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

Project Deliverable

Summary of experiment series E5.1 (Ignited discharge) results

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JOINT UNDERTAKING

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1.1	Jennifer Wen	UWAR	28.2.2021
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Cryogenic release, ignition, high pressure, discharge coefficient, jet dispersion, electrostatic field, far field observation

Acknowledgements, Preface and Disclaimer

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

The test program for cryogenic hydrogen releases was split after initial discussions into a high pressure and a low pressure liquid hydrogen temperature part. This report deals with the high pressure releases at temperatures down to 80K only. However, because of certain adaptions a part of the experimental program planned for the last project phase could be addressed in combination with these experiments, i.e. considerably earlier.

This report contains the "meta data" of the respective experiments, providing detailed description of the experimental set-up, sensors and result data storage. The actual result data will be provided via KITopen. Also detailed evaluation of the results, e.g. determining the discharge coefficient, as well as any modelling work is excluded here and left for subsequent work.

Because of the interrelation with the published result data it is intended to turn this confidential report into a public one.

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Publishable Short Summary

In the frame of the PRESLHY project almost 300 ignition experiments were made with the DisCha-facility at KIT. With 105 cold tests more than one third of these experiments were carried out at cryogenic temperatures (approx. 80 K). Main drawback during the experimental campaign was the problem of a freezing release valve in some of the cold tests, especially under ambient conditions with high relative humidity. However, the tests showed very good reproducibility. Although the actual exploitation of the data is left for the further modelling work in the work packages WP4 and WP5, some interesting observations are as follows.

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1 Purpose of the Tests – Knowledge Gap Addressed

In the work package WP5.1 of the PRESLHY project the blow-down behavior of cryogenic hydrogen stored at elevated pressure is investigated by the project partners Karlsruhe Institute of Technology (KIT) and Pro-Science (PS). Similar to the first part A of the tests, where the DisCha facility was utilized to investigate releases of cryogenic hydrogen at temperatures of approximately 80 K and pressures up to 200 bar for a comparison with similar releases at ambient temperature, again two series at cryogenic (approx. 80 K, boiling temperature of liquid nitrogen (LN2)) and ambient temperature were performed. 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).

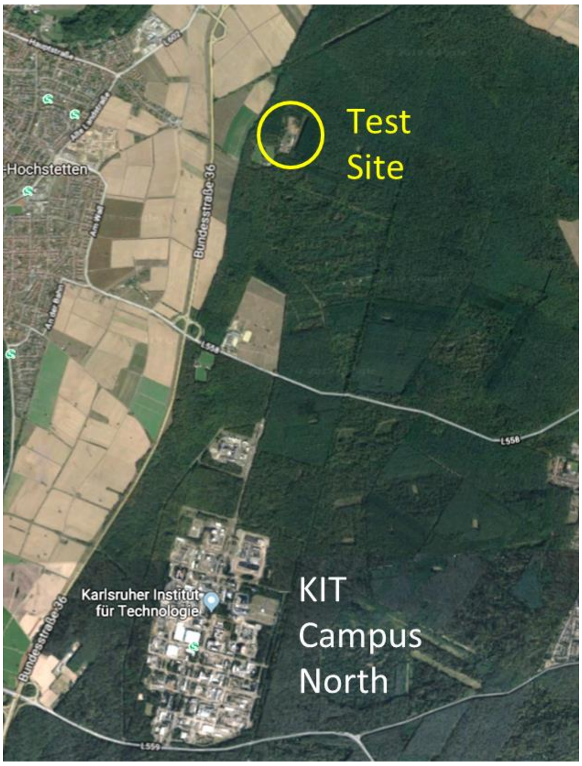


Figure 1: DisCha-facility in the free-field test site north to KIT-Campus north.

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. So 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

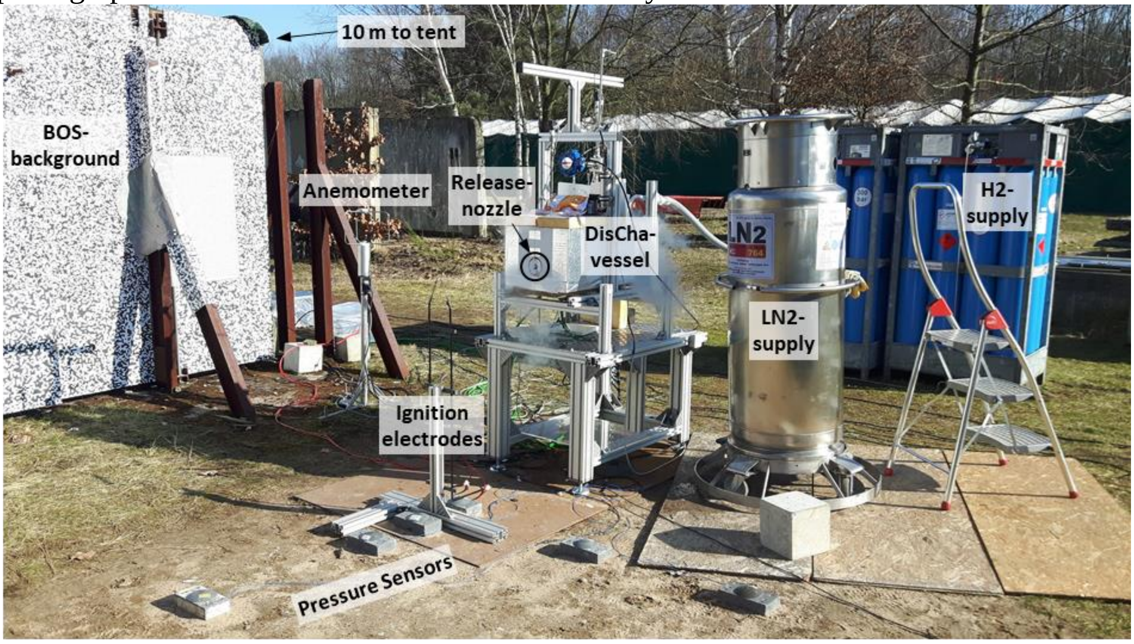
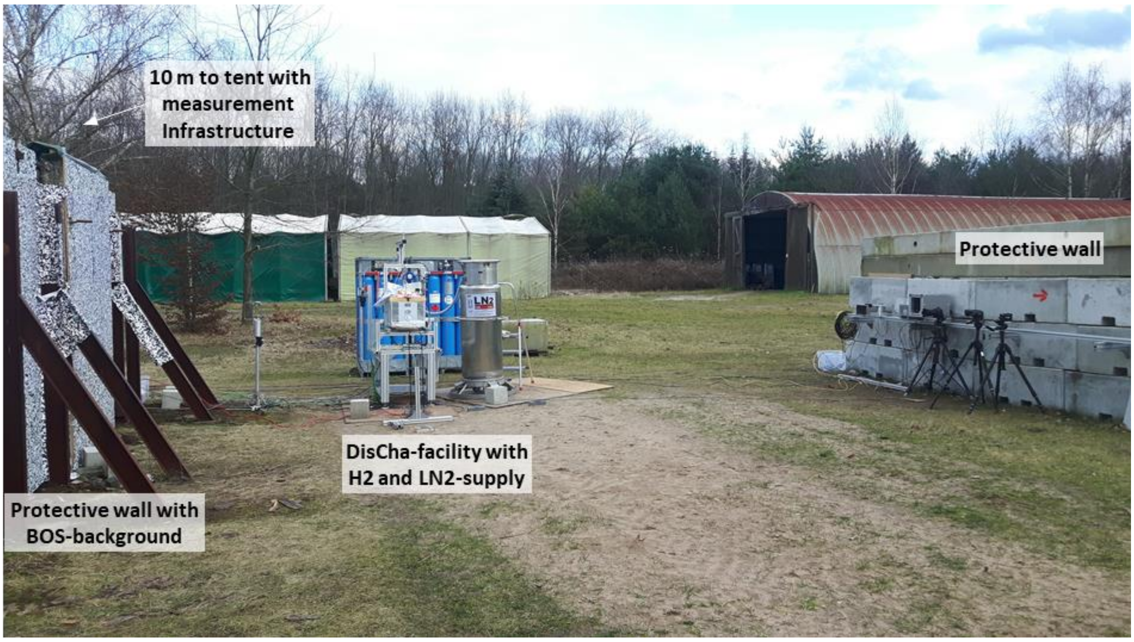


Figure 2.



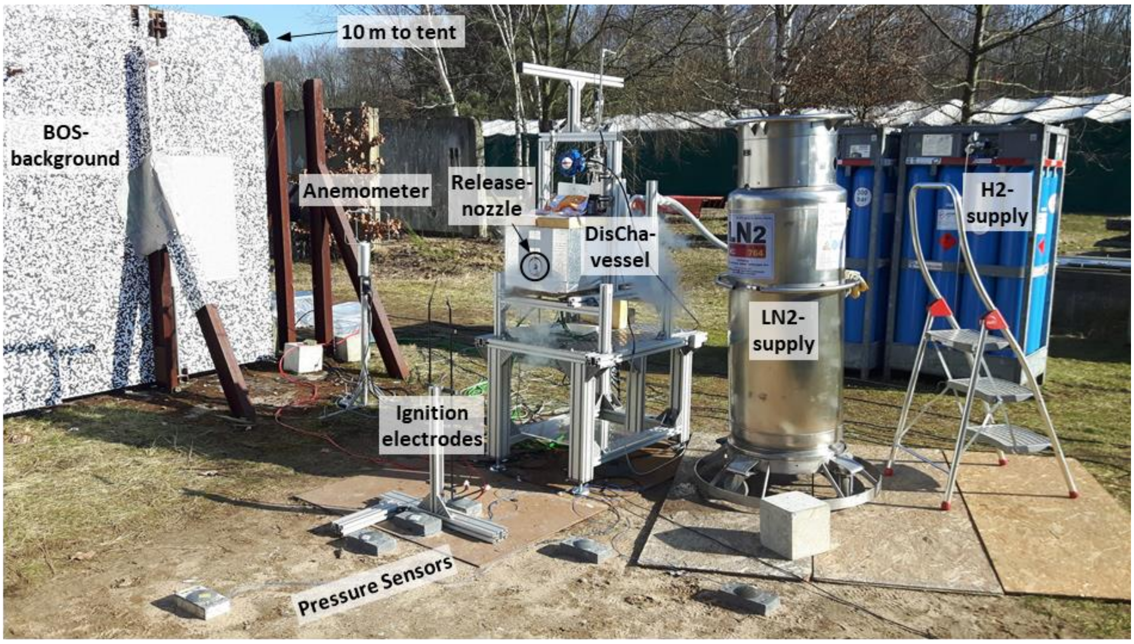


Figure 2: DisCha-facility in the free-field test site north to KIT-Campus North.

On the one hand the remote location has a huge advantage, since it allows to perform highly energetic experiments, but on the other hand the free-field was already invaded several times by burglars and hooligans since it is not under tight surveillance at night. To avoid damages or theft all technical equipment, exempt for the DisCha-facility and the backgrounds used, had to be removed in the evening after an experimental series and had to be rebuilt in the morning for the next series. This rather inconvenient circumstances and the fact that daylight was needed for the BOS-photography allowed only few experiments during the darkest weeks of the year, where most of the Ignited DisCha experiments were performed.

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.

2 General Description of the Experimental Set-up

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 .

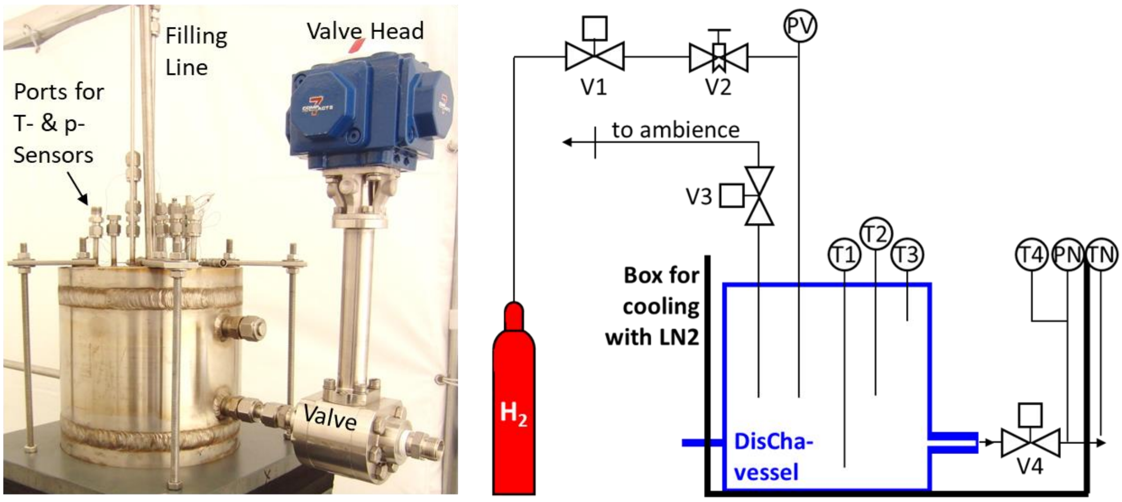


Figure 3: Photo of DisCha-vessel with valve (left) and sketch of the complete facility(right).

Through the filling line and the valves V1 and V2 the test vessel can be filled with gaseous hydrogen up to pressures of 200 bar from a bundle of hydrogen bottles. The vessel is equipped with several ports for instrumentation on its top and a rod that points on a force sensor on its rear side. Opposite to the force sensor a tubular exhaust pipe is welded to the vessel, where release nozzles with different aperture sizes can be fastened. The vessel is positioned in an insulated pool that can be filled with liquid nitrogen to cool down the complete setup.

Three nozzles with circular apertures of 1, 2 and 4 mm were used in the ignited DisCha experiments. The nozzles were mounted from outside the pool to the tube that connects them to the release valve (Figure 4). Another connection, which is kept as short as possible, is needed in between the release valve and the vessel exhaust

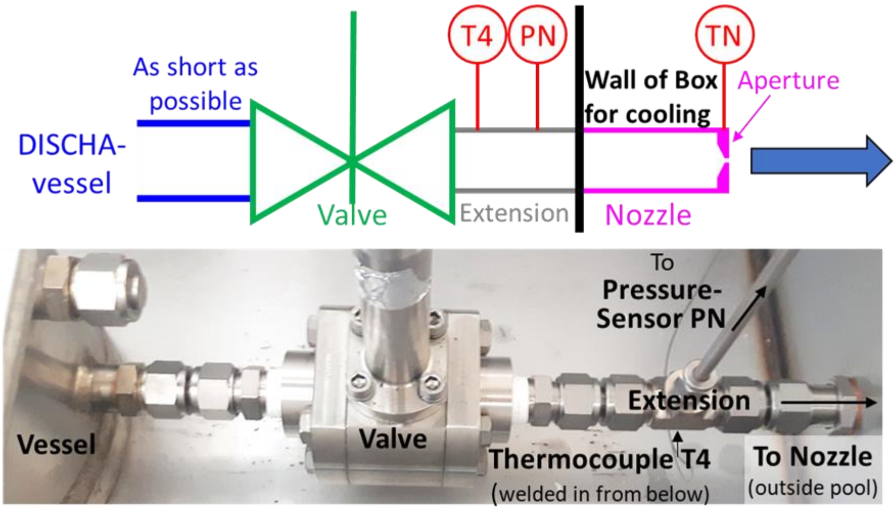


Figure 4: Sketch and photo of the release pipework of the DisCha-facility

3 Instrumentation of the DisCha-facility

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.

<u>Static pressure sensors:</u> 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.

<u>Thermocouples (TCs):</u> 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 and Figure 5).

<u>Dynamic pressure sensors:</u> Five dynamic pressure sensors of Type PCB 112A22 and 113B28 (range 0 - 3.5 bar, open circles in Figure 5) and 113B21 (range 0 - 14 bar, solid

black circles in Figure 5) 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.

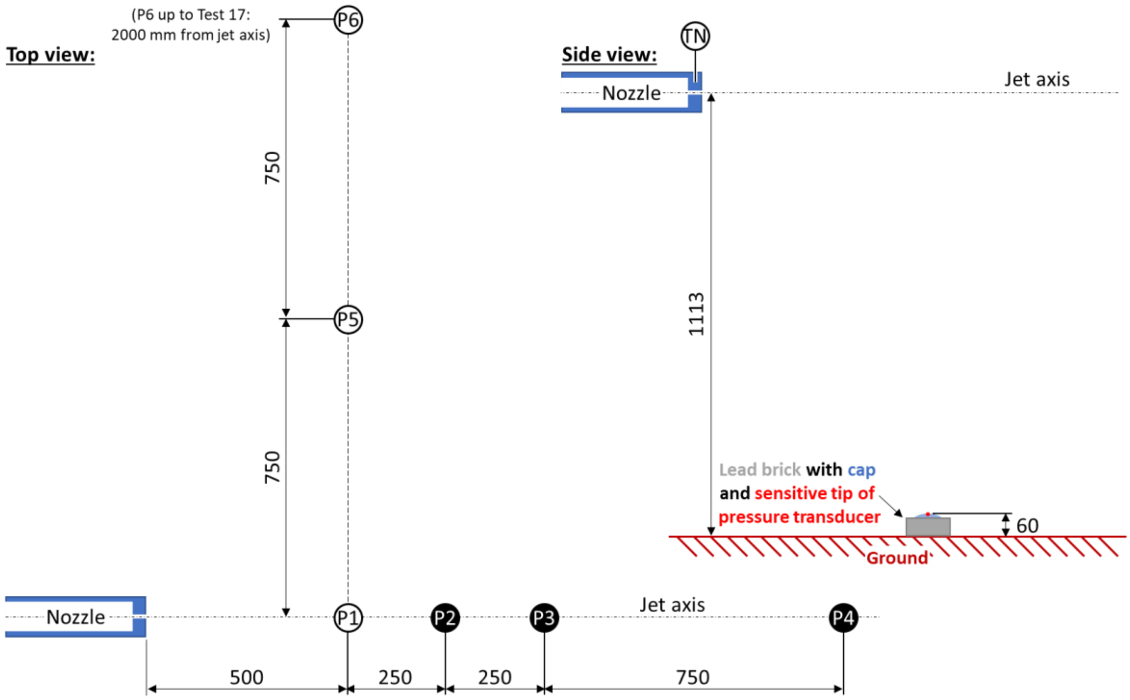


Figure 5: Sketches of the ex-vessel instrumentation of the DisCha-facility with fast pressure transducers.

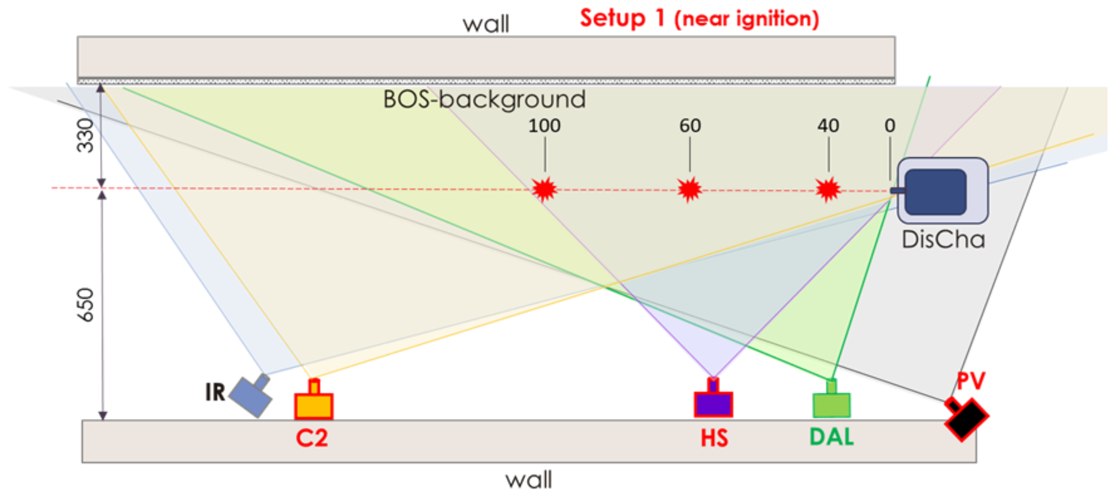
<u>Ambient conditions:</u> An ultrasonic anemometer was utilized to record the ambient temperature and wind conditions during the experiment. It records the wind speed in three directions (N to S, E to W, and in vertical direction) and also records the temperature. It was positioned on a tripod in 1.2 m distance besides the DisCha-vessel (see Figure 6).

<u>Ignition source:</u> 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 (see Figure 6).

Figure 6: Photo of the DisCha-facility with highlighted anemometer, ignition electrodes and pressure sensors as well as different BOS-background patterns.

<u>Cameras:</u> 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 7). 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 7).

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 6).



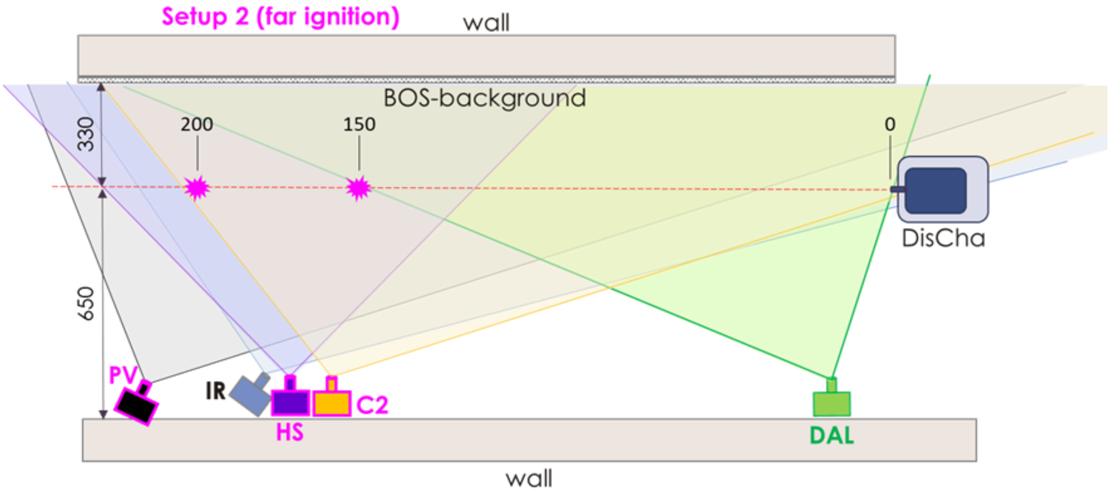


Figure 7: Sketch of positions and view field of the various cameras in the ignited DisCha-experiments

3.1 Estimate of Measurement Errors

The accuracy of the sensors used in the experiments is given in Table 1. The values were taken from the respective manuals for ambient temperature conditions. For cryogenic temperatures no data is available.

Table 1: Accuracy of the sensors used in the ignited DisCha experiments

Sensor	Manufacturer	Type (Range)	Non-linearity @ 290 K
Pressure (PV & PN)	WIKA	S-20 (250 bar)	< 0,125% FS
Pressure (P1 & P5)	PCB	112A22 (3.5 bar)	≤ 1% FS
Pressure (P2 – P4)	PCB	113B21 (14 bar)	≤ 1% FS
Pressure (P6)	PCB	113B28 (3.5 bar)	≤ 1% FS
Temperature	KIT-Workshop	Type K, d = 0.36 mm	1.66 °C

In the experiments, only the thermocouples in the vessel were directly exposed to cryogenic temperatures and so their deviation from the temperature of LN2 (77 K) was measured in a separate test prior to the unignited DisCha experiments. In this test all thermocouples (T1 – T3 and T_{Nozzle}) except T4, which is not accessible since it is welded into the extension tube, showed similar values of approx. 84 K, which corresponds to a difference of 7 K.

In a later test series on the behavior of LH2-pools the thermocouples installed to the DisCha-vessel (T1 – T3) were exposed to LH2 in the pool, while T4 in the release branch was exposed to LH2 in LH2-release experiments from a Cryostat. Using the temperatures recorded in contact with LH2 three calibration points were gained (ambience, LN2 and LH2) that were used to formulate a calibration equation for the temperature measurements with which the measured temperatures of all DisCha-experiments were corrected (Figure 8).

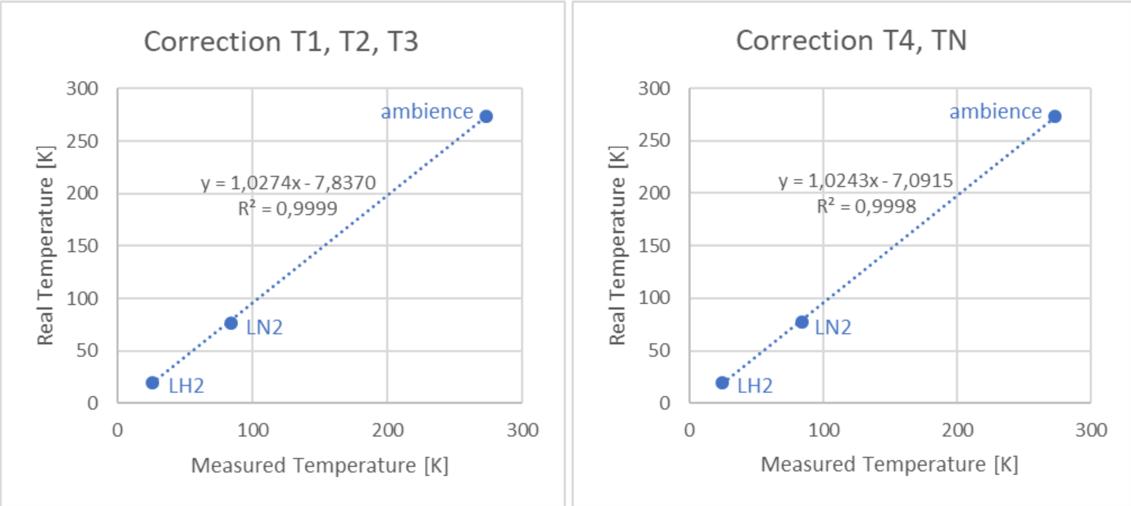


Figure 8: Calibration curves of the thermocouples used in the ignited DisCha-experiments

The PCB pressure sensors used in the facility show a strong heat sensitivity which results in a strong signal decay when they are exposed to flames. This decay cannot be completely prevented, but a thin layer of grease on the sensitive tip of the sensor delays this temperature effect in a way that a precise measurement of the maximum pressure in the experiment becomes possible prior to the signal decay.

4 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 initial conditions of these experiments are summarized in Table 2 and Table 3.

Table 2: Test matrix of the initial series of ignited DisCha experiments at ambient temperature (Names of experiments correspond to date and time of execution).

D_{ign} [cm]	Del_{ign} [s]	Pini [bar]			
		5	50	100	200
			2 mm Nozzle		
39,5	20		20191125-151441		
	40	20191127_135215	20191125-152254	20191204-121203	20191127-142839
		20191127_141717		20191204-122150	
	60		20191125-152935	20191204-123423	20191127-143250
	80		20191125-153549	20191204-124435	20191127-144341
	100			20191204-133102	20191127-145059
	150			20191204-134012	20191128-134102
	200			20191204-134915	20191128-135942
	250			20191204-141327	20191128-140929
	300			20191204-142423	20191128-141721
				20191204-143220	20191203-114802
	350				20191203-120602
62,5	20		20191125_132533		
	40	20191203-153707	20191125_131327	20191204-144216	20191203-122520
			20191125_135347		
	50		20191125_133536		
	60		20191121_162144	20191204-145454	20191203-132915
			20191125_134400		
	80		20191121_152508	20191204-150707	20191203-133656
			20191121_155135		
	100				20191203-134600
	150				20191203-135240
106,5	20		20191125-145505		
	40	20191203-153201	20191125-141847		20191203-140507
	60		20191125-142630		20191203-141431
	80		20191125-144347		20191203-142357
	100				20191203-143242
	150				20191203-144340
150	40	20191203-152700			20191203-145445
	60				20191203-150223
	80				20191203-151120
	100				20191203-151915
			4 mm Nozzle		
39,5	40		20200122-132201	20191216-134925	
				20191217-112651	
				20200116-112509	
	80		20200122-133055	20191216-153124	
				20191217-113554	
	120		20200122-133946	20191217-120314	
	200			20191217-122241	
	250			20191217-123014	

	300		20200122-134711	20191217-123906	
	350			20191217-124632	
	500		20200122-135548	20191217-125646	
	700		20200122-140707		
			20200122-141358		
			20200122-142257		
62,5	40		20200122-143339	20191217-130952	
	80		20200122-144120	20191217-132250	
	120		20200122-144854	20191217-133511	
	160			20191217-134155	
	200			20191217-134652	
	250		20200122-145607	20191217-135505	
	300			20191217-140131	
	350		20200122-150421	20191217-141513	
	500		20200122-151052		
	700		20200122-151710		
			20200122-152535		
106,5	40			20191217-143202	
	80			20191217-144038	
	120			20191217-144810	
	160			20191217-145442	
	200			20191217-150240	
	250			20191217-150929	
	300			20191217-151615	
	350			20191217-152355	
150	40		20200108-133648	20200108-115753	
	80	20200108-145027	20200108-134419	20200108-120739	
	120		20200108-135309	20200108-121441	
	160		20200108-135918	20200108-122803	
	200		20200108-140655	20200108-123452	
	250		20200108-141400	20200108-125409	
	300		20200108-142029	20200108-130030	
	350		20200108-142924	20200108-130740	
	500		20200108-143522	20200108-132125	
			20200108-144315		
	700		20200122-153606	20200108-145646	
200	40			20200109-133118	
	80			20200109-134132	
				20200109-142658	
	120			20200109-134902	
	250			20200109-135517	
				20200109-143611	
				20200109-144253	
				20200109-145014	
	350			20200109-140226	
	500			20200109-140835	
	700			20200109-141519	
250	250			20200109-150024	

Red: no ignition

Table 3: Test matrix of the initial series of ignited DisCha experiments at approx. 80 K (Names of experiments correspond to date and time of execution).

D_{ign} [cm]	Del_{ign} [s]	Pini [bar] 5	50	100	200
			2 mm Nozzle		
39,5	40	20191205-150953		20191205-132820	20191205-135544
	60	20191205-151700		20191205-143401	
	80			20191205-144334	
	100			20191205-150025	
				20191206-131921	
	150			20191206-130513	
	200			20191206-132924	
	250			20191206-134011	
	300			20191206-135818	
	350			20191206-140905	
	400			20191206-141851	
	450			20191206-143106	
62,5	40	20191205-152826		20191206-115712	
	60			20191206-120507	
	80			20191206-121149	
	100			20191206-122002	
	150			20191206-122824	
	200			20191206-123751	
	300			20191206-125301	
			4 mm Nozzle		
39,5	40		20200123-123026	20200115-114956	
	80		20200123-123858	20200115-115919	
	120		20200123-124826	20200115-121153	
	120			20200115-130647	
	250		20200123-125601	20200115-122134	
				20200115-133015	
	350		20200123-130202	20200115-123436	
				20200115-133902	
	500		20200123-131439		
	700		20200123-132426		
			20200123-133357		
			20200123-134551		
	900		20200123-141529		
			20200123-142539		
62,5	50		~~**20200123-143658**~~		
			~~**20200123-145951**~~		

~~**Strikethrough**~~: frozen valve

In Figure 9 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.

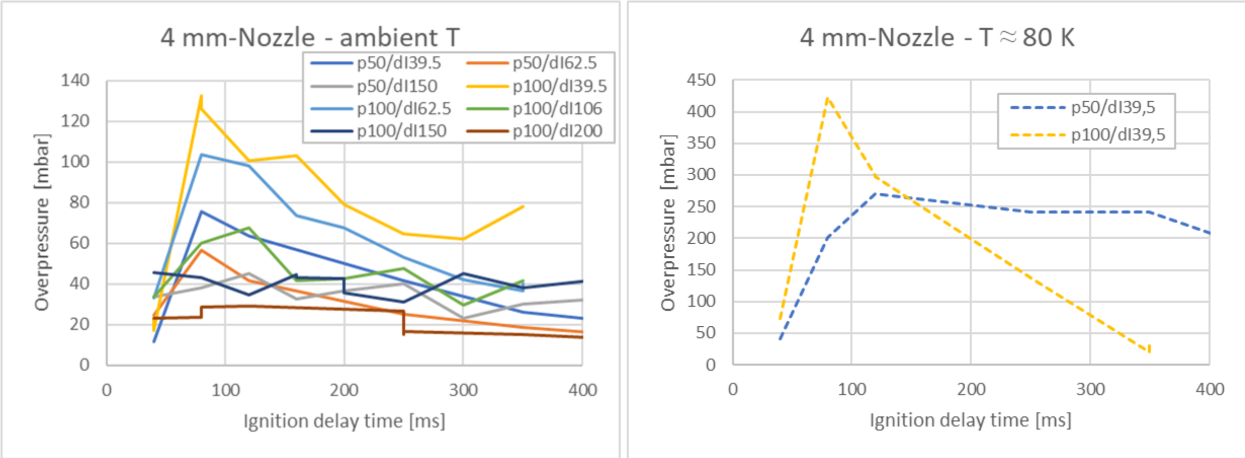


Figure 9: Measured maximum overpressures over ignition delay time for different initial pressures (e.g. "p50" means pini = 50 bar), ignition distances (e.g. "dI39.5" means ignition distance = 39.5 cm to nozzle) and temperatures for the experiments with the 4 mm nozzle at ambient temperature

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). The experiments performed with these parameters are summarized in Table 4.

Table 4: Test matrix of the second series of ignited DisCha experiments with an ignition delay of 120 ms. (experiment names correspond to date and time of execution).

p_{ini}	D_{ign}	Nozzle-Diameter [mm]		
[bar]	[cm]	1	2	4
Ambient Temperature				
5	39,5	20200130-153716	20200130-144119	20200130-130444
	62,5	~~20200206-153140~~	~~20200130-143504~~	20200130-131900
	106,5	~~20200206-154902~~	~~20200130-141220~~	~~20200130-134553~~
	150	omitted	omitted	~~20200206-120530~~
	200	omitted	omitted	~~20200206-122353~~
50	39,5	20200130-152936	20200130-144952	20200122-133946
	62,5	20200206-152140	20200130-142721	20200122-144854
	106,5	~~20200206-154446~~	20200130-140429	20200130-133910
	150	~~20200206-132310~~	20200206-133844	20200108-135309
	200	omitted	20200206-140450	20200206-141331
100	39,5	20200130-152108	*20191204-134012*	20191217-120314
	62,5	20200206-150830	20200130-142005	20191217-133511
	106,5	20200206-153635	20200130-135640	20191217-144810
	150	20200206-131405	20200206-133001	20200108-121441
	200	~~20200206-130852~~	20200206-135543	20200109-134902
200	39,5	20200130-145933	*20191128-134102*	20200130-124939
		20200130-151323		20200130-125756
	62,5	20200206-145930	*20191203-135240*	20200130-131140
	106,5	20200206-144550	*20191203-144340*	20200130-132602
	150	20200206-124728	20200206-124013	20200206-120820
	200	20200206-125639	20200206-123208	20200206-121550
Approx. 80 K				
5	39,5	20200207-151042	20200207-153955	20200131-142502
	62,5	~~20200207-144038~~	20200207-160600	20200131-135803
	106,5	~~20200207-135944~~	20200131-154849	20200131-132018
	150	omitted	20200205-152605	20200205-134450
	200	omitted	20200205-145649	20200205-130548
50	39,5	20200207-150146	20200207-153311	20200131-141755
	62,5	20200207-143044	20200207-155834	20200131-135150
	106,5	20200207-135241	20200131-154136	20200131-131215
	150	~~20200205-1633xx~~	20200205-151733	20200205-133707
	200	~~20200205-161205~~	20200205-144846	20200205-125706
100	39,5	20200207-145340	20200207-152522	20200131-141018
	62,5	20200207-141902	20200207-155033	20200131-133606
	106,5	20200207-134219	20200131-153321	20200131-125646
	150	20200205-162056	20200205-150947	20200205-132730
	200	20200205-160351	20200205-143856	20200205-124527
200	39,5	20200207-131000*	20200131-145042	20200131-120937
	62,5	20200207-125437*	20200131-150307	20200131-122212
	106,5	20200207-132715*	20200131-151413	20200131-124521
			20200131-152533	
	150	20200205-154145	20200205-142637	20200205-121045
	200	20200205-155209		20200205-123619

~~strikethrough~~: no ignition   green: chosen for evaluation   *italic*: ignition delay 150 ms
*: less than 200 bar (remaining pressure of 300 bar bundle)

The test itself and the respective result files are labeled with the date and time (“date”-”time”), at which the test was initiated. The labeling is further explained below. The whole test campaign with close to 300 tests lasted almost 2½ months (end of November 2019 to beginning of February 2020) with a longer break due to Christmas and New Year vacations, but also delays in LN2 supply frequently resulted in interruptions. The majority of the tests of the second test series (Table 4) were performed in the last month of the campaign with an almost unchanged facility. Due to the time pressure and the large test matrix only few repetitions were made. Some experiments of the matrix were omitted, mostly when experiments under same conditions with smaller ignition distances did not show an ignition of the released H2-jet.

5 Structure of Experimental Result Data explained with Cold Case 20200205-123619

All experimental data of the ignited DisCha tests listed in Table 4 will be (are) published as zipped Excel-files via the PRESLHY repository on KITopen https://www.bibliothek.kit.edu/cms/english/kitopen.php in packages with identical nozzle diameter, separately for the ambient (referring to upper part of Table 4 and labeled “300K”) and cryogenic (referring to lower part of Table 4 and labeled “80K”) hydrogen temperatures, which corresponds to the respective columns in the above tables. Photographs of the camera 1 and 2 have been packed in zip-files per experiment, and then - similarly as for the Excel datasets - packed in larger zip-files for same diameter and temperature.

So, the naming convention of the corresponding zip-files largely follows the one provided in the Data Management Plan and reads as follows:

PRE5P1_KIT_D**mm_ttt**K_**extn**.zip

With **mm** indicating the nozzle diameter (”1”,”2” or “4”), **tt** the nominal start temperature (“080” for LN2 boiling or “300” for ambient) and **extn** the type of data contained (“DATA” for Excel sheets containing all numerical and some predefined graphs, “CAM1” for pictures from the near nozzle flow field, “CAM2” from the wider gas jet area). In the zip-files sub-folders can be found, in which the data is further separated in twelve blocks for experiments with the same initial pressure, corresponding to the twelve blocks separated in the upper and lower parts of Table 4. In the sub-folders the experiments are named with the beginning time of the experiment and the ignition distance in the name.

5.1 Structure of the Datasets

The result data is stored in Excel files. The Excel-files are named with date and time of the beginning of the respective experiment in the format “2020MMDD-hhmmss-SE-xxxcm” with “SE” indicating data acquisition using Signal Express and “xxx” representing the ignition distance. A separate file with the name in the format “2020MMDD-hhmmss-PFast-xxxcm” contains the measured values of the external pressure sensors and the sound level meter, recorded with another system at a higher measurement frequency of 100 kHz.

Each “SE”-Excel file consists of three worksheets, corresponding to the three different data acquisition systems/routines applied in the experiments. The first sheet of the “SE”-Excel-file, named “2020MMDD-hhmmss-**presV**”, contains the data of the fast pressure measurements inside the DisCha-vessel and a column for the trigger signal of the release valve (Figure 10).

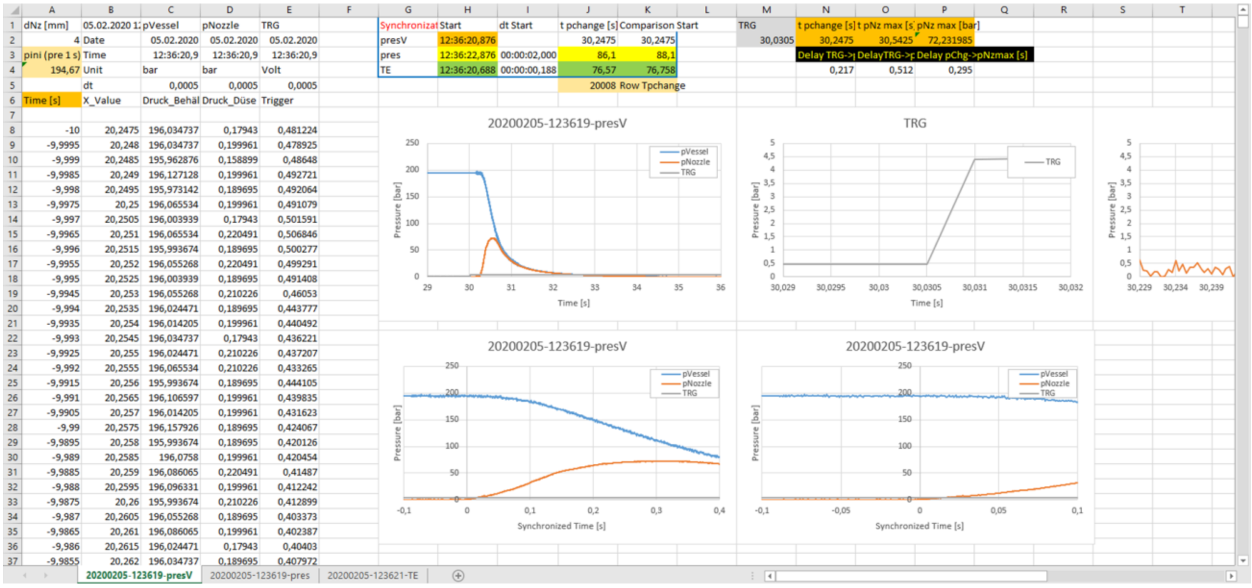


Figure 10: Example for the structure of the first data sheet with the fast vessel pressure measurements in the Excel-file of experiment 20200205-123619 at LN2-temperature (4 mm nozzle, 200 bar)

The first column in this sheet is the synchronized time that was calculated from the actual beginning of the release, which was identified by the first pressure increase in the signal of the pressure sensor PN in the pipe between valve and nozzle. Using this pressure increase and the trigger signal it is possible to synchronize this sheet with the other sheets of the Excel file.

For synchronization, the second sheet with the title “2020MMDD-hhmmss-**pres**” contains again the records of the pressure sensors in the vessel, but also the ambient data of the wind measurements with the anemometer (Figure 11). On this sheet, the measuring frequency is much lower (10 Hz), since the anemometer is unable to deliver faster measurements.

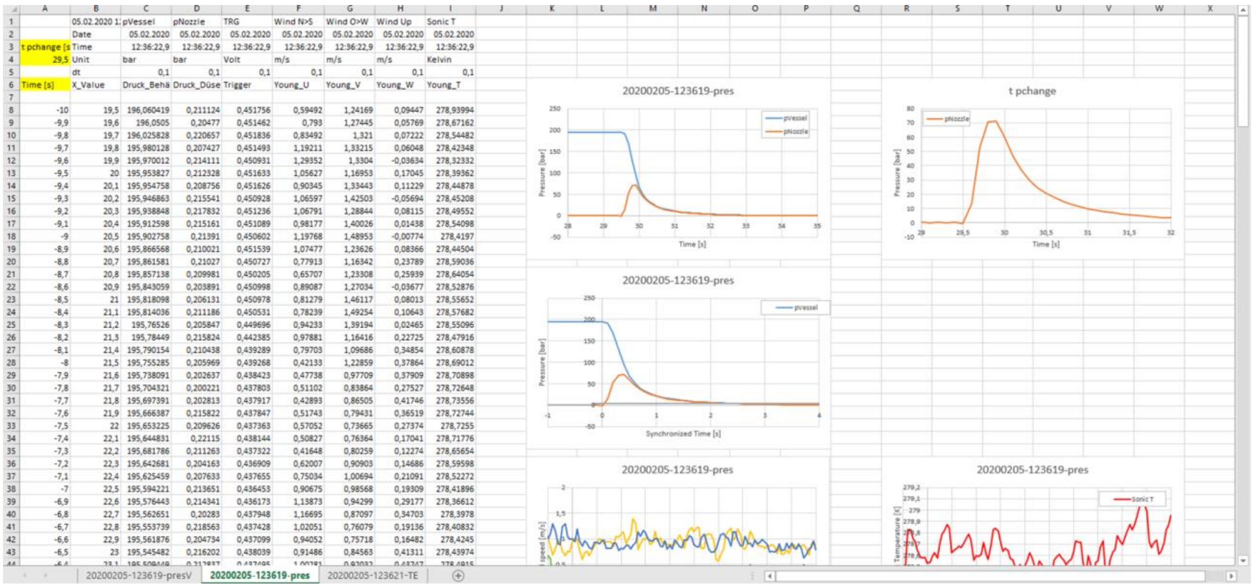


Figure 11: Example for the structure of the second data sheet with the slow vessel pressure measurements and the wind data in the Excel-file of experiment 20200205-123619 (80 K, 4 mm, 200 bar)

The third sheet has the name "2020MMDD-hhmmss-**TE**" and contains the temperature measurements inside the vessel and close to the nozzle (Figure 12). As additional signal again the trigger signal is added to allow synchronization. As explained in chapter 3.1, the temperature values of the thermocouples had to corrected when cryogenic temperatures were approached, and so in the right part of the sheet these corrected values are given.

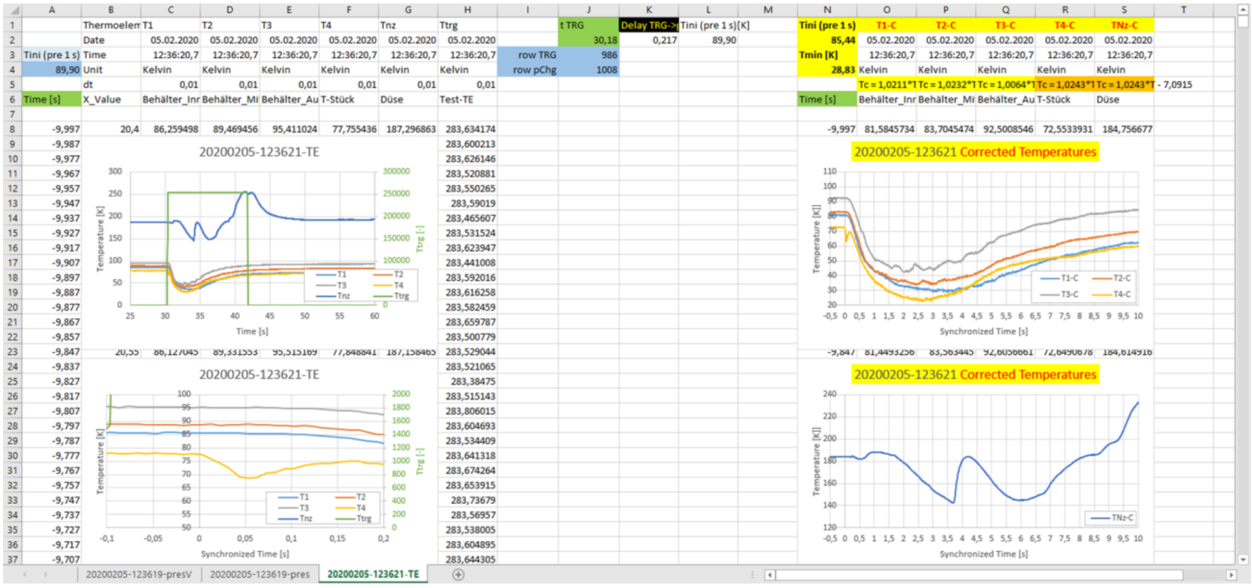


Figure 12: Example for the structure of the third data sheet with the original (left) and corrected (right) temperature measurements in the Excel-file of experiment 20200205-123619 (80 K, 4 mm, 200 bar)

A screenshot of the separate file "2020MMDD-hhmmss-FP-xxxcm" is shown in Figure 13. The time scale of this data corresponds to the trigger signal used to initiate the experiment.

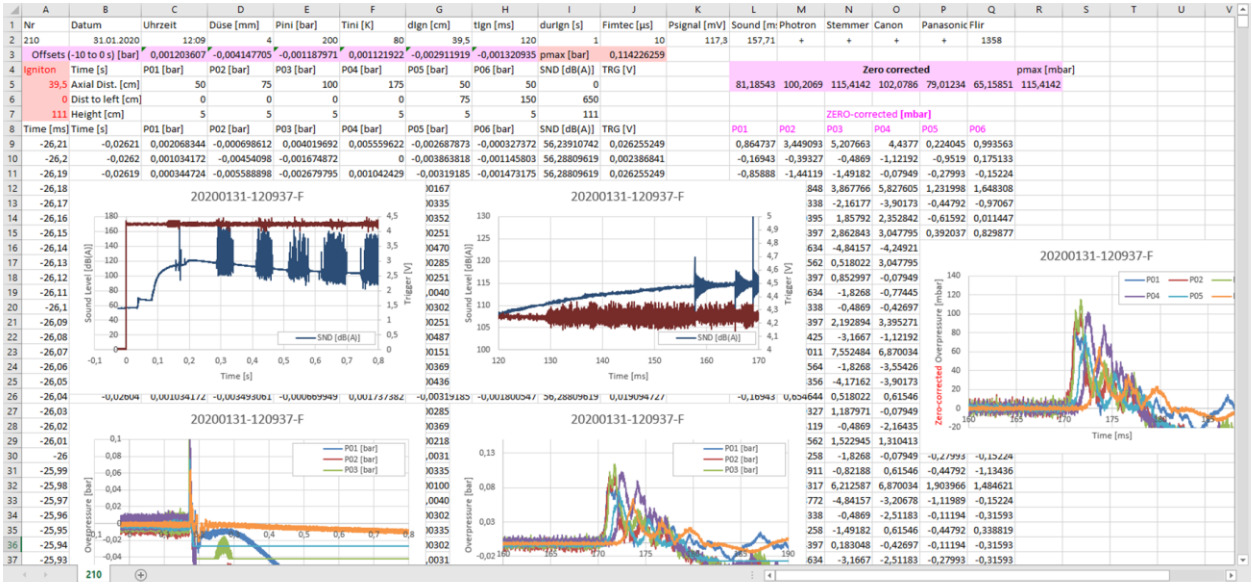


Figure 13: Example for the structure of the third data sheet with the original (left) and corrected (right) ex-vessel pressure measurements in the Excel-file of experiment 20200131-120937 (80 K, 4 mm, 200 bar)

In the right part of the sheet the "Zero-corrected values" of the pressure signals are given which are the pressure values that should be used for analysis. The correction is necessary since the sensors show a slight offset signal even if no pressure is applied. To correct this deviation the mean offset in the last 10 ms prior to the ignition is calculated (cells C3 to H3) and subtracted from the pressure values. Due to the very low pressures recorded the values were also converted to mbar in these columns.

6 Summary, Conclusions and Outlook

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. These data are publicly available at PRESLHY repository on KITopen.