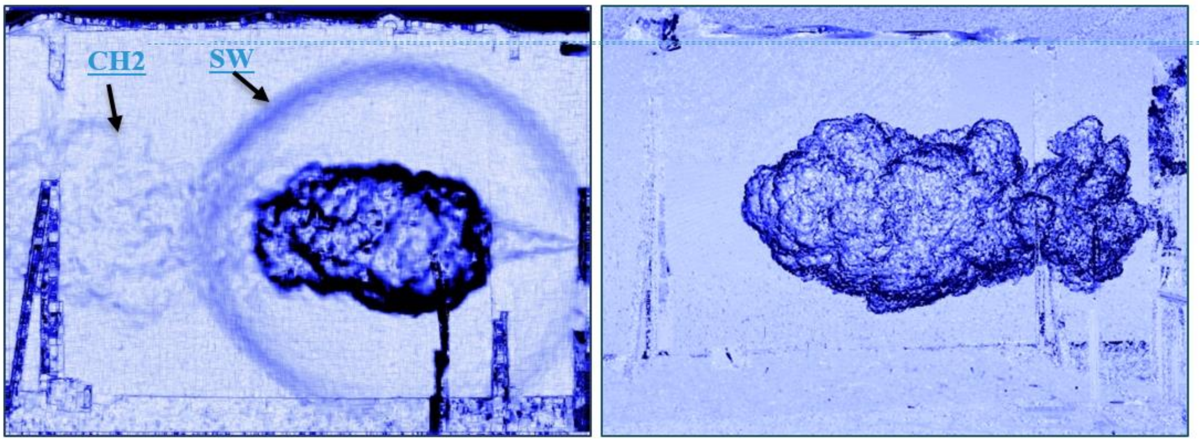

Figure 6: A shock wave formation (left) and a stationary jet fire (right) established under ignition of 4-mm nozzle and 20 MPa pressure hydrogen release: SW –shock wave; CH2 –unignited hydrogen.

A sequence of frames with temperature distribution is obtained by thermo-vision FLIR-Camera (15 fps) (Figure 7). For ambient conditions 285K the local maximum combustion temperature changes from 1100 to 540K corresponding to maximum heat flux of 85 kW/m2. At the same time, the average integral heat flux of whole surface is about 6.5 kW/m2. At cryogenic temperature of 80K, the maximum temperature changes from 1330 to 710K corresponding to maximum heat flux of 177 kW/m2 in the center of jet fire. The average integral heat flux of whole surface is about 11 kW/m2. The reason of such difference is four times larger hydrogen inventory and also 2.5 times higher mass flow rate at cryogenic temperature leading to 1.3 times higher temperature, 2 times higher heat flux of flame radiation, 1.5 times larger flame length and 1.4 times longer release time.

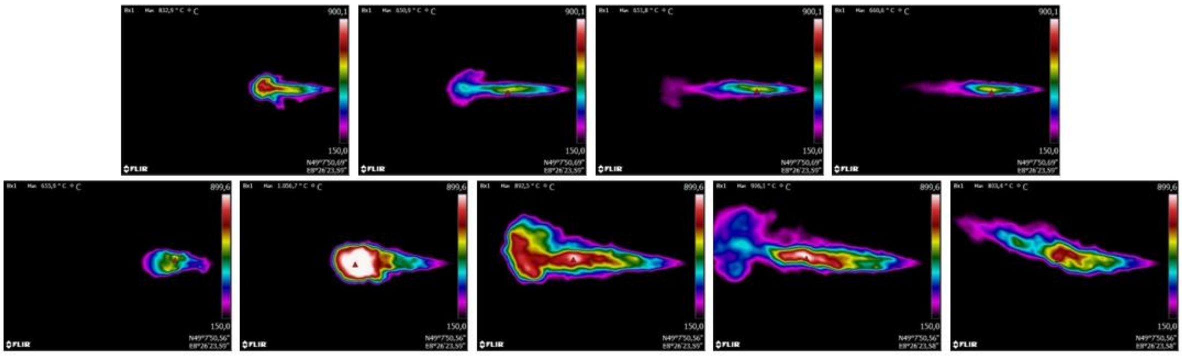

Figure 7: Temperature distribution within jet fire structure. Jet fire radiation for 2-mm nozzle and 10 MPa of initial pressure at T=285 K (upper) and T=80 K.

Using the pressure records and the results of extensive optical observation with up to five cameras the ignition and combustion behaviour of the jets could be analysed.

In Figure 8 measured maximum overpressures are plotted over the ignition delay time for several series with different initial pressures (e.g. “p50” stands for pini = 50 bar) and ignition distances (e.g. “dI39.5” stands for ignition distance = 39.5 cm to nozzle) for the experiments with the 4 mm nozzle at ambient temperature. The highest overpressures were measured for ignition delays in the range from approx. 80 ms to 160 ms, so for the second series an ignition delay time of 120 ms was chosen.

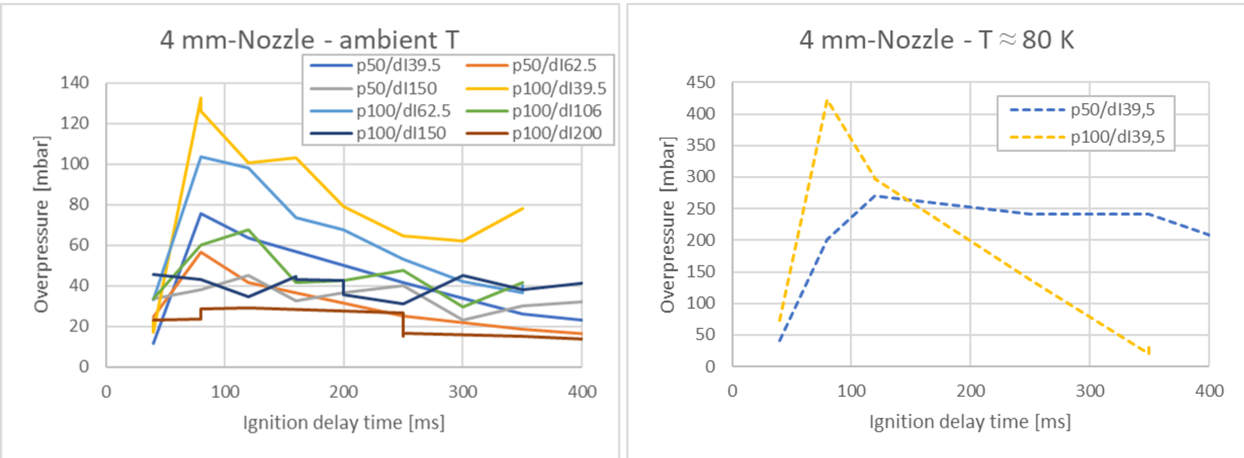

Figure 8: Measured maximum overpressures over ignition delay time for different initial pressures (e.g. “p50” means pini = 50 bar), ignition distances (e.g. “dI39.5” means ignition distance = 39.5 cm to nozzle) and temperatures for the experiments with the 4 mm nozzle at ambient temperature

After ignition flame can either burn back to nozzle or not. This difference is important since in case the flame burns back to the nozzle it will continue burning when ignition source is turned off, while in case the flame does not burn back to the nozzle it will quench after the ignition source is turned off. Using sensor records and optical observation on flame behaviour tests can be divided in two groups, where the flame burns back to the nozzle or not. When this data is combined with the results of the H2-concentration measurements of the unignited tests a clear trend can be observed.

For very low H2-concentrations in the ignition position no ignition occurs, while for H2-concentrations lower than approx. 10 Vol% the jet is ignited but does not burn back to the nozzle. For H2-concentrations higher than approx. 10 Vol% in the ignition position the flame burns back to the nozzle.

Concerning the combustion overpressures also several trends were observed. In general, the maximum measured overpressures increase with increasing nozzle diameter, while the gas temperature in the vessel seems to have no significant influence on the maximum pressure load. But at ambient gas temperature the measured overpressures increase with decreasing ignition distance, while in the cryogenic tests the highest overpressures are measured for an ignition distance of 62.5 cm.

1.5 Summary of results

In the frame of the PRESLHY project almost 300 ignition experiments were performed with the DisCha-facility by project partners Karlsruhe Institute of Technology (KIT) and Pro-Science (PS). More than one third of these tests were carried out at cryogenic temperatures (approx. 80 K), whereas the rest involved ambient temperature tests (300 K).

This experimental campaign, E5.1, is linked to discharge tests performed within E3.1, which analyses the unignited jets with same DisCha-facility and release parameters.

The scope of this experimental campaign is to characterise pressure and thermal effects from delayed ignition of cryogenic hydrogen jets depending on the following parameters: storage pressure (5-200 bar), nozzle diameter (1-4 mm), ignition location and delay time.

The generated experimental data consist of pressure and temperature measurements in the DisCha-vessel, combustion overpressure and heat flux measurements of the ignited jet. High-speed video combined with BOS imaging is provided for visual observation of explosion phenomena. Several times higher combustion pressure and heat flux were measured at cryogenic temperatures compared to ambient conditions. These data are publicly available at PRESLHY repository on KITopen.

2 CRYOTUBE experiments (experimental series E5.2)

In the work package WP5.2 of the PRESLHY, the flame propagation regimes at cryogenic temperatures are investigated by the project partners Karlsruhe Institute of Technology (KIT) and Pro-Science (PS).
The objective is to evaluate the critical conditions for flame acceleration (FA) and detonation transition (DT) for gaseous hydrogen-air mixtures at cryogenic temperatures, without the presence of condensed oxygen and nitrogen. The data are required for safety analysis to evaluate the strongest possible combustion pressure and safety distances for cryogenic hydrogen explosions.

2.1 General description of the CRYOTUBE facility

A series of experiments on flame acceleration and DDT at 1 bar of initial pressure and different temperatures from T =90K to ambient temperature T = 293 K has been conducted. The facility consists of a stainless steel tube of 5-m long with an outer diameter of 73 mm and an inner diameter of 54 mm. To provide the cryogenic temperatures, the tube was exposed in a metal basin filled with liquid nitrogen (LN2). The tube and the basin were supported by metal frame structure (Figure 9). A basin made of stainless steel insulated with Styrofoam providing the cooling. The cooling degree was controlled by varying amount of LN_2.

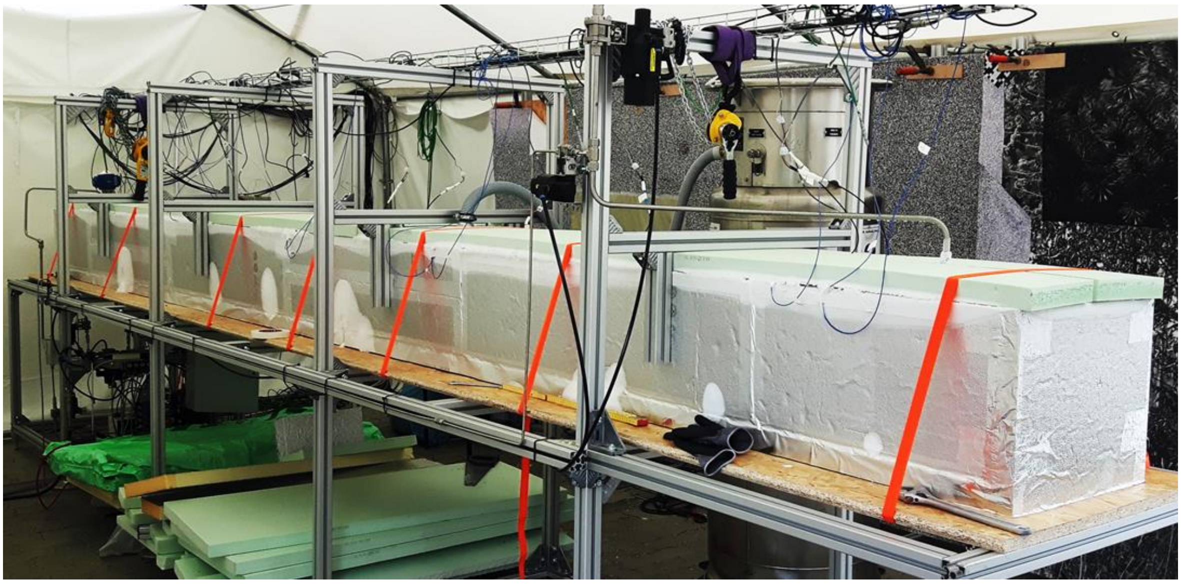

Figure 9. Cryo-shock tube inside a bath of LN2 with supporting structure.

The experimental procedure was different for ambient and cryogenic initial temperatures. Only the Cryo valves are exposed to LN_2 prior to the cryogenic experiments. All other valves and devices are at ambient temperature. All valves have pneumatic actuators. To extract water, the tube was first purged with dry compressed N_2. Then, the tube was evacuated down to < 1 mbar. The bath was filled with liquid N2. The temperature of the tube wall was controlled at 3 outside points along the tube with thermocouples clamped to the wall.

A test mixture was prepared according to scheme (Figure 10) with 2 Mass Flow Controllers (MFC, Bronkhorst), one for H2 and another for synthetic air (N2+O2). The mixture was flowed through a pipeline loop below the LN2 level to cool the mixture down before entering the tube. Then, the mixture was kept flowing through the tube until the concentration at the outlet reached a required value. When the gas temperature inside were stabilized, all the valves were closed to be ready for the test. Finally, the mixture was ignited triggering the data acquisition. A standard automotive spark plug was used for ignition. The number of repetitions was limited, because the cooled tube acts as a cold trap. It was nearly impossible to remove the condensed combustion products by pumping them at temperatures below 183 K. Then, we needed to heat the tube up to ambient temperature to remove condensed water/ice.

The experiments on hydrogen flame propagation have been conducted in a tube geometry with 3 different blockage ratios BR = 0, 30 and 60%. 0% of blockage simply means a smooth tube without obstacles. The blockages 30 and 60% are provided by a set of metal rings fully filled the tube length and spaced by the tube diameter. The blockage ratio is defined as follows: $BR = 1 – d^2/D^2$, where d is the internal diameter of the obstacle ring; D is the inner tube diameter. All ports and sensors are placed midway in between the obstacle positions. Two types of dynamic pressure sensors suitable for cryo-temperatures with PCB 116B and PCB 112A05 were used. InGaAs photodiodes were chosen as the light sensors. Because the photo sensor material does not withstand the low temperature, the light signal was guided by a polymer optical fiber to the sensor outside of the LN_2 bath.

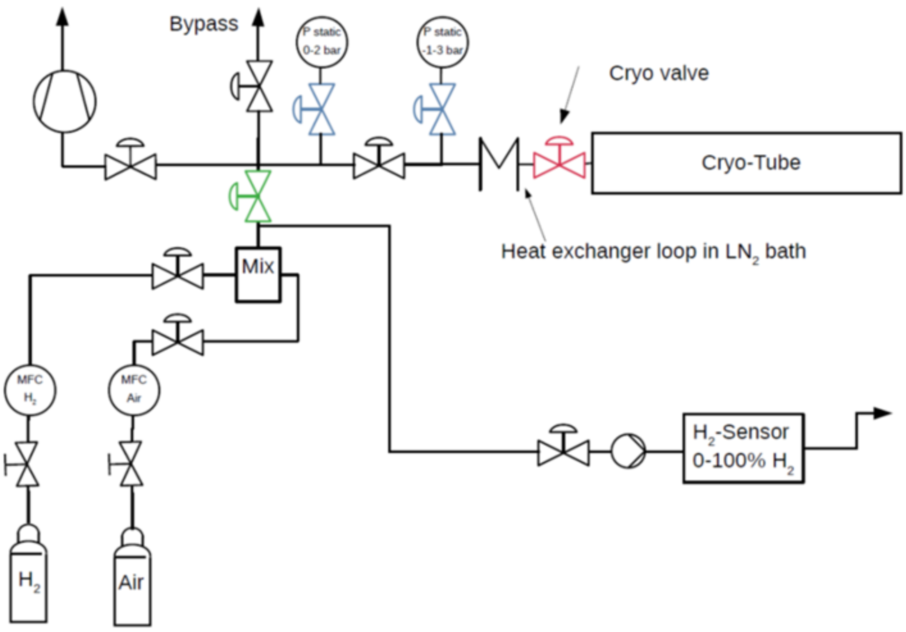

Figure 10. Gas filling system.

To monitor the cooling process, four thermocouples (type K) were placed at the outer tube surface, and two thermocouples were inside the tube, just at the inner surface. Their distances from the front flange were 22.5 cm, 102.5 cm, 103 cm, 227 cm, 378 cm and 472.5 cm respectively. In preliminary experiments, the thermocouples were exposed at ambient and LN2 boiling temperature of 77K. Then, a linear correlation is used to adjust the measured temperature to the real one. By the averaging, it yields the linear correction with an RMS = ± 0.18 K:

$$T_r \,[K] = 1.1013 * T_m \,[K] – 31.024$$

where T_r and T_m are the real and measured temperatures in Kelvin. An actual initial temperature for each test was assumed to be as an average for all six thermocouples.

2.2 Instrumentation

The small dimension and the cryogenic conditions in and around the tube imposed some limitations on the selection of sensors. Two types of dynamic pressure sensors with p_{max} = 6.9 bar (PCB 116B) and 345 bar (PCB 112A05) were used. These are special cryogenic sensors suitable for temperatures even lower than certified -100C (173K). These sensors have no built-in charge converters. Therefore, "In-Line Charge Converters" had to be used in the signal path between the sensors and the data acquisition system "PCB Sensor Signal Conditioner Series 481". For the pressure sensor PCB 116B the converter PCB 422E2 and for the sensor PCB 112A05 the convertor PCB 422E53 were employed. The charge converters are outside the cold region. The low-pressure sensors were mounted in adaptors welded to the tube, because of their bigger size. To avoid deformation during the welding, these ports are distributed helically in the positions along the tube. The high-pressure sensors were directly screwed into the tube wall using adaptors provided by the sensor manufacturer. The adaptors for optical fibers for the photo sensors and the high-pressure sensors have the same thread. All sensors were mounted flush to the inner tube wall.

To monitor the cooling process, four thermocouples (type K) were placed at the outer tube surface, two thermocouples were inside the tube, just at the inner surface. Their distances from the front flange were 22.5 cm, 102.5 cm, 103 cm, 227 cm, 378 cm and 472.5 cm respectively. The thermocouples at 102.5 cm and 472.5 cm were inside the tube.

2.3 Experimental results: Warm tests

A series of reference tests at ambient pressure and temperature and different blockages of the tube 0, 30 and 60% was conducted to check the well known criteria for flame acceleration and DDT [1-2] for the same tube geometry as for the forthcoming cryogenic tests. The experiments with a smooth tube (BR=0) cover hydrogen-air mixtures in the range 8-60%. That was mainly relatively slow subsonic deflagration registered because of longer run-up-distance (RUD) to detonation than the length of the tube L=5 m. The only stoichiometric mixture was able to detonate at the shock wave reflection on the far end flange.

According to paper [3], the run-up distance to detonation in a smooth channel should be 500 times larger than the detonation cell size $x_D = 500\ \lambda$. The run-up-distance to detonation x_D = 5000 mm for stoichiometric hydrogen-air with detonation cell size λ=10 mm exactly fits to tube length L=5000 mm. *Vice versa*, for 45%H_2-mixture, the flame accelerates very slowly and, since the run-up distance to fast sonic flame was larger than the tube length, the detonation did not occur: x_D = 8400 mm which exceeds the tube length L=5000 mm. This happens independent of the high mixture reactivity and small enough detonation size λ = 16.8 mm sufficient for detonation propagation in a smooth tube ($\lambda < \pi D$ = 170 mm).

With the obstructions, we can experimentally evaluate the critical expansion ratio σ^* for an efficient flame acceleration to the speed of sound because obstacles reduce the run-up-distance almost three times compared to smooth tube. In presence of obstacles, the flame continuously accelerates until a steady-state velocity is established. For both obstacles (BR=0.3-0.6), for hydrogen concentration above 11%H_2 (σ=3.77), characteristic flame velocity above the speed of sound (blue dotted line in Figure 11, right) and characteristic combustion pressure above the adiabatic combustion pressure ΔPicc (red dotted line in Figure 11, left) is established. For more reactive mixtures, the velocity approaches the detonation velocity D_CJ, when the detonability criteria are satisfied. The detonation cell size of test mixture should be larger than the orifice diameter, λ < d=45.2 mm for BR = 0.3 or λ < d/3=9.5 mm for BR = 0.6 according to papers [2,5-6,14]. In reality, it corresponds to more than 19.5%H_2 for BR=0.3 or

30%H_2 for BR=0.6. Figure 11 confirms well known critical expansion ratio σ*=3.75 for hydrogen-air mixtures at ambient conditions in a tube with BR=0.3 [1]. The same threshold was found for BR=0.6.

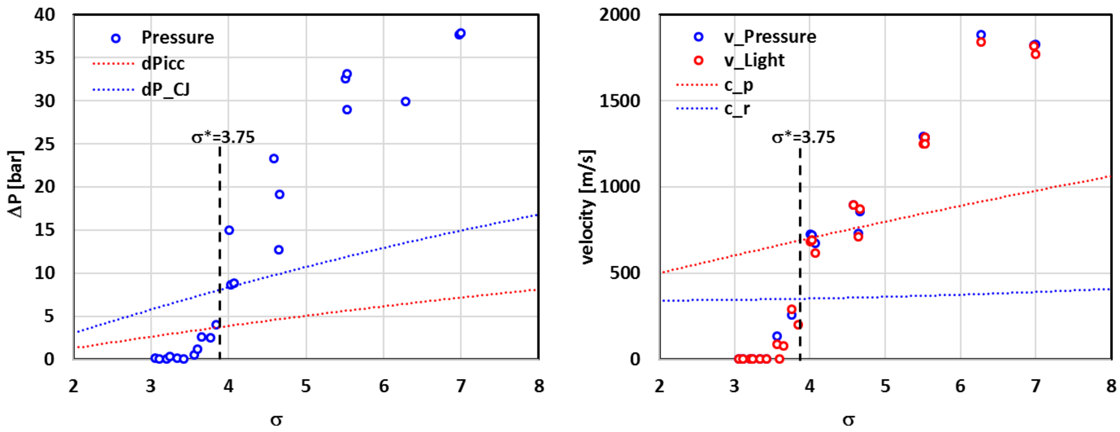

Figure 11. Characteristic pressure (left) and flame velocity (right) in obstructed tube (BR=0.3) as function of expansion ratio at ambient conditions: black dashed line is a cut-off line at σ*=3.75.

2.4 Experimental results: Cryogenic tests

The tube is cooled down in the basin surrounded the tube with LN_2, and the experiments are conducted during the warm-up phase. It takes about 2 hours to cool the tube down from ambient to the test temperature 90-130 K. Temperature uniformity along the tube is monitored by six thermocouples. The temperature of test mixture is assumed as an average one before the test.

The analysis of x-t diagrams for cryogenic hydrogen combustion in a smooth tube (BR=0) shows that for the first time a stationary supersonic flame propagation in a channel without obstacles was discovered. For hydrogen-air mixtures of 16 - 20%H_2 a stationary flame front coupled with shock wave propagates with characteristic velocity of the order of speed of sound in combustion products Uf=600-800 m/s (Mach number M=3). It can be classified as a chocked flame supported by spatial problems and energy losses. If the detonability of tested mixture would be larger, then the detonation for mixtures above 20% could occur. Since the critical condition for detonation propagation in a smoot channel is $d > \lambda/\pi$, we can assume the detonation cell size $\lambda < \pi d = 170$ mm for mixtures of more than 20%H_2. In contrary, for non-detonable mixtures with 16 and 17%H_2 the detonation cell size is $\lambda > \pi d = 170$ mm. Assuming that the run-up distance to detonation $x_D = 500\cdot\lambda$, the detonation cell size for stoichiometric hydrogen-air at cryogenic temperature T=101.7K is estimated to be $\lambda = 9$ mm and for 45%H_2 the detonation cell size $\lambda = 5$ mm. Since the quasi-detonation has occurred, the detonation cell size for 20 and 50%H2 shouldn't be larger than the tube diameter ($\lambda_{max} = d = 54$ mm)

A comparison of flame velocity for warm and cold experiments shows that cryogenic temperature promotes the sonic flame propagation or even quasi-detonation for lean (20%H_2) and rich (50%H_2) hydrogen-air mixtures in comparison with ambient temperature combustion with a velocity below 80 m/s. For more reactive mixtures with 29 and 45% H_2-air, cryogenic temperatures shorten the run-up distance to detonation compared to ambient temperatures. This might be due to more efficient flame acceleration in more viscous and dense gas and also due 2 times lower speed of sound at cryogenic temperatures because it leads to two times higher dynamic pressure for the same flow/flame velocity. The Reynolds number at cryogenic temperatures might be 5 times higher to reach the same threshold velocity for sonic deflagration. It promotes creation of turbulent flow ahead of the flame, which leads to faster flame acceleration to sonic deflagration.

Figure 12 shows that the critical expansion ratio σ*=12.5 is typical for hydrogen-air mixtures in obstructed tubes at cryogenic temperature T=100K. For hydrogen concentration above 16%H_2 (σ=11.9) characteristic flame velocity is above the speed of sound in reactants c_r (blue dotted line in Figure 12, right) and characteristic combustion pressure is above the adiabatic combustion pressure ΔPicc (red dotted line in Figure 12, left). Similar to warm tests, for more reactive mixtures the velocity establishes at the level of the speed of sound in combustion products c_p typical for chocked flames in congested areas when the detonation transition is suppressed by the detonation cell size larger than the orifice diameter, λ > d=45.2 mm for BR = 0.3, according to papers [2,5-6]. The same flame acceleration threshold σ*=12.5 was found for BR=0.6 with the difference that the critical detonation cell size is λ < d/3=9.5 mm.

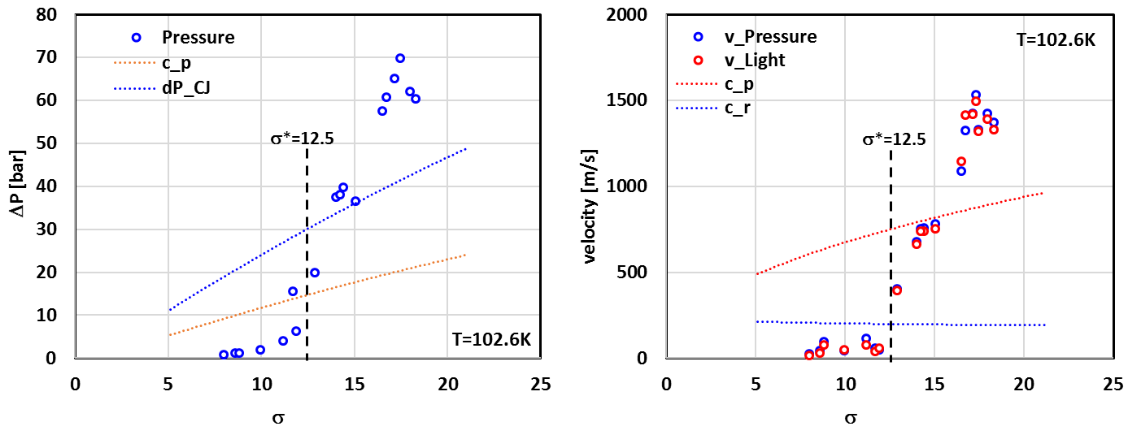

Figure 12. Experimental characteristic pressure (left) and flame velocity (right) as function of expansion ratio in obstructed tube (BR=0.3) at cryogenic temperature (T=102.6K): black dashed line is a cut-off line at σ*=12.5.

In general, at cryogenic temperatures the flame propagates with higher velocity and leads to higher combustion pressure and higher danger than at ambient conditions (Figure 13).

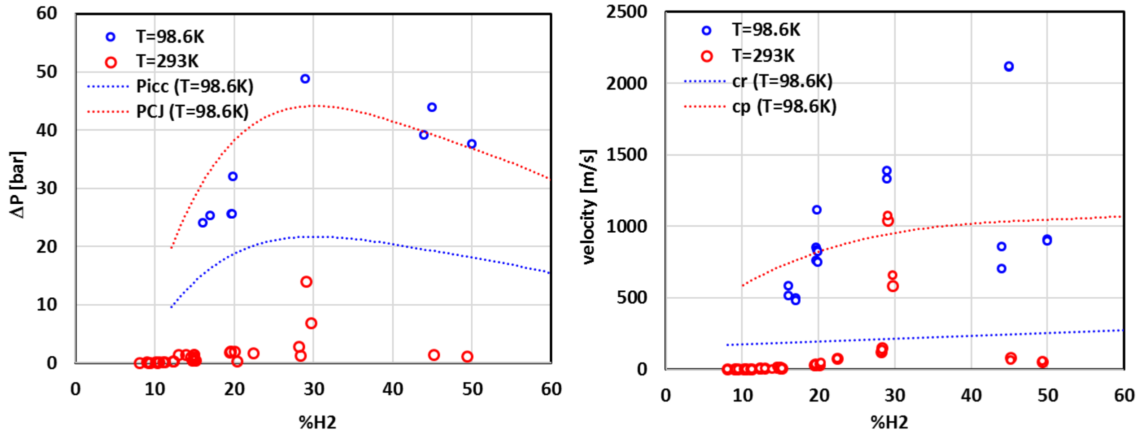

Figure 13. Experimental characteristic pressure (left) and flame velocity (right) as function of hydrogen concentration in smooth tube (BR=0%) at cryogenic and ambient temperature: experimental data (open points); theoretical calculations (dotted lines).

Figure 14 summarizes the current experimental data on flame propagation regimes in a tube with obstacles blocked in 30% (BR=30%). The critical expansion ratio for flame acceleration to the speed of sound can be approximated by exponential function:

$$\sigma^* = 2400 \cdot T^{-1.12} \quad (2)$$

where T is the initial temperature. Approximation (2) covers the range of temperatures from 90 K to 300 K. As follows from paper [2], the critical expansion ratio is not sensitive to the blockage of the channel and shape of the obstacles. We expect it should be the same critical expansion ratio σ* at cryogenic temperatures for larger blockage BR=60%, similar to warm experiments at T=293 K. The validity of the critical expansion ratio obtained in a channel with obstacles was also confirmed for high pressure hydrogen jet ignition [11].

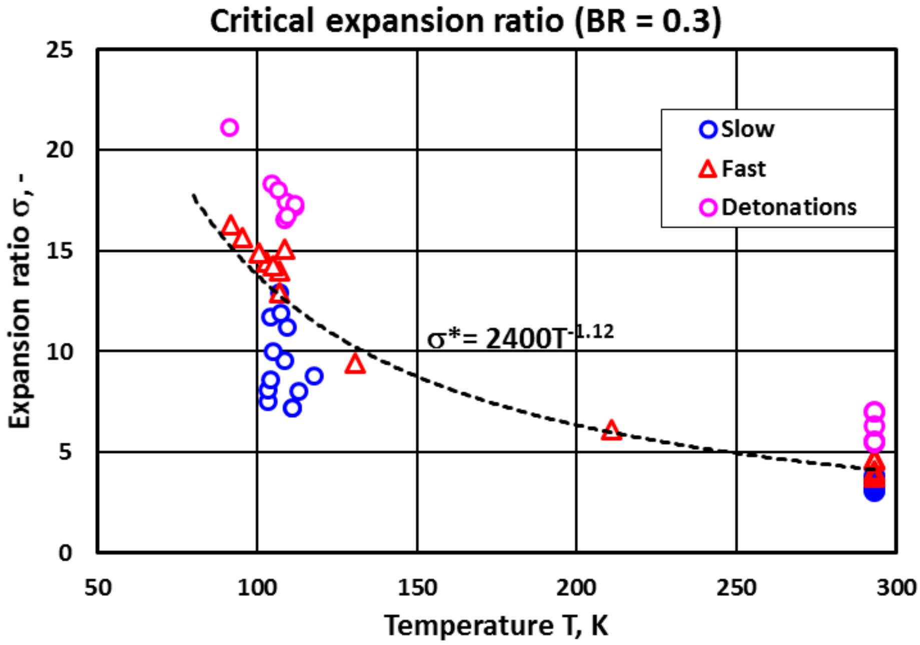

Figure 14. Critical expansion ratio as function of initial temperature based on experiments in obstructed tube (BR=30%).

2.5 Summary of results

In the frame of the PRESLHY project, more than 100 experiments were made with the Cryogenic Combustion Tube facility at HYKA KIT. About half of the experiments were made at cryogenic temperatures (approx. 80 to 130 K). During the experimental campaign, many difficulties were encountered as temperature nonuniformity, condensation of the mixture, ignition problems approaching the flammability limits, flame visualization and some others. It turned out to be impossible to ignite even hydrogen-rich mixtures at 77 K and it was not possible to achieve uniform temperatures along the tube at higher (approx. 150 K) temperatures. The photo sensors turned out to be too insensitive for slower combustion processes with less intensive radiation. However, all the problems were satisfactory solved and the flame propagations regimes at cryogenic temperatures were found.

The critical conditions for flame acceleration were evaluated as a function of initial temperature within the range 90 – 650 K. It shows a much higher hydrogen concentration leading to sonic deflagration than was predicted by advanced extrapolation before the tests. The correlation based on current experiments is quite simple and useful:

$$\sigma^* = 2200 \cdot T^{-1.12} .$$

The run-up distance to sonic flame in a smooth tube at cryogenic temperature was found to be roughly two times shorter than at ambient temperature. For the first time a steady-state choking regime with the speed of sound in combustion products was registered in a smooth tube at cryogenic temperatures.

The detonation cell sizes at cryogenic temperature T = 100 K are evaluated on the basis of existing criteria for detonation onset in smoot and obstructed tubes and can be presented as a polynomial function of hydrogen concentration [H_2, % vol.]:

$$\lambda[\text{mm}] = 0.0006724[H_2]^4 - 0.1039[H_2]^3 + 6.0786[H_2]^2 - 159.74[H_2] + 1603.3.$$

With the measured detonation cell sizes, the well known detonability criteria can be used to assess the possibility of detonation for hydrogen –air mixtures at cryogenic temperatures in different geometries and scales.

It was experimentally found that the maximum combustion pressure at cryogenic temperatures is 2-3 times higher than that for ambient conditions. It demonstrates a high level of the danger under cryogenic hydrogen combustion. Theoretically, even adiabatic combustion pressure corresponding to sonic deflagration at cryogenic temperature is 1.5 times higher than the CJ-detonation pressure at ambient temperature.

All the data and criteria can be used for RCS recommendations and safety distance evaluations. Original experimental data will be valuable for numerical code validation as well.

3 Semi-open channel experiments (experimental series E5.3)

In the frame of the PRESLHY project more than 100 combustion experiments with cryogenic hydrogen-air-mixtures were made in a semi-confined obstructed channel. In the experiments a large H2-concentration range from 10 vol% up to 60 vol% as well as different blockage ratios (BR = 0, 30 and 60%) were investigated. Besides the main experiment series at cryogenic temperatures (approx. 100 K inside the channel) most of the experiments were also performed at ambient temperature for comparison.

3.1 General description of the Cold Channel facility

Main goal of the Cold Channel Experiments is to evaluate the danger of flame propagation over a spill of LH2 in presence of a vertical hydrogen concentration gradient at cryogenic temperatures.

The tests were performed in a half open box 3 x 0.6 m² with a height of 0.4 m, whose ceiling was located approx. 2 m above the ground level of a concrete pit on the free field test site north of KIT Campus North. which had become available during the PRESLHY project. The test site is located in the woods approx. 2 km north of the northern end of KIT Campus North and the closest inhabited buildings have a distance of approx. 2 km to it (see Figure 1).

Figure 15: Location (left) and aerial view from the north (right) of the free-field test site north of KIT Campus North with position of the concrete pit (red rectangle).

On the test site, a large concrete pit is available from an earlier project. The pit with a length of approx. 100 m, a width of 5 m and a depth of 4 m is embedded in the ground and it is protected against the weather by a large foldable tent. The combustion channel utilized in the current test series is assembled at one end of the pit using the narrow pit side to fasten the background needed for the optical observations with the BOS-technique.

In the tests, it was aimed to ignite H2-air mixtures with concentration gradients similar to the natural hydrogen concentration gradients above the spill of LH2. Simultaneously with the H2-concentration gradient, the corresponding temperature profile was also created in the combustion channel. The gas mixture was ignited at the position of higher hydrogen reactivity and then, flame propagation velocity and combustion pressure were measured in configurations with and without obstacles in the channel.

To generate the test mixtures cold hydrogen with a temperature of approx. 80 K (boiling temperature of liquid nitrogen (LN2)) was injected from the LN2-cooled channel ceiling into the channel volume. To determine the concentration and temperature profiles generated inside the channel, measurements of local hydrogen concentration and temperature profiles were performed in distribution experiments. In the subsequent combustion experiments, in which the mixture was ignited, pressure sensors and high-speed video combined with BOS technique were used to capture the characteristics of the combustion behavior.

The Cold-Channel-facility mainly consists of a steel-tube for gas pre-cooling in a bath of LN2 and the combustion channel with an LN2-cooled ceiling. To the cooled ceiling injection lines are fastened from below, which are fed with cold H2 from the cooling tube via LN2-cooled filling lines. Figure 16 and Figure 17 show a sketch and photos of the setup of the Cold-Channel-facility.

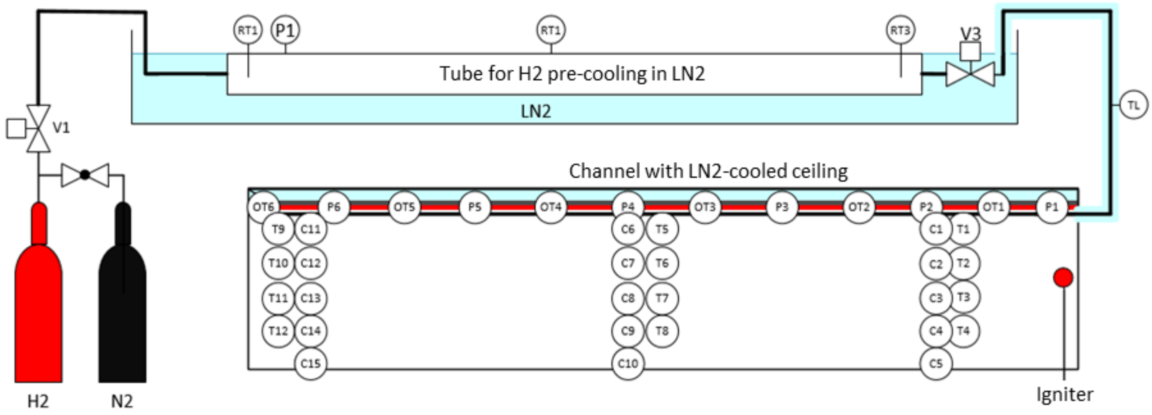

Figure 16: Sketch with main parts of the Cold-Channel-facility. Positions of pressure sensors (P), thermocouples (T) and concentration samples (C) are indicated in circles.

Figure 17: Side-view of the Cold-Channel facility. Subpicture shows an internal view of channel.

The combustion channel has a length of 3 m, a height of 40 cm and a width of 60 cm and is hanging from a welded support structure that holds its ceiling at a height of approx. 2 m above the ground level (Figure 17). The channel has an open ground face and can be equipped with eleven obstacles (two sets of wooden obstacles for blockage ratios of 30% and 60% were fabricated) with a spacing of 250 mm.

For optical observation the sidewalls of the combustion channel are made of transparent Makrolon plates (thickness of 11 mm) that are stabilized by eleven frame structures around the channel cross section in the obstacle positions. The ceiling of the channel is made of an aluminium plate fastened to four aluminium channels (cross section 120 mm x 40 mm) that allow cooling of the top plate with LN2. On its ignition end, the channel is closed tightly by a metal sheet, while its opposite end is open, but sealed by a thin plastic film in the experiments.

The cold hydrogen provided by the cooling tube is released through 96 holes (12 holes on either side of every injection line) with a diameter of 2 mm in horizontal direction into the combustion channel. The holes are located in distances of 25 cm to each other with the first hole having a distance of 25 cm to the ignition wall. With the horizontal release it is aimed to generate a stratified H2-air-mixture with a vertical H2-concentration gradient inside the channel, that is ignited in the main experimental series. To control the formation of the stratified mixture distribution experiments were performed, in which gas samples were taken at the point in time when the ignition is planned in the combustion experiments.

3.2 Instrumentation

Two principal experimental series were performed with the Cold-Channel facility:

- distribution experiments on H2-concentration gradient and temperature profile formation in the channel, and
- ignited experiments on the combustion behaviour of the gradient mixtures characterized in the distribution experiments.

For the determination of the H2-concentration profiles generated in the combustion channel distribution experiments were performed, in which several gas samples were taken from the channel atmosphere at the point in time in which the mixture is ignited in the combustion experiments. The samples were taken using 12 sample taking cylinders (V = 16 ml) that were positioned in three rows of 5 cylinders outside the channel and extracted the sample from the sampling point inside the channel through a thin cannula (di = 1 mm, l = 800 mm). Different hydrogen concentration profiles characterized by maximum concentration at the ceiling and a vertical gradient of concentration were taken as function of time. Then, it should be used for ignition experiments controlled by time delay.

In the distribution experiments also the temperature gradients generated inside the channel by the injection of the pre-cooled hydrogen are measured. For this purpose, 12 thermocouples (Type K, 1 mm), are positioned close to the cannula positions in the combustion channel in the three rows.

As ignition device a glow wire in a perforated tube (di = 50 mm, l = 500 mm) is used. The glow wire ignites the mixture inside the tube and the flame then propagates primarily through the tube, but also leaves it through the holes in its circumference. In this way a planar flame is spread over the entire channel width within a relatively short distance to the ignition wall.

For the determination of the flame velocity and the pressure loads generated during the combustion the combustion channel is equipped with 6 open thermocouples (OT1 – OT6 in Figure 16) for flame detection and 6 pressure sensors (P1 – P6) that are located on the centerline of the channel ceiling in a central position in between two obstacles. 6 ionization probes (IP1 – IP6) were installed to the uppermost bar of every second obstacle along the channel centerline.

The pressure sensors inside the channel (PCB, type 112A05, range 0 – 35 bar) were mounted flush to wall surface. To protect the sensors the membranes were covered with a thin film of silicon grease during the experiments. The ionization probes were directly fastened to the upper surface of the uppermost bar in every second obstacle of the channel.

A BOS(Background-Oriented-Schlieren)-method combined with a high speed camera Photron was used for invisible hydrogen flame tracking.

3.3 Test matrix

A series of combustion experiments with and without obstacles at cryogenic temperature approaching the LN2 temperature have been carried out (Table 1-Table 3). The maximum hydrogen concentration of stratified gas mixture was controlled by injection pressure and time delay of 2 s after injection. The maximum hydrogen concentration was changing from 8 to 57%H2 for unobstructed channel and from 8 to 30% for channel with obstacles. Lower hydrogen concentration at the bottom was approaching the LFL (Lower Flammability Limit) of about 4%H2.

Table 1: Test matrix of the Cold-Channel experiments at 80K with a blockage ratio of 0% (unobstructed channel)

Exp. No.	Injection – cH2/Ignition				cH2 [Vol%]			
	p_{ini} [bar]	t_{Inject} [ms]	Δp [bar]	t_{Delay} [ms]	Top (Avg.)	Botm (Avg.)	Max	Min
1	10.8	500	1.9	2000	8.7	6.4	14.3	2.4
2	10.8	600	2.3	2000	8.1	4.9	14.2	1.7
3	10.8	750	2.9	2000	14.9	6.7	19.6	4.4
4	10.8	750	2.7	2000	17.3	5.0	18.8	2.1
5	10.8	2200	6.7	2000	31.7	8.0	35.6	5.1
6	11.1	5000	10.4	2000	44.7	17.7	48.6	6.1
7	22.1	7000	21.5	2000	57.1	29.4	58.8	20.8

Table 2: Test matrix of the Cold-Channel experiments at 80K with a blockage ratio of 30%

Exp. No.	Injection – cH2/Ignition				cH2 [Vol%]			
	p_{ini} [bar]	t_{Inject} [ms]	Δp [bar]	t_{Delay} [ms]	Top (Avg.)	Botm (Avg.)	Max	Min
1	11.4	300	1.0	2000	8.0	2.0	12.6	0.6
2	10.9	350	1.4	2000	8.8	6.6	15.3	1.3
3	11.4	350	1.2	2000	12.8	2.5	20.6	1.0
4	11.3	400	1.4	2000	16.1	6.4	20.0	3.5
5	11.4	400	1.5 1.6	2000	12.9 15.4	2.6 2.6	15.3 21.0	2.2 0.5
6	11.4	450	1.5	2000	14.7	1.3	22.4	1.1
7	11.4	500	2.2	2000	18.7	3.8	20.7	1.8
8	11.4	500	2.7	2000	21.2	3.0	23.3	1.3
9	11.4	600	2.4	2000	23.4	2.8	28.3	1.2
10	11.4	700	2.1	2000	22.1	4.2	23.6	3.0
11	11.4	800	2.9	2000	25.7	8.3	28.2	2.6
12	11.4	900	2.9	2000	23.6	5.6	30.9	1.7
13	11.0	1000	3.9	2000	22.1	8.8	25.3	5.7

Table 3: Test matrix of the Cold-Channel experiments at 80K with a blockage ratio of 60%

Exp. No.	Injection – cH2/Ignition				cH2 [Vol%]			
	p_{ini} [bar]	t_{Inject} [ms]	Δp [bar]	t_{Delay} [ms]	Top (Avg.)	Botm (Avg.)	Max	Min
1	11.4	300	1.1	2000	7.1	2.8	11.8	0.6
2	11.4	350	1.3	2000	9.5	2.4	16.1	0.5
3	11.4	400	1.4	2000	13.8	3.3	21.2	1.7
4	11.4	450	1.4	2000	10.2 12.5	2.7 3.6	18.1 16.1	0.6 1.7
5	11.5	500	11.8	2000	16.2	3.2	23.5	2.8
6	11.5	600	2.0	2000	17.0	1.6	22.7	0.5
7	11.4	700	2.3	2000	19.9	3.9	24.5	3.3
8	11.5	700	2.3	2000	20.9	6.9	25.3	5.6
9	11.4	700	2.0	2000	26.9	2.7	32.3	1.2
10	11.4	800		2000	24.2	3.6	30.5	3.3
11	11.4	900		2000	26.5	6.2	33.5	3.5
12	11.5 11.4	1000	3.1 3.3	2000	23.9 26.0	5.7 6.4	30.3 35.4	3.2 2.6
13	11.5	1250	4.4	2000	27.9	9.5	34.1	7.2
14 15	11.5	1500 1600	5.3 5.4	2000	30.5 30.7	15.2 12.6	36.2 36.0	10.5 8.1

3.4 Summary of results

In the frame of the PRESLHY project more than 100 combustion experiments with cryogenic hydrogen-air-mixtures were made in a semi-confined obstructed channel. In the experiments a large H2-concentration range from 10 vol% up to 60 vol% as well as different blockage ratios (BR = 0, 30 and 60%) were investigated. Besides the main experiment series at cryogenic temperatures with pre-cooled hydrogen from the cooling tube (approx. 80 K, resulting in approx. 100 K in the channel) most of the experiments were also performed at ambient temperature for comparison.

The series of experiments carried out gives a first insight into the combustion process of cryogenic hydrogen-air layers in the semi-confined geometry. The measured values provide a database for the further development and validation of complex simulation tools dedicated to hydrogen safety.

Due the enormous experimental program executed by Pro-Science/KIT and the resulting lack of time the data was only processed, but not evaluated in detail up to the end of the PRESLHY project and thus no preliminary results can be presented here.

4 Flame propagation in obstructed /confined cold cloud (experimental series E5.5)

4.1 General description of the facility

The experiments were conducted using the LH_2 release facility, which was located on a 32 m diameter concrete pad at the Frith Valley site at the HSE Science and Research Centre in Buxton, UK. An image including a sketch of the experimental layout is shown in Figure 18.

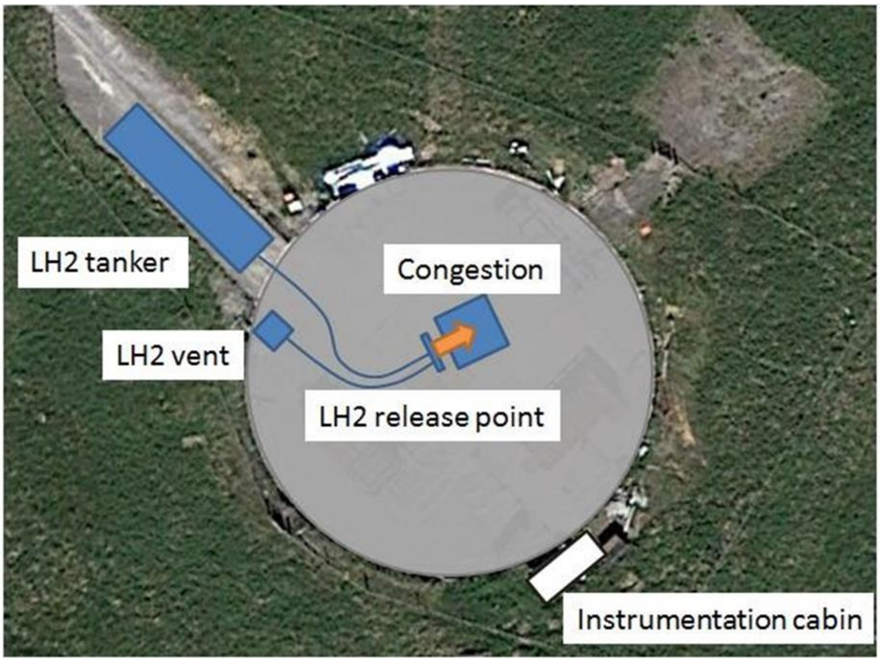

Figure 18. Diagram of WP5 layout.

The tanker, vent stack and release station was the same as used in previous experimentscarried out in Work Package 3. This consisted of insulated steel pipework, remotely operated valves and instrumentation. The instrumentation enabled measurements of thepipework temperature and pressure at various points, and the mass flow rate. The electrically isolated pipework used in work packages 3 and 4 was also still in place to create consistent outflow behaviour across the work packages. Deliverable 3.6 [3] contains a more thorough description of the equipment used. The release height was approximately 0.8 m for these experiments.

The congestion rig is a steel frame consisting of 18, 1 m^3 sections configured as a 3 m square base with a height of 2 m. Congestion is added in the form of ladder-like structures, referred to as congestion frames. Each of these is made up of made up of 26 +/- 1 mm (nominal 1") cylindrical bars spaced 125 mm apart between two 5 mm x 50 mmbars. These have varying lengths dependant on the position in the rig.

In the top half, the congestion frames were inserted horizontally and spanned the entire length of the congestion rig (3 m). Three congestion frames were used in each layer, andfour layers were used.

The bottom half had a more complex congestion pattern with the congestion grids installed vertically. Photographs and sketches of this is shown in figures 3 to 6. The arrow in Figure 19 indicates the LH_2 release, the sparks show the potential ignition points and the circles are instrument locations (small, red are collocated thermocouples and sampling tubes and the large green are pressure transducers).

Scaffold poles (o.d. 48 mm) were inserted vertically to achieve a higher level of congestion. They were placed in a pattern with 11 in each 1 m^2 area of the grid and protruded from the congestion frame.

The congestion resulted in a volumetric blockage ratio of approximate 1.52% for the low level, and 4.2 % for the high.

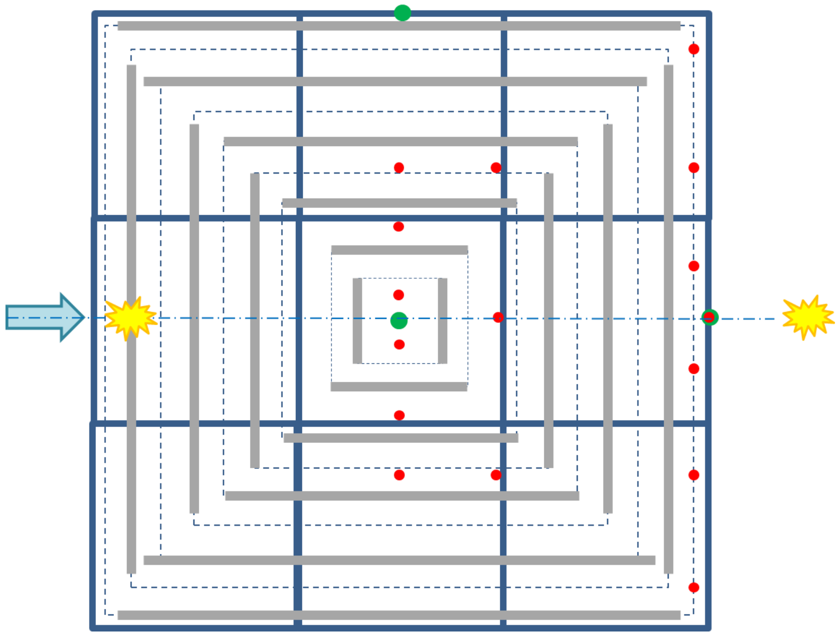

Figure 19. A sketch of the lower congestion frame positions.

In order to avoid misfires, pyrotechnic igniters that created a fountain of sparks were used, bringing the probability of ignition close to 1. The ignition system was separate from the other systems and could be configured for either front or rear ignition points.

4.2 Instrumentation

The purpose of the instrumentation fell into three broad categories: release and dispersion measurements, explosion measurements, and general measurements including ambient conditions and video footage.

To characterise the blast wave, 8 Kulite HKL-375 (M) series pressure transducers were arranged in and around the congestion rig, centred on the midpoint. Each stood approximately 0.5 m off the ground and was oriented 90° from the expected blast wave toregister an incident blast pressure. K1 to K4 were held horizontally and K5 to K8 were held vertically.

The temperature and hydrogen concentration was measured inside the congestion frame at 16 points. Each point held a type T sheathed thermocouple collocated with a stainless steel gas sampling line. These sampling lines ran approximately 30 m and each connectedto a Xensor thermal conductivity sensor. The hydrogen concentration system was supplied by NREL (HyWAM) and logged at 4 Hz, whereas the thermocouples were logged through the primary control and logging system at 1 Hz.

The heat flux was measured by three Medtherm radiometers positioned at a height of 0.5 m and distances of 2.5, 3.5 and 6.5 m from the centre of the congestion rig. Theorientation was perpendicular to the release direction.

Ambient conditions were measured using two systems: a Skye SKH-2053 temperatureand humidity probe mounted alongside a WindSonic ultrasonic anemometer on a 3 m high stand on the downwind edge of the concrete pad approximately 20 m from the release point; and a PCE-FWS-20 weather station was positioned locally to the releasestation at 1.5 m height.

A subsection of the following cameras were used to capture the events in each trial: three Sony FDR-AX53 handy cams recording at 50 fps provided standard footage with three views; a high speed Phantom Mira LC320 recording at 3600 fps captured detailed footageof the blast; and a FLIR X8400sc thermal camera indicated the flame front.

4.3 Results

A series of 23 ignited congestion trials were conducted as a part of work package 5. Table3 shows the initial conditions of each trial, the peak measured overpressure (and the location of that pressure transducer), the noise measured outside of the control room and approximate maximum pressures recorded at a range of 6.5 and 11.5 m from the centre ofthe congestion rig.

Table 1: Experimental series initial conditions and results overview.

Test No.	Orifice Diameter (mm)	Tanker pressure (barg)	Ignition point	Congestion level	P max (bar)	At	Noise (dB)	Pmax 6.5m (mbar)	Pmax 11.5m (mbar)
1	6	1	Front	Low	0.01	K6	*[1]	2	1
2	12	1	Front	Low	0.52	K7	*[1]	40	23
3	25.4	1	Front	Low	0.16	K5	*[1]	5	4
4	12	1	Front	Low	0.03	K5	123	12	7
5	25.4	1	Front	Low	0.02	K5	117	11	5
6	12	1	Front	Low	0.04	K5	125	12	7
7	25.4	1	Front	Low	0.38	K5	114	7	4
8	12	1	Rear	Low	0.07	K6	*[2]	14	8
9	12	1	Rear	Low	0.04	K6	123	10	5
10	25.4	1	Rear	Low	0.01	K6	108	4	2
11	6	5	Front	Low	0.14	K5	122	13	7
12	12	5	Rear	Low	0.39	K5	132	40	25
13	12	5	Front	Low	0.13	K5	131	50	30
14	12	5	Rear	Low	0.53	K5	127	20	12

15	12	5	Front	Low	0.10	K5	132	40	20
16	12	5	Rear	Low	0.55	K6	134	40	20
17	12	5	Front	Low	0.67	K5	129	30	15
18	25.4	5	Front	Low	0.04	K5	120	15	7
19	25.4	5	Rear	Low	0.15	K5	137	70	40
20	6	1	Front	High	0.01	K6	*2	3	2
21	12	1	Front	High	0.15	K5	134	40	25
22	12	1	Front	High	0.13	K5	132	65	40
23	12	1	Front	High	1.28	K5	145	470	205

*1 Noise measurements not made. *2 Noise too low to discern from local ambient noise.

The wind conditions during the releases had an impact on the outcome by acting on the cloud. The wind speed was measured at two locations for the experimentalcampaign and table 4 shows the output. The 5 minute average wind speed and direction measured at the release point, and the average wind speed and direction measured in the far field averaged for 30 seconds prior to ignition. In some experiments (Trial 2) due to the wind conditions the cloud of cold hydrogen can be shifted and inclined from vertical axis of metal rig.

Trials 1, 11 and 20 were carried out through the 6 mm nozzle and showed consistently low overpressures and noise. A qualitative review of the footage shows a much smaller visible mist when compared to the other nozzle sizes, indicating a much lower hydrogen inventory in these trials. The congestion did not appear to have a significant impact on themeasured overpressures as both trial 1 and 20 show similar behaviour. The higher tanker pressure resulted in a larger hydrogen inventory and therefore overpressures.

Peak overpressures were consistently measured at K5 and those from the larger nozzle were typically higher, due to the larger hydrogen inventory. However, trial 5 showed particularly low measured overpressures.

Trials 12 to 17 were tests involving the same initial conditions of 5 barg tanker pressure releases through the 12 mm nozzle and the low level of congestion, but with alternating ignition locations. When grouped by ignition location, the average measured peak overpressure is 0.3 bar for front ignitions and 0.49 bar for rear ignitions, although there is much higher variation in the front ignitions. Figure 20 shows an example of the measured peak overpressures against the distance from the ignition point. The highlighted region shows where congestion is present.

Trials 21 to 23 were repeat tests with initial conditions of 1 barg tanker pressure, 12 mm nozzle and front ignitions using the high level of congestion. All three tests were carried out in sequence over a period of about 40 minutes in very similar average weather conditions. Trials 21 and 22 showed consistent behaviour, but 23 showed almost a tenfoldincrease in overpressure. This is shown in figure 13, which has the overpressure output from K1 and K2 for each of these trials. These pressure transducers were approximately 8m and 13 m from the front ignition point respectively, along the centre line of the release on the far side of the congestion.

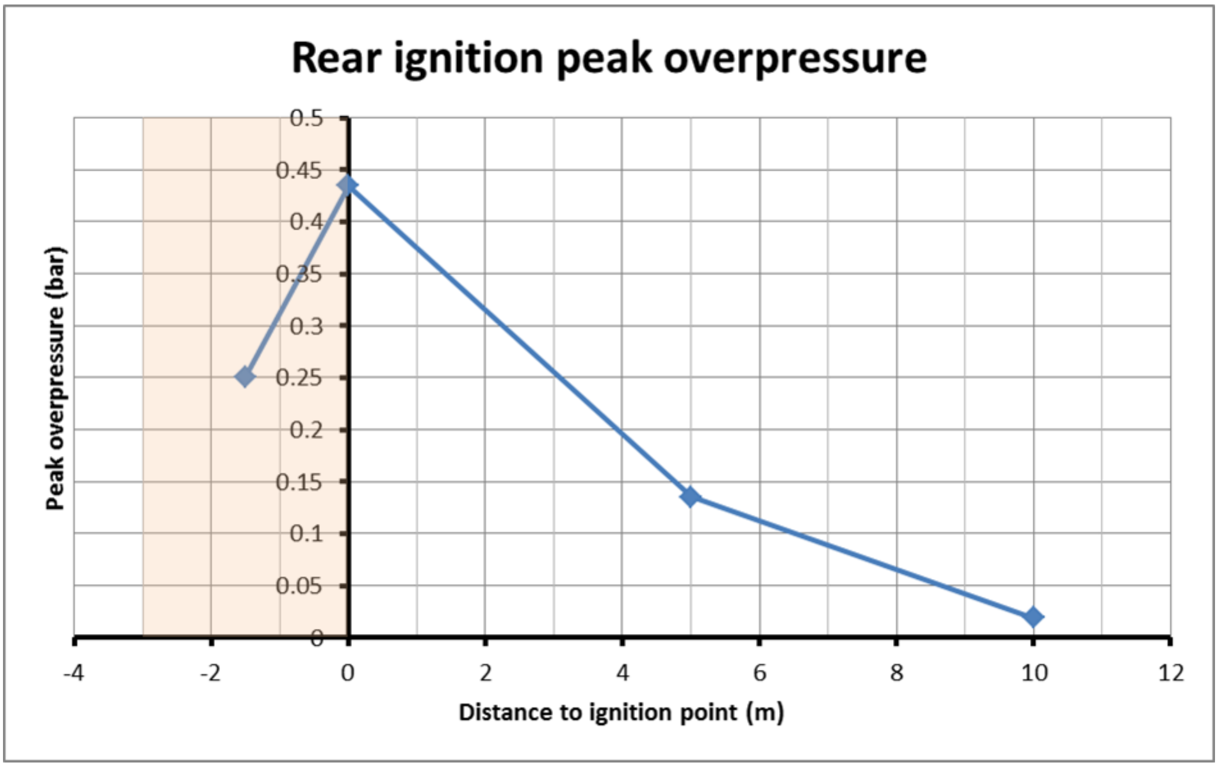

Figure 20. Average peak measured overpressures against distance for rear ignitions

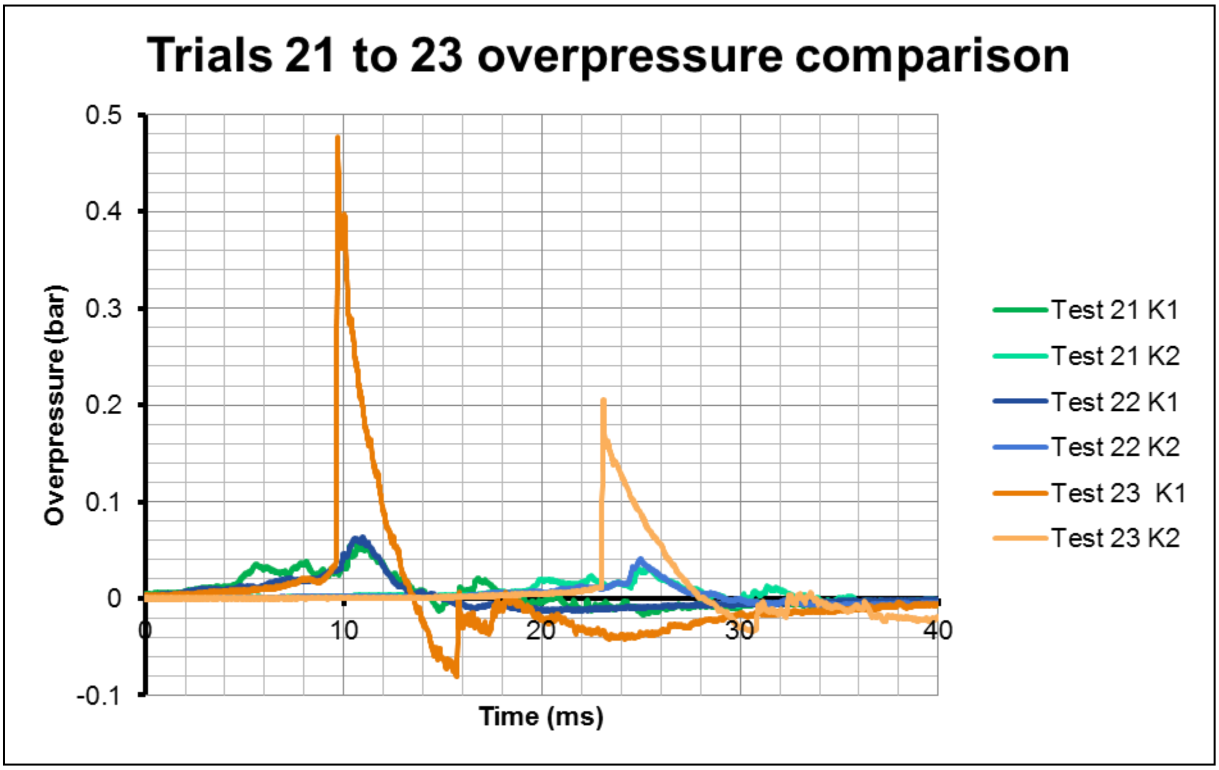

Figure 21. Overpressure comparison for the repeated trials 21 to 23.

Three radiometers were used at varying distances in an attempt to measure the heat flux of the combusting cloud. Unfortunately, between the narrow field of view of the sensors,the obstruction caused by the congestion frame and the uncertain nature of the events, only one sensor consistently provided reportable measurements. These measurements, however, did identify both the initial blast and jet fire phases. Figure 14 shows the measured heat flux from trials 21 to 23.

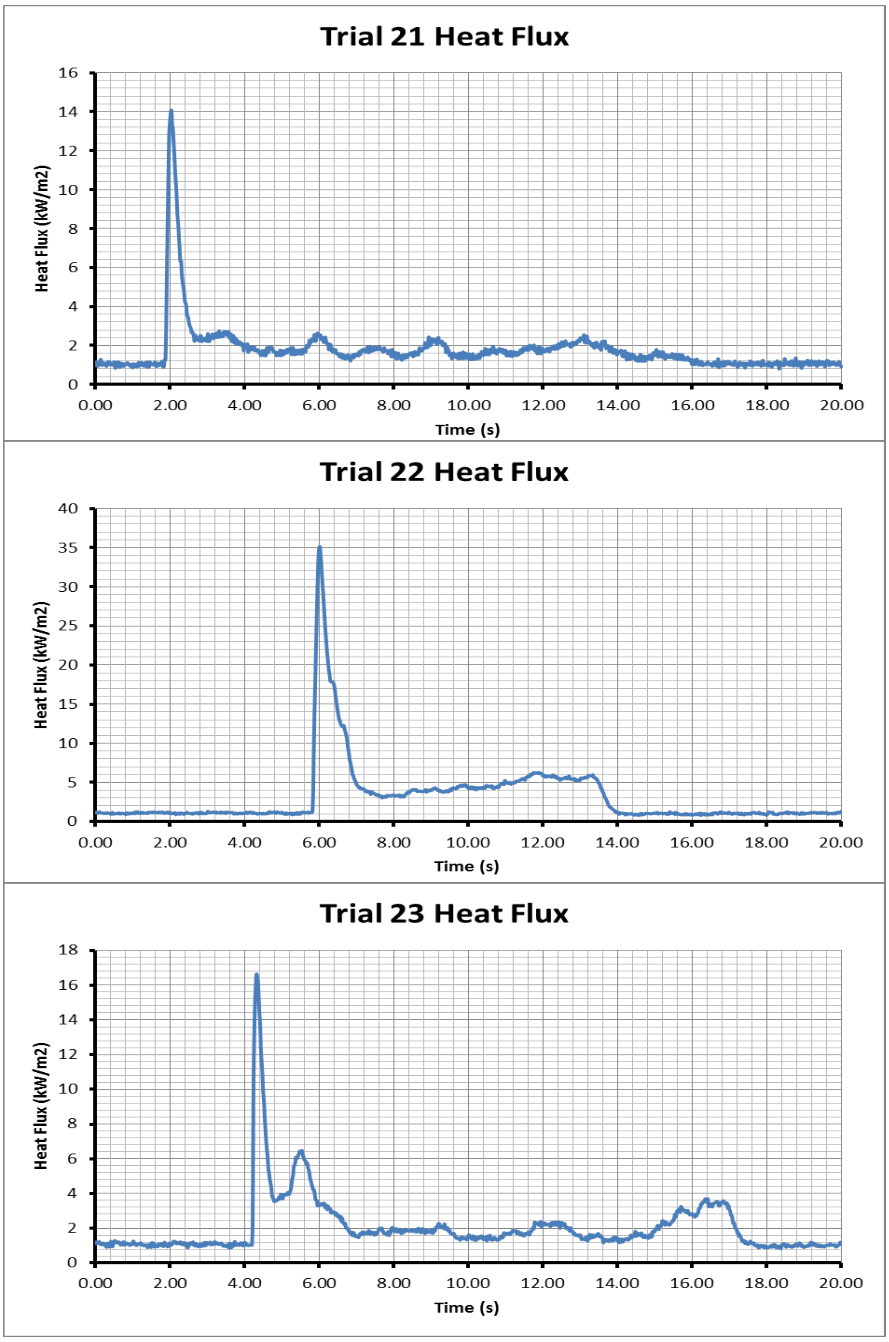

Figure 22. Heat flux outputs from trials 21 to 23.

4.4 Summary

The objective of this experimental campaign was to determine the effect of different levels of congestion upon the ignition behaviour of a cryogenic hydrogen plume. To this end, 23 ignited trials were carried out at the HSE Science and Research Centre whereby cryogenic hydrogen was released into a steel congestion frame. As well as two levels of congestion, the initial conditions of the release were altered with similar conditions to the other experiments carried out as part of this project, within Work Packages 3 and 4.

By comparing the results with those from a previous set of experiments in which LH2 was released and ignited in the free field, it is clear that higher levels of volumetric congestion increases the measured overpressures in releases with the same initial conditions. The results also show that an increasing hydrogen inventory, either through an increased release pressure or larger nozzle, can result in a larger event upon ignition. However, the mixing of the jet also plays a part; some releases through the largest release orifice diameter showed lower overpressures potentially due to the hydrogen cloud being too rich.

A severe deflagration or detonation was observed in the final trial, although trials with similar initial conditions did not show the same behaviour. This has been attributed to wind conditions causing recirculation and encouraging a slightly higher hydrogen volume within the congestion frame at ignition. While some consistency was observed between tests with similar initial conditions, a qualitative review of the footage shows that the wind played a dominant role in the dispersion and development of the hydrogen cloud from a release of LH2. This includes transient and localised gusts that are difficult to measure and predict.

Notwithstanding the variability introduced by the wind our results suggest the following as a reasonable basis for risk assessment for some releases during tanker operations:

Location with a low level of congestion

For the low level of congestion (Volume blockage ratio <1.5%, Area blockage <1 m2/m3, Congestion length scale 25-50 mm) there is little risk of uncontrolled flame acceleration. An assumption of TNO Level 5 would be appropriately conservative; to be applied only to the portion of the cloud within the congested area. As a rule of thumb, if all of the cloud could be in the congested area, the explosive energy release for 1 bar tanker pressures would be approximately 20 MJ and for 5 bar pressure 50 MJ.

Location with a high level of congestion

Where there is a densely congested area (Volume blockage ratio >4 %, Congestion length scale 25-50 mm) with a volume of more than about 15 m3 then it would be appropriate to assume that a high level explosion or DDT could occur. It would be reasonable to assume that such an explosion could involve all of the cloud.

Since the definitive boundary of congestion level beyond which severe explosions have a higher propensity to occur was not found, depending on the sensitivity of potential targets it might be appropriate to assume that a severe explosion could occur for congested volumes of limited size or of intermediate levels of congestion.

5 General conclusions

A number of experiments on cryogenic hydrogen jet fire, flame propagation regimes of premixed hydrogen-air in a shock tube at cryogenic temperature, flame propagation in a channel geometry filled with stratified atmosphere similar to that above the LH2 spill and flame propagation in obstructed /confined cold cloud have been conducted within WP5 (Combustion).

Maximum combustion pressure is considered as an integral property of combustion processes relevant to hydrogen safety. In general, for all processes and all geometrical layouts the maximum combustion pressure at cryogenic temperatures is 2-3 times higher than at ambient conditions. This ratio is roughly equal to the densities ratio at cryogenic and ambient conditions. This means higher danger and larger safety distances for cryogenic combustion. Even for slow deflagration, the maximum combustion pressure may lead to fatal losses and failure of structures.

The critical conditions for flame acceleration were evaluated as a function of initial temperature within the range 90 – 130 K. Detonation cell sizes at cryogenic temperatures were experimentally evaluated to be used as a measure of detonability of cryogenic hydrogen composition.

Different degree of enclosure for hydrogen cloud and obstructions result in higher severity of cryogenic hydrogen explosion due to the effect of turbulence and shock wave reflections.

Independent of lower chemical reactivity, the flame at cryogenic temperature may propagate faster than at ambient temperature because of two times lower speed of sound and lower viscosity leading to higher level of turbulence due to the higher Reynolds number and Mach number.

Current experimental data uploaded to KIT Open Server and will be used as benchmark experiments for numerical simulations and safety assessment and RCS recomendations.