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

Fuel Cells and Hydrogen Joint Undertaking (FCH 2 JU)

Grant Agreement Number 779613

Summary of experiment series E3.1 (Discharge) results – part A high pressure

Deliverable Number:	3.4 (D21)
Version	1.1
Author(s):	A. Friedrich PS, A. Veser PS T. Jordan, KIT
Submitted Date:	5 July 2019
Due Date:	30 November 2018
Report Classification:	Confidential

History		
Nr.	Date	Changes/Author
1.0	19.7.2019	Original version by A. Friedrich, A. Veser and T. Jordan PS/KIT
1.1	23.7.2019	Sequential table of experiments in the Appendix B; Correction of electric field scale

Approvals			
Version	Name	Organisation	Date

Key words

Cryogenic release, high pressure, discharge coefficient, jet dispersion, electrostatic field, far field observation

Preface and Disclaimer

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, so-called part A. However, because of certain adaptions the electrostatic build-up/ignition experiments 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, result data structure and access (sub-set of the result data is provided via KITopen). 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.

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.

Acknowledgements

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.

Publishable Short Summary

In the frame of the PRESLHY project more than 200 hydrogen blow-down experiments were made with the DisCha-facility at KIT and about half of the experiments were made at cryogenic temperatures (approx. 80 K). During the experimental campaign the facility was continuously improved and extended, since several problems with the facility and instrumentation were encountered. 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 WP3 and WP4, some interesting observations are: not a single test showed a spontaneous ignition, although the cold jets generated relative strong electrostatic fields. This static electricity seems to be generated by ice crystal which form on the release nozzle before the tests. The cold tests with large diameter and high pressure show strong temperature decay in the reservoir close to the boiling point of hydrogen and quite a huge fraction of "particles" entrained in the released jet were recorded. It is assumed that this is ice from ambient humidity and frozen on the nozzle before the actual test. However, there might be condensed hydrogen involved, as the acceleration of the gas through the nozzle might bring down the temperature below the boiling point. Only detailed multi-phase simulations accounting for non-equilibrium effects of the real gases' behaviour might clarify this issue.

Table of Contents

1 Purpose of the Tests – Knowledge Gap Addressed

In the work package WP3.1 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).

In the first part A of the tests the DisCha facility is utilized to investigate releases of cryogenic hydrogen at temperatures of approximately 80 K and pressures up to 200 bar, and to compare this behavior with similar releases at ambient temperature. Therefore two experimental series, one at ambient temperature and the other at cryogenic temperature, the boiling temperature of liquid nitrogen (LN2) were performed with DisCha facility. The facility was integrated in a larger experimental set-up, which was protected from too strong environmental influence with a tent. The set-up was installed on the free field behind the main hall of the hydrogen test site HyKa at KIT (see Figure 1).

Figure 1: Location of DisCha-facility in a tent behind the main hall of the hydrogen test site HYKA at KIT

The main purpose of the tests was to provide validation or reference data for

- models defining or using a discharge coefficient,
- subsequent explosion tests, where the released gases will be ignited (see E5.2), and
- electrostatic field excitation and associated ignition potential of high pressure hydrogen gas jets

at cryogenic temperatures.

2 General Description of the Experimental Set-up

The DisCha facility mainly consists of a stainless steel pressure vessel with an internal free volume of 2.815 dm³ and a weight of about 28 kg, which is fastened in an insulated box for the LN2 pool cooling (Remark: the original plan to cool the DisCha facility with a LH2 pool was discarded because of the high costs and the volatile boiling behavior expected for LH2, and because the pressure vessel was only designed for LN2 boiling temperature).

The cooling box with the vessel is mounted on a sledge and this sledge is mounted on a balance. The total weight of the experimental set-up, as measured by the balance is about 120 kg. Photographs of the facility and a sketch of the facility are shown in Figure 2 and Figure 3.

Figure 2: Photographs of the pressure vessel (left) and the general set-up of the DisCha-facility (right)

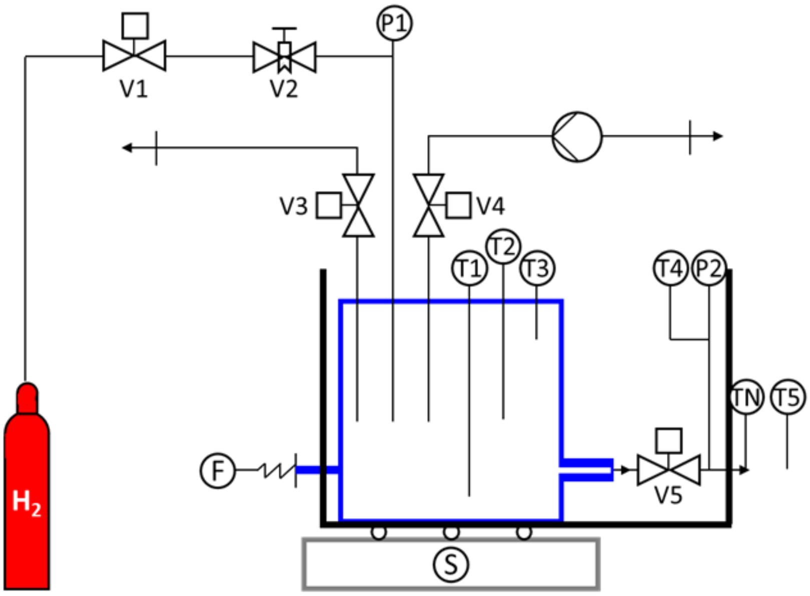


Figure 3: Sketch of the DisCha-facility
(DisCha in blue color, cooling box in bold black color, balance in grey color)

Through the filling line and the valves V1 and V2 the test vessel can be filled with 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, nozzle diameters respectively, can be fastened.

The sledge provides an almost slip free movement of the setup for the measurement of the repulsive forces, that act on the vessel during the release experiments. The balance is used to measure the loss of weight caused by the effusing gas in the hydrogen release experiments.

Four nozzles with circular apertures of 0.5, 1, 2 and 4 mm were used in the 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 mounted in between the release valve and the vessel exhaust

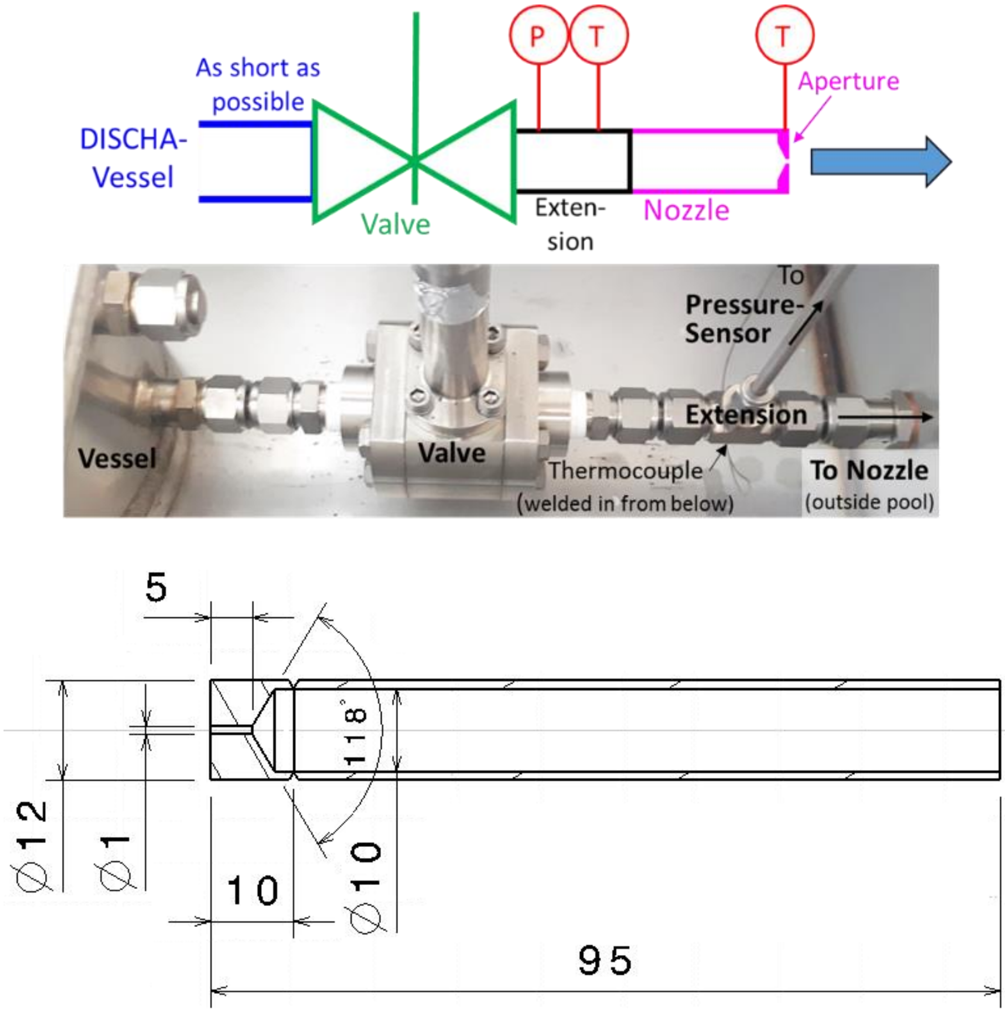


Figure 4: Sketch and photo of the release pipework of the DisCha-facility and the technical drawing of the 1 mm release nozzle (only the diameter Ø 1 is changed for the other nozzles)

3 Instrumentation of the DisCha-facility

Apart from the force sensor (Althen, Type ALF318CPR0K0, 0 - 2 kN) and the balance (F and S in Figure 3) mentioned above, the test vessel and the release nozzle are instrumented with two pressure sensors and eight thermocouples. Outside the release nozzle further five thermocouples and a set of five H2-concentration measurement devices are installed. Additionally, two field mills for measuring static electric field strength and three cameras (2 photo cameras and 1 video camera) are used to monitor the releases using the BOS-technique for the visualization of density gradients.

Pressure sensors: One static pressure sensor (P1 in Figure 3) in the filling line is used to control the initial pressure inside the vessel during the filling procedure, while the second one 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): Three sets of NiCr/Ni-thermocouples (Type K) are used in the DisCha facility. Two sets (three TCs each) are installed inside the vessel to record the gas temperature during the experiment in different heights. The two sets are used to check the accuracy and the rise time of the three standard TCs (T1 to T3, diameter 0.36 mm, sensitive tip covered by thin stainless steel shell) with a second set of three very thin open TCs (T1o to T3o, diameter 0.25 mm, stainless steel shell of sensitive tip removed) that are no longer available at the workshop at KIT. Both sets are installed in comparable positions inside the vessel. In the release line two further standard TCs 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. In total five standard TCs are distributed outside the release nozzle. Three of these (T5 to T7) are located in distances of 250 mm, 750 mm and 1750 mm from the nozzle on its centerline, while T8 and T9 are positioned in distances of 250 mm and 500 mm slightly to the right and to the left of the nozzle centerline (see Figure 5).

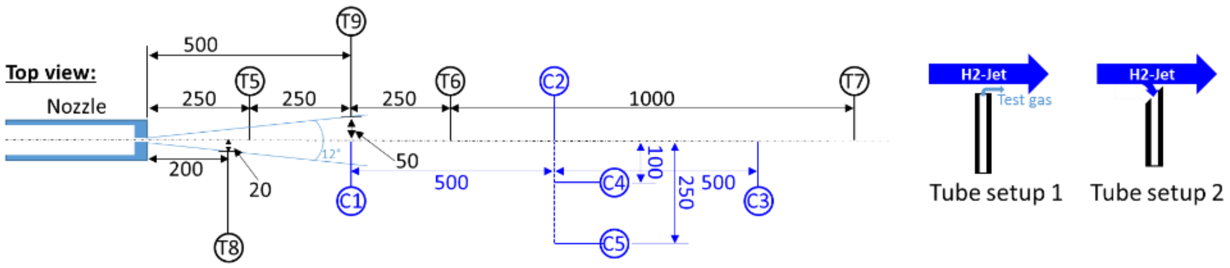


Figure 5: Sketches of the ex-vessel instrumentation of the DisCha-facility and configurations of the plastic tubes for the H2-concentration measurements

Concentration measurements: Five Messkonzept H2-sensors are utilized to determine the hydrogen concentration in different positions in the free hydrogen jet release. Three of these positions are on the jet axis, while the remaining two positions are in different horizontal distances to the jet centerline (see Figure 5). Since these sensors are quite large and require a constant gas flow they were not mounted physically to the positions shown in Figure 5, but were connected to these positions via thin plastic tubes of 2.55 m length. One small pump is used to supply all sensors with the same volume flow of test atmosphere during the measurements. In pre-experiments the delay time due to this setup was determined by exposing the open tip of the plastic tube with pure or diluted hydrogen (20% H2, forming gas) from a balloon (without forcing an additional flow of the test gas in the tube). A similar delay time of 2 s was found for all five sensors in this setup from the opening of the hydrogen balloon to the first increase in the signals of the hydrogen sensors.

In the first test series the open tip of the plastic tube was pointing straight upwards, with the planar cross section of the tube as horizontal plane in the jet centerline (tube setup 1 in Figure 5). While evaluating the test records after the first series it was found that this setup causes irregularities in the arrival times, since the first sensor besides the centerline C4 detected hydrogen prior to C1, which is located much closer to the nozzle. The reason for this unrealistic behavior is most likely the fast flow passing the tip of the plastic tube, causing a suction effect in the tube which leads to an additional delay time for the transport of the test gas to the sensor.

To avoid this effect all experiments were repeated once with a tilted cut of the plastic tube, with the open side of the cut pointing towards the nozzle (tube setup 2 in Fig. 5). But since the sensor of position C5 never detected significant amounts of H2 in all experiments, it was decided to use this channel for reference measurements in position C1 with the old tube configuration (column H: C1-). Due to this change in the setup the hydrogen arrival times became more realistic, but in some cases with very high initial pressures hydrogen was detected already before the release valve was even opened. In this case the fast jet pushed the gas inside the tube which led to shorter delay-times than the 2 s determined for cases without any additional flow.

Field mills: Two field mills (model Kleinwächter EFM 113B) were positioned in the height of the nozzle in distances of 0.5 and 1.5 m from it and with horizontal distances of 0.9 m from the jet axis (see Fig. 6).

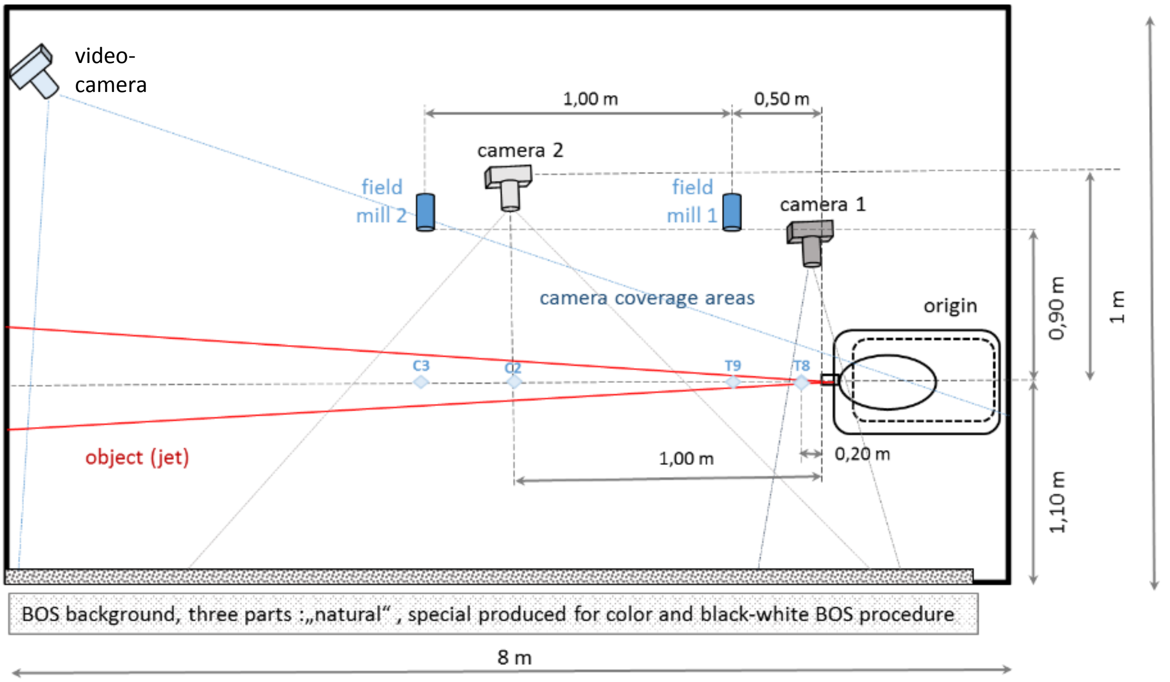


Figure 6: Sketch of the positions of the field mills and the cameras in the DisCha-facility (top view)

Cameras: The two photo-cameras were positioned at 5 cm (Camera 1) and 1 m (Camera 2) in jet downstream direction, on the same height as the center of the release nozzle and with a distance of 0.9 m (Camera 1) and 1.1 m (Camera 2) to the horizontal center line, the nominal jet center line. The specifications of the two cameras are as follows:

Camera 1

CANON EOS5D Mark I

- lens type telephoto
- resolution 4368 x 2912 pix
- distance from camera to horizontal release axis equals to 0.9 m
- the size of the observation area in the central jet plane is about 0.33 x 0.22 m

Camera 2

CANON EOS5D Mark II

- lens type wide angle
- resolution 5616 x 3744 pix
- distance from camera to horizontal release axis equals 1.1 m
- the size of the observation area in the central jet plane is about 1.25 x 0.83 m (Version 1) or about 1 x 0.67 m (Version 2)

The photos were synchronized with the release time by utilizing a high speed optical clock (see Figure 8), which shows changing LED-signals to indicate the time that has passed after was initiated.

The video-camera was positioned below the roof of the tent in a distance of several meters downstream the nozzle pointing towards the release. To the right of the jet, opposite to the two photo-cameras, different background patterns were glued to wooden walls to test the BOS optical method for the visualization of the cold hydrogen jet releases. In the part close to the nozzle a fine random black and white box-pattern was used, while in farther distances "natural" backgrounds (branches and shrubs) were tested.

Figure 7: Position of the cameras and BOS background patterns on the floor and back wall

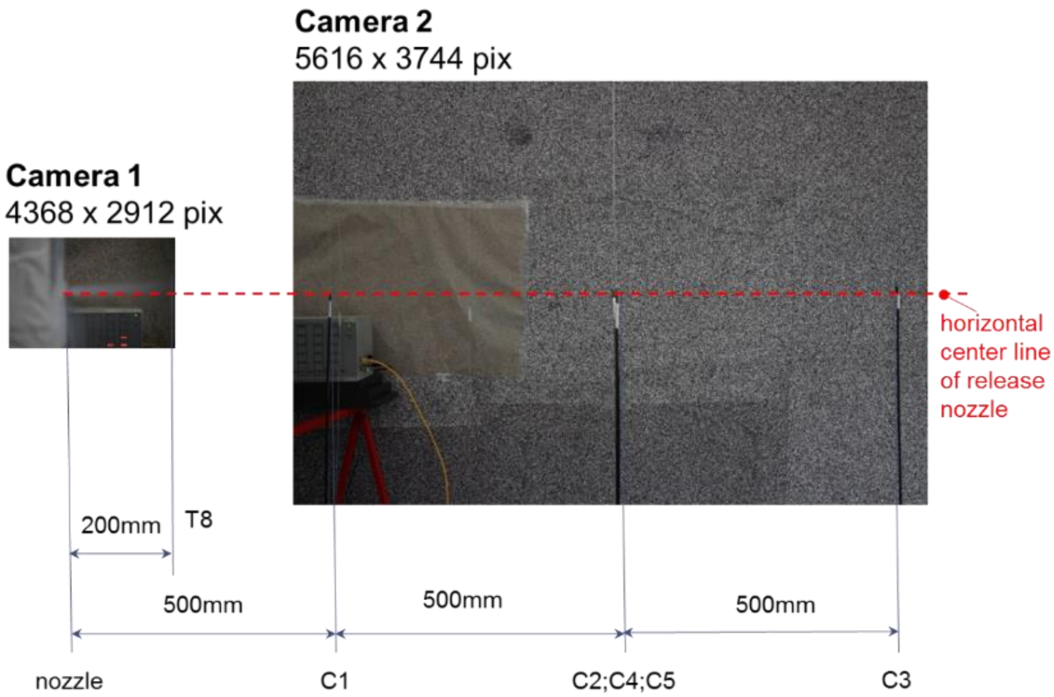


Figure 8: View fields of the cameras related to special elements of the experimental set-up, Version 1 (nozzle on the left end of the horizontal center line; thermocouples T8, concentration sensors C1, C2, C4 and C5); optical clock visible in both photographs

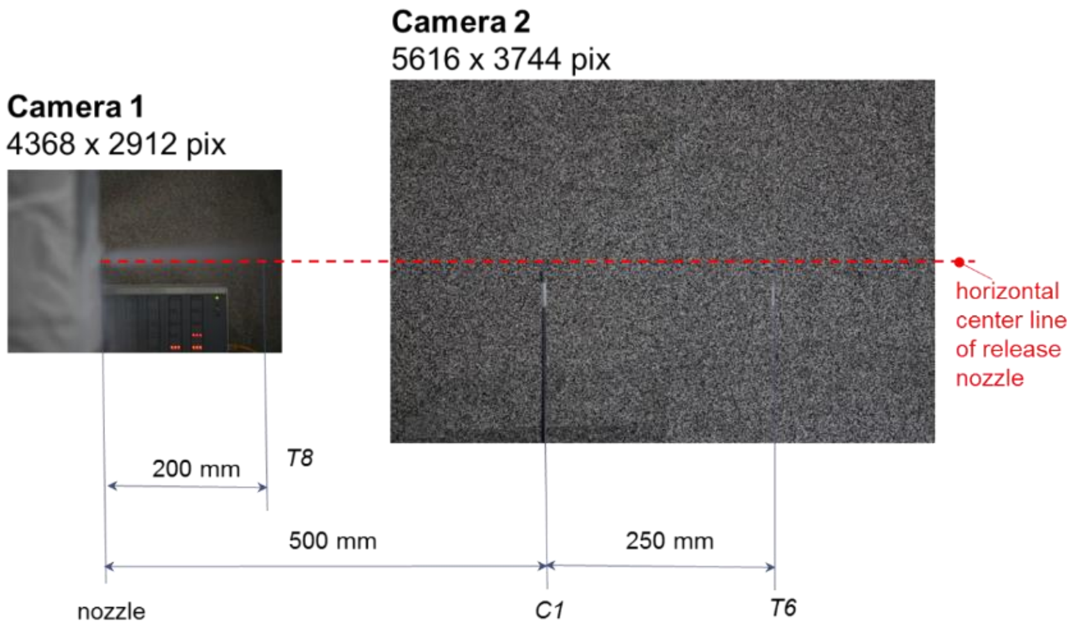


Figure 9: View fields of the cameras related to special elements of the experimental set-up, Version 2 (nozzle on the left end of the horizontal center line; thermocouples T8 and T6, concentration sensor C1), optical clock on visible for Camera 1

3.1 Estimate of Measurement Errors

The accuracy of the sensors used in the experiments is given in the table below. 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 DisCha experiments

Sensor	Manufacturer	Type (Range)	Non-linearity @ 290 K
Force	Althen	ALF318CPR0K0 (2 kN)	± 0,1 % FS
Scales	Mettler-Toledo	PBA430x (150 kg)	0.006% FS
Pressure	WIKA	S-20 (250 bar)	< 0,125% FS
Field mill	Kleinwächter	EFM 1138 (5 kV/m)	< 5% FS
H2-Sensor	Messkonzept	FTC300 (100% H2)	< 1% FS
Temperature	KIT-Workshop	Type K, d = 0.36 mm	1.66 °C

In the experiments only the thermocouples are exposed to cryogenic temperatures and so their deviation from the temperature of LN2 (77 K) was measured in a separate test. In this test all closed thermocouples (T1 – T9 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. The three open thermocouples T1o, T2o and T3o, used additionally inside the test vessel, were also tested in the same way, but showed quite large deviations with values of approximately 105 K for the temperature of liquid nitrogen. The reason for this behavior might be a combination of their age (about 10 years) and the open tip that might already show some degeneration. These sensors could not be replaced by new ones, since this type is no longer available at the KIT workshop. Because of their lower thermal capacities, their signal might be used to determine characteristic changes in time rather than to read accurate, absolute temperature values.

4 Test Matrix

The test matrix for the blow-down experiments was constructed by varying the release nozzle diameter (4 diameters: 0.5, 1, 2 and 4 mm) and the initial hydrogen storage pressure (7 nominal pressure values: 5, 10, 20, 50, 100, 150 and 200 bar) for two hydrogen storage temperature levels (2 nominal storage temperatures: 80 and 300 K). Typically, at least three repetitions of one pressure/nozzle diameter combination were conducted. In many cases the test has been repeated more than three times, for 200 bar and 2 mm even seven tests were done to provide an estimate for the stability, reproducibility respectively, of the measurement system in general.

The whole test campaign with more than 224 tests lasted almost 4 months (middle of February to end of June 2019) with several interruptions for improving the measurement set-up, setting up the pre-cooling or because of delays in LN2 supply. Several pre-tests have been excluded from this report. Also those tests have been excluded, which were used to validate the modified concentration measurement, which is explained in Chapter 3 above.

The test itself and the respective result files are labeled with the date and time ("date"_"time"), at which the test was initiated:

2019**MMDD_hhmmss**(**.ext**)

with **MM** for month, **DD** for day, **hh** for hour, **mm** for minute, **ss** for second of the formal start of the experiment; **ext** is either empty for just labelling the experiment, "xlsx" for the Excel files containing the dataset or "zip" for the set of photographs, pictures respectively, taken from this experiment.

The labeling of the zip-files containing several of those data or picture files for identical nozzle diameter and temperature is explained below.

All tests are listed in sequential order together with the information about effective initial temperature and pressure and about nozzle diameter in Appendix B. This helps in finding the parameters associated with each test simply via its "date"_"time" name. The reference tests done first with hydrogen at ambient temperature are summarized in the test matrix shown in Table 2. The test matrix for the cold experiments done with LN2 cooling - the actual cryo-release tests - is shown in Table 3.

In both tables the experiments, for which the datasets are published via KITopen [1], are highlighted with black bold font. The labels of those experiments, for which photographs are published also via KITopen, have a grey background color.

The cold tests 20190528_104204 (i.e. the test, which started 28th of May 2019 at 10:42 am) and for photography 20190503_140045 are used as representative examples in the further text.

Table 2: Test matrix of DisCha experiments at **ambient temperature**
(n_{total}= 126, experiment label 2019MMDD_hhmmss for start date and time)

Pressure [bar]	Nozzle-Diameter [mm] 0.5	1	2	4
5	~~20190218_152803~~ ~~20190218_153211~~ 20190312_140742 **20190523_155208**	~~20190218_145937~~ ~~20190218_150203~~ 20190312_141636 **20190523_151618**	~~20190218_143922~~ ~~20190218_144147~~ 20190312_142444 **20190523_144219**	~~20190218_135240~~ ~~20190218_135848~~ ~~20190221_105323~~ 20190312_143216 **20190523_141327**
10	~~20190218_153516~~ ~~20190218_154048~~ 20190312_141024 20190523_154849	~~20190218_150528~~ ~~20190218_150851~~ 20190312_141909 20190523_151411	~~20190218_144358~~ ~~20190218_144713~~ 20190312_142706 **20190523_144022**	~~20190218_140223~~ ~~20190218_140530~~ ~~20190221_110229~~ 20190312_143846 **20190523_141008**
20	~~20190218_154318~~ ~~20190218_154510~~ **20190523_154414**	~~20190218_151140~~ ~~20190218_151621~~ **20190523_151013**	~~20190218_145002~~ ~~20190218_145411~~ **20190523_143801**	~~20190218_140858~~ ~~20190218_141305~~ **20190523_140705**
50	20190307_143703 20190326_152315 20190523_153958	20190307_141026 20190326_144506 20190326_144755 20190523_150640	20190307_111816 20190307_113513 20190326_140441 20190326_140752 **20190523_143501**	~~20190221_110511~~ ~~20190221_111257~~ 20190307_133159 20190523_140344 **20190624_145615**
100	20190307_144122 20190326_151458 20190326_151931 **20190523_153415**	20190307_141324 20190326_143750 20190326_144109 **20190523_150133**	20190307_113815 20190326_135707 20190326_140034 20190523_143020 **20190624_152500**	~~20190221_140324~~ ~~20190221_140517~~ ~~20190221_141846~~ 20190307_133454 20190322_104748 20190523_115747 **20190624_145052**
150	20190307_144458 20190326_150440 20190326_150854 20190523_152829	20190307_142436 20190326_142958 20190326_143412 20190523_145700	~~20190221_150608~~ ~~20190221_150950~~ 20190307_114105 20190326_135313 20190523_142651 **20190624_151944**	~~20190221_142431~~ ~~20190221_142819~~ 20190307_135327 20190322_103008 20190523_113338 **20190624_144205**
200	20190307_144904 20190326_145458 20190326_150007 **20190523_152309**	20190307_141656 20190326_141916 20190326_142523 **20190523_144939**	~~20190221_143934~~ ~~20190221_144801~~ ~~20190221_145609~~ ~~20190221_150110~~ 20190307_114908 20190326_134758 20190523_142245 **20190624_151045**	~~20190221_143129~~ ~~20190221_142424~~ 20190307_134340 20190307_140303 20190322_100645 20190523_113015 **20190624_143040**

Published Excel **datasets** for instance in:
PRE3P1A_KIT_**D05_300K**_DATA.zip
corresponding photographs in
PRE3P1A_KIT_**D05_300K**_PICS.zip

Legend:

~~Not processed, no sync.~~
Not processed, sync. difficult
~~Processed, no sync.~~
Processed and synchronized
~~Published Photo~~graphs
Published Datasets

Table 3: Test matrix of DisCha experiments at **LN2-temperature**
(n_{total}= 98, experiment label 2019MMDD_hhmmss for start date and time)

		Nozzle-Diameter [mm]			
		0.5	1	2	4
Pressure [bar]	5	20190509_143959 20190509_144955 20190604_151150 **20190604_153521**	20190507_155308 20190507_160047 **20190531_120333**	20190430_150817 20190430_151117 **20190531_103828**	20190503_112024 20190503_112408 **20190528_111918**
	10	20190509_142254 20190509_143252 20190604_150515 20190604_152905	20190507_153753 20190507_154609 20190531_115603	20190430_144909 20190430_150600 **20190531_103408**	20190503_110955 20190503_111525 **20190528_111240**
	20	20190509_111408 20190509_112201 20190604_145638 **20190604_152254**	20190507_152321 20190507_153041 **20190531_114903**	20190430_143105 20190430_144308 **20190531_102810**	20190503_110259 20190503_121635 **20190528_110441**
	50	20190509_135757 20190509_141151 20190604_144425	20190507_150252 20190507_151256 20190531_113940	20190430_141445 20190430_142516 **20190531_101948**	20190503_115334 20190503_120719 **20190528_105437**
	100	20190509_132731 20190509_134535 **20190604_142752**	20190507_143257 20190507_144631 **20190531_112944**	20190423_120305 20190430_111836 20190430_114028 **20190531_101249**	20190503_104121 20190503_105250 20190528_112837 **20190528_143608**
	150	20190509_104138 20190509_105344 20190604_140657	20190507_135605 20190507_141457 20190531_111808	20190423_121441 20190430_135153 20190430_140732 **20190531_100257**	20190503_100144 20190503_102600 **20190528_142048**
	200	20190509_100955 20190509_102557 **20190604_134543**	**20190531_110440**	20190430_102456 20190430_110643 **20190531_094951**	20190503_134536 20190503_140045 **20190528_104204**

Published Excel **datasets** for instance in:
PRE3P1A_KIT_**D1_80K**_DATA.zip
corresponding photographs in
PRE3P1A_KIT_**D1_80K**_PICS.zip

Legend:

Not processed, sync. difficult
Processed, wrong format, sync. difficult
~~Processed, no sync.~~
Processed and synchronized
Published Photographs
Published Datasets
used for further explanations

5 Structure of Experimental Result Data explained with Cold Case 20190528_104204

All experimental data of the unignited DisCha tests highlighted (in black bold font) in Table 2 and Table 3 are published as zipped Microsoft Excel-files via the PRESLHY repository on KITopen https://www.bibliothek.kit.edu/cms/english/kitopen.php [1] in packages with identical nozzle diameter, separately for the ambient (referring to Table 2 and labeled “300K”) and cryogenic (referring to Table 3 and labeled “80K”) hydrogen temperatures, what corresponds to the respective columns in the above tables. Photographs of the camera 1 and camera 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 follows in principle the one provided in the PRESLHY Data Management Plan[1] and reads as follows:

PRE3P1A_KIT_D**mm**_**tt**K_**extn**.zip

with **mm** indicating the nozzle diameter (“05”,”1”,”2” or “4”), **tt** the nominal start temperature (“80” 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, “PICS” for the photographs taken with camera 1 and 2). Two examples for the large zip-files are shown Table 2 and Table 3. For the preparation of the zip-files the free software 7-Zip[2] (64 bit version 19.0) has been used.

5.1 Structure of the Datasets

The result data, the datasets respectively, are stored in Microsoft Excel files with the *.xlsx extension. Each Excel file consists of 4 worksheets, corresponding to the 4 different data acquisition systems/routines applied in the experiments. The Excel-files are named with same “date_time” convention as the experiments with the format “2019MMDD_hhmmss.xlsx”. Compared to the raw data gained from the measurement system, only an additional top line and the column A were added to provide English column names and an additional, synchronized time, which corresponds to the time after the release valve was opened.

Due to improvements and additions the test set-up became more and more complex with increasing test number. So, the structure of the data is explained using one of the last experiments as an example: 20190528_104204, an experiment with 80 K, 4 mm nozzle and initial nominal pressure of 200 bar. The detailed results of this experiment are additionally provided in the Appendix A in form of result diagrams, as they are prepared and included in the Excel files also for all other experiments. If specific columns are missing in some Excel file, typically for experiments done earlier, this solely indicates that the corresponding sensor was not yet implemented at the time the data was recorded.

[1] https://www.hysafe.info/wp-content/uploads/sites/3/2018/10/PRESLHY_D1_3_DataManagementPlanV1_4.pdf

[2] https://www.7-zip.org/

The first sheet of the Excel-file, named "20190528_104204-**Press**", contains the data of the fast pressure measurements and, in the later stage, a column for the signal of the release valve (see Figure 10). In the cells A2 and F2 the nozzle diameter and the initial pressure (as mean value of the last 5 s before the release valve was opened) of the experiment are given. In the upper row of graphs to the right of the data the beginning of the experiment is shown using the original time (column B) of the record, which was started some time before the release valve was opened. In the blue box above these graphs the times of the first changes in the records of all four data sheets of the Excel-file are summarized. So in line 3 the beginning times of the three sensor records of the current sheet are given, with the background of the cell corresponding to the color of the line in the graphs. In all cases the relay's signal increases first, followed by the pressure sensor in the release line (Pnoz) and the sensor in the test vessel (Pves). The grey highlighted cell O3 gives the delay time between relay and Pnoz, which corresponds to the valve delay time. This delay time is not a constant value but changes slightly with changing initial pressure and more pronounced with decreasing temperature.

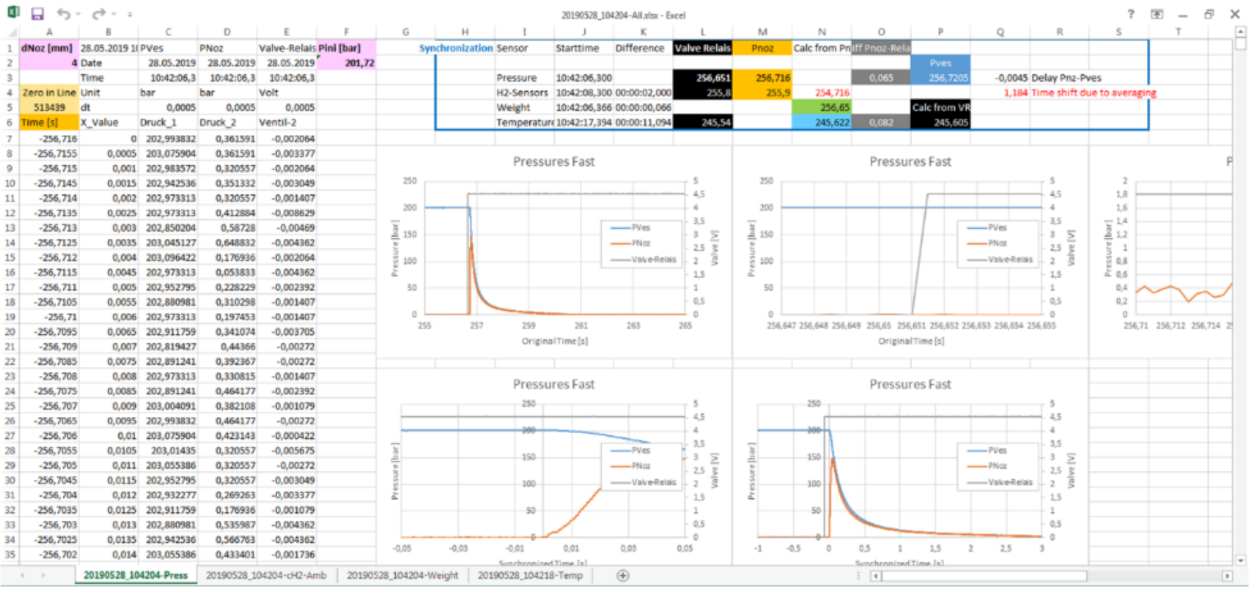


Figure 10: Example for the structure of the first data sheet with the fast pressure measurements in the Excel-file of experiment 20190528_104204 at LN2-temperature (4 mm nozzle, 200 bar)

For the synchronization the time of the first significant pressure increase in the release line (Pnoz) was used as t = 0, since this sensor is the one that detects the effusing hydrogen first (see Figure 11). So the time of this first pressure increase (cell M3) was subtracted from the value of column B to yield the new synchronized time in column A. The initial phase of the experiment using this synchronized time is shown in the lower row of graphs. Due to the extremely high frequency of the pressure measurements (2 kHz) and the long test duration it is not possible to draw a graph in Excel showing the complete signal histories for all experiments.

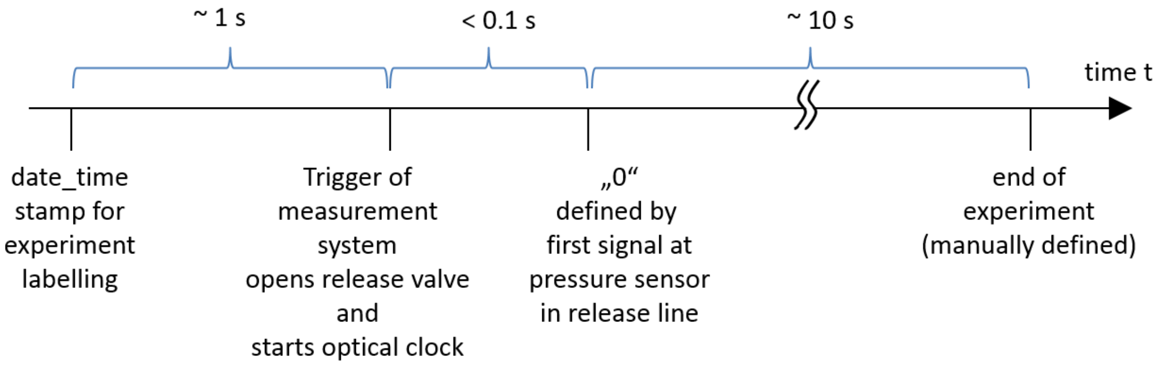


Figure 11: Characteristic times of a DisCha blow-down experiment

The second sheet of the Excel-file is named “20190528_104204-**cH2-Amb**” (Figure 12) and is recorded with a much lower frequency (10 Hz), since most of the sensors recorded are not able to provide faster measurements. For synchronization the pressure sensors and the valve relay are recorded again. Further signals of the sheet are: H2-concentrations, force-sensor, ambient humidity and temperature, as well as the signals of the two field mills used in the late test series. The last column of the sheet contains a second new time scale, in which the time delay of the H2-sensors due to the transport time of the sample from the measuring position to the sensor itself is considered (delay time 2 s, see above in section concentration measurements of chapter Instrumentation of the DisCha-facility).

In the uppermost two graphs the synchronization is demonstrated by showing two graphs with the pressure signals over original and synchronized time. Then the records of the H2-sensors are plotted with their corrected time (including 2 s time delay), followed by graphs of the other sensor signals of this worksheet. In the blue box above the graphs again the times of the first changes in the records of the pressure sensors of all data sheets are summarized. The corresponding times of the current sheet are listed in line 4.

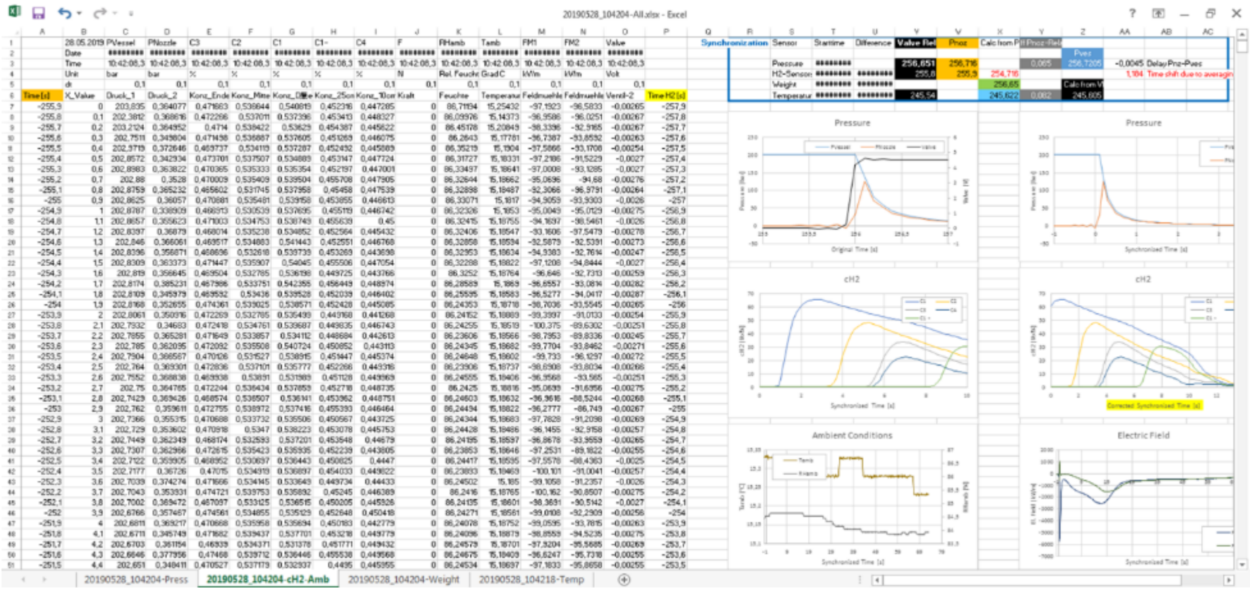


Figure 12: Example for the structure of the second data sheet with the H2-concentration and force measurements, the ambient conditions and the field-mill records in the Excel-file of experiment 20190528_104204 at LN2-temperature (4 mm nozzle, 200 bar)

The third sheet has the name “20190528_104204-**Weight**” and contains only the data recorded by the scales with its maximum frequency of 2 Hz (see Figure 13). Due to software problems this sensor had to be recorded separately, and thus no other signal for the synchronization is available. In this case the opening time of the valve is calculated using the generation time of the data-file, which is given in line 3 in all column headers. The difference between the fast pressure records (first sheet in Excel-file) and the scales data is calculated in cell K5 and the result is used to generate the synchronized time in column A. Signal histories of the scales record with the original and the synchronized time are shown in the two graphs of the sheet.

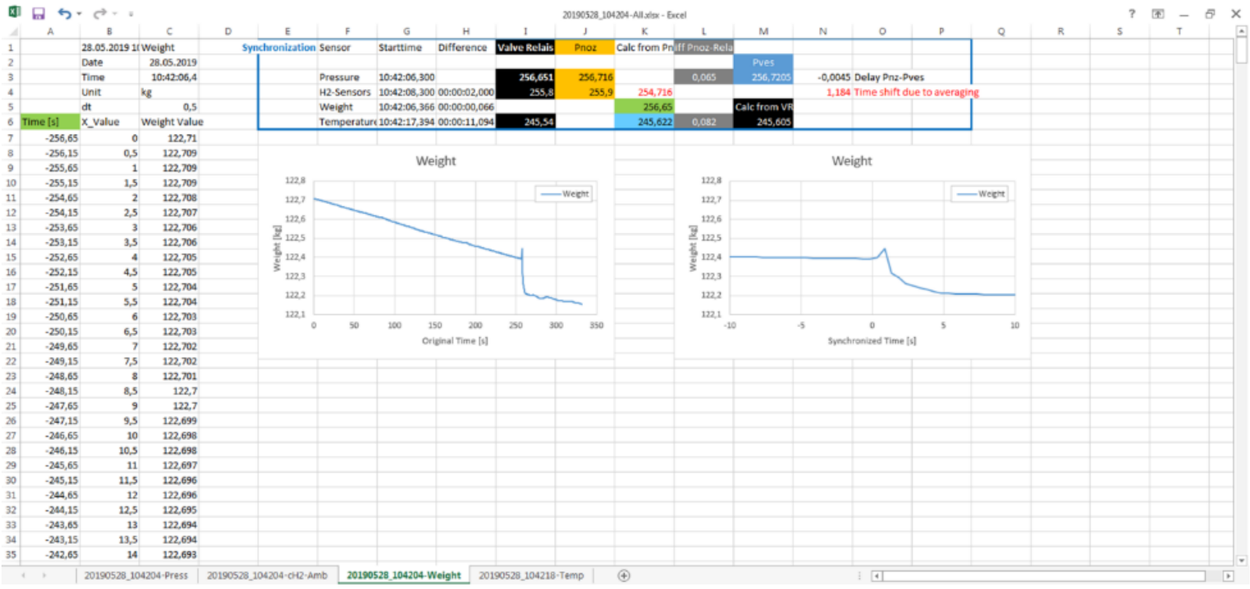


Figure 13: Example for the structure of the third data sheet with the balance-records in the Excel-file of experiment 20190528_104204 at LN2-temperature (4 mm nozzle, 200 bar).

The last sheet of the Excel-file has the name “20190528_104218-**Temp**” and contains the temperature measurements in- and outside the test vessel with the maximum frequency of 100 Hz (see Figure 14). Additionally, the signal of the valve relay is recorded for synchronization. Since a different routine was necessary to record the temperatures a record of Pnoz together with the thermocouples was not possible (and for the same reason the time in the name of this sheet is slightly different from the time in the names of the other sheets). So a synchronization can be either made by a comparison of the generation times of the data-files (line 3) or a synchronization via the relay time, which was also recorded with the fast pressure sensors (see first sheet). The results of both methods are shown in the cells X6 and Z6 in the blue box above the graphs. The values are slightly different due to the different time resolutions of the files. The result of the method using the valve relay was chosen to calculate the synchronized time given in column A. In the upper graphs of the sheet the effect of the synchronization is shown, while the remaining graphs show the temperature histories in the different measuring positions.

Figure 14: Example for the structure of the fourth data sheet with the temperature-records in the Excel-file of experiment 20190528_104204 at LN2-temperature (4 mm nozzle, 200 bar)

5.2 Structure of the Images

The photographs taken of one experiment by camera 1 and camera 2 (typically 5-30 jpeg images per camera) are post-processed and packed in one zip-file, which is named – similarly as the Excel files - with the experiment's "date_time" stamp provided in the test matrices (see Table 2 and Table 3). In Table 2 and 3 it is indicated, for which actual test photographs are stored and published. For all temperature, pressure and nozzle diameter combination, the test documented with photographs is a relative early test and not identical with the latest test of this combination, for which the data has been stored in an Excel file. However, the experimental results do not vary for the same conditions (see reproducibility discussion below) only some sensors arrangements or measurement were changed. Therefore it was decided not to repeat the effort of taking photographs of the later experiments.

All photographs are post-processed in several steps. The most important one is the application of background oriented Schlieren (BOS) methodology. For the photographs taken with camera 1 close to the release nozzle a color BOS scheme with 7 colors was applied. The interrogation area is 8 -16 pix with a 1 pix stepping. The resolution area is 0.6 mm - 1.2 mm. Additional functions applied are a denoising, equalizing and a weight function with a 1D or 2D Gaussian sub-pixels. The color code was carefully chosen to provide best contrast for identification of the jet boundaries. Figure 15 shows the original picture and the result of the post-processing.

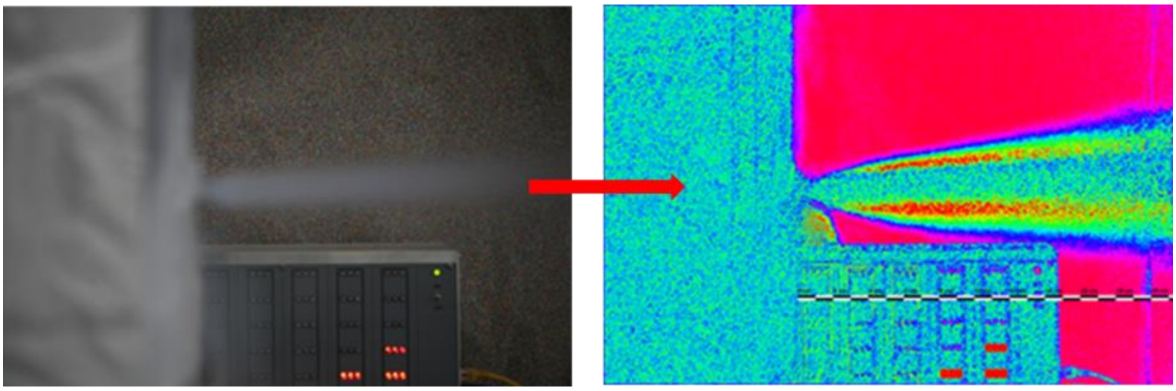


Figure 15: Original picture and results of the color BOS post-processing of a photograph taken from the jet release with camera 1

For the photographs taken from jet from the jet far field with camera 2, a black/white BOS scheme was applied. The interrogation area is 16 pix, 24 pix or 32 pix 8 -16 pix with a 1 pix stepping. The resolution area is 0.6 mm - 1.2 mm. Additional functions applied are a denoising, equalizing and a weight function with a 1D or 2D Gaussian sub-pixels. The color code was carefully chosen to provide best contrast for identification of the jet boundaries. Figure 16 shows the original picture and the result of the post-processing.

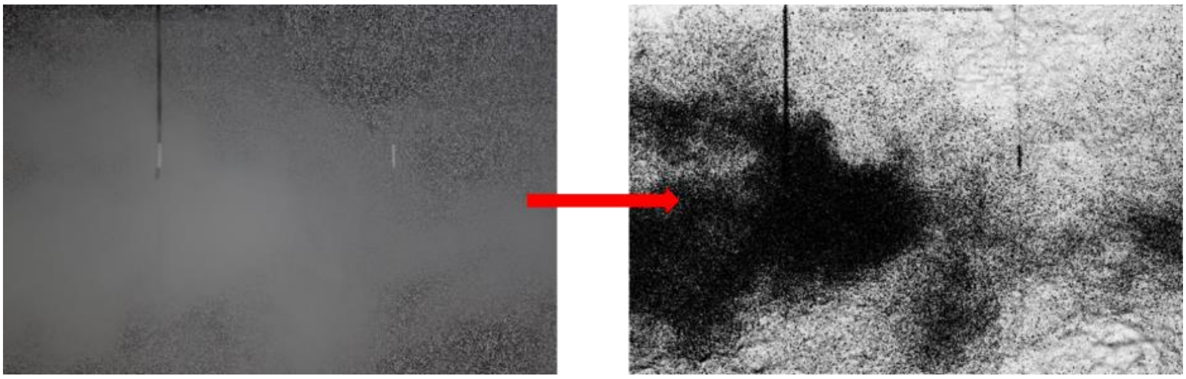


Figure 16: Original picture and results of the black and white BOS post-processing of a photograph of the jet far field observed with camera 2

The next figures show time sequences of original pictures taken with camera 1 and camera 2 from the near field, respectively far field of the jet release experiment 20190503_140045 (80K, 200 bar, 4 mm nozzle) and the same pictures post-processed with the corresponding BOS methods. The time 0 refers to the time of the trigger initiation.

These pictures may be retrieved from file PRE3P1A_KIT_D4_80K_PICS.zip, containing the experiment 20190503_140045 related pictures in 20190503_140045.zip. The corresponding dataset is to be found in 20190528_104204.xlsx (see Table 3, last line, right row, entries highlighted with grey background and bold black font) in PRE3P1A_KIT_D4_80K_DATA.zip.

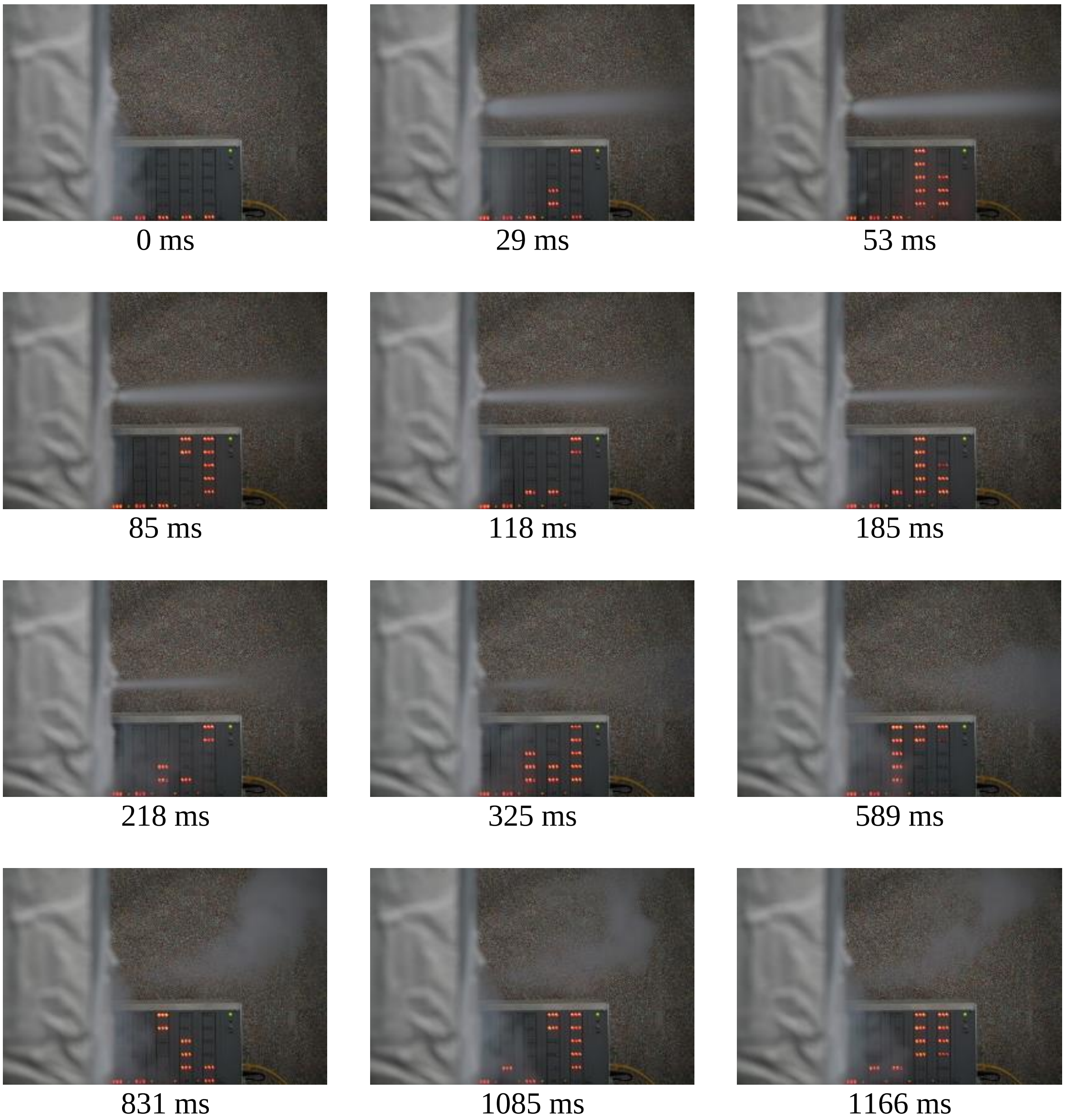


Figure 17: Original photograph series taken from the jet release close to the nozzle (camera 1) of experiment 20190503_140045 (cold, 200 bar, 4 mm nozzle); time = 0 ms refers to the time of the trigger initiation

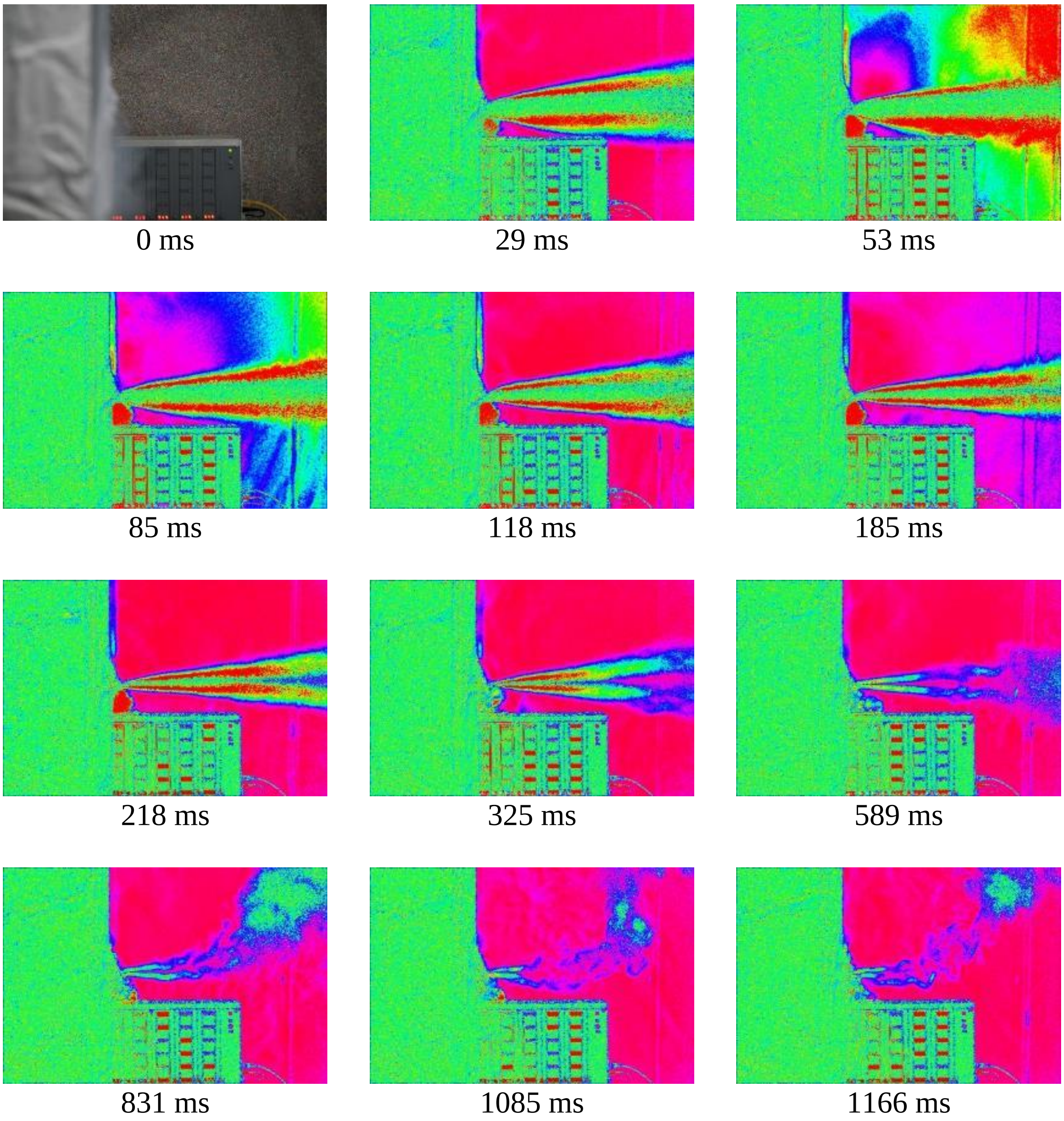


Figure 18: Color BOS post-processed photograph series taken from the jet release close to the nozzle of experiment 20190503_140045 (cold, 200 bar, 4 mm nozzle); time = 0 ms refers to the time of the trigger initiation; the photograph at 0 ms serves as reference for the BOS procedure and therefore is "empty"

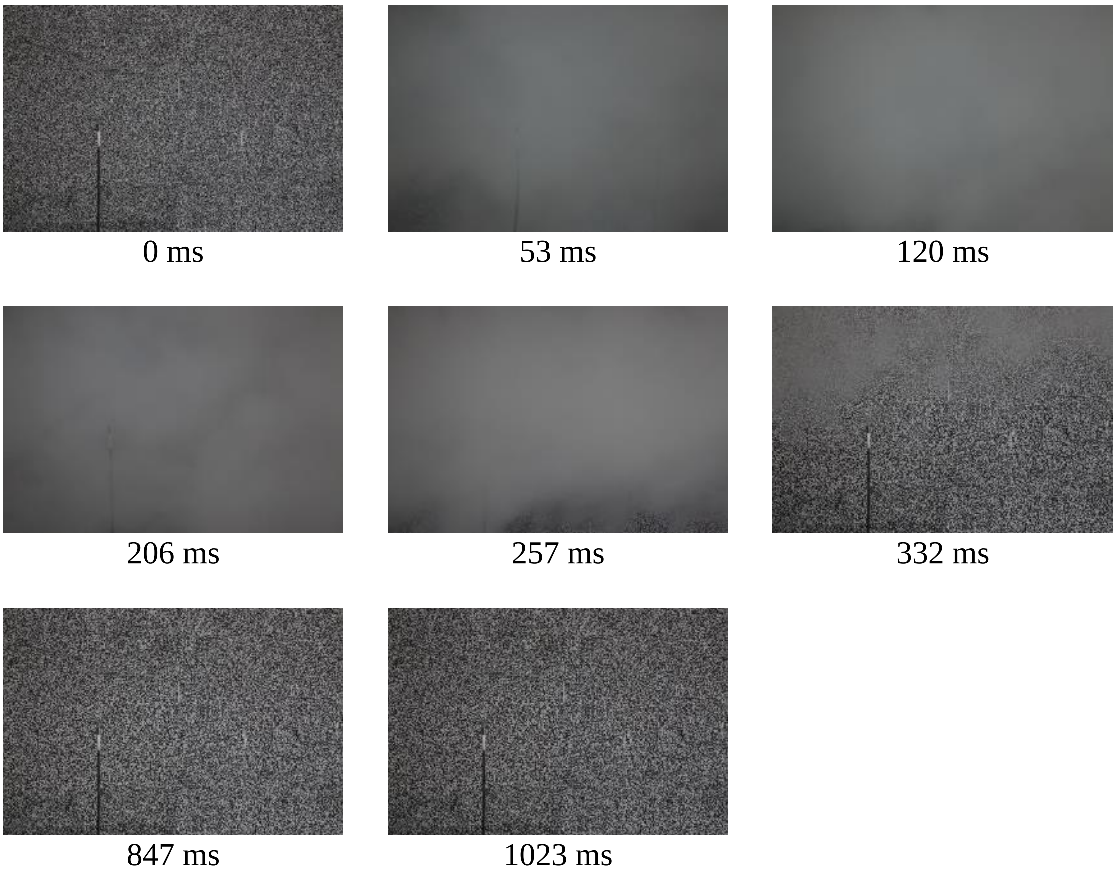


Figure 19: Original photograph series taken from the jet far field (camera 2) of experiment 20190503_140045 (80 K, 200 bar, 4 mm nozzle); time = 0 ms refers to the time of the trigger initiation

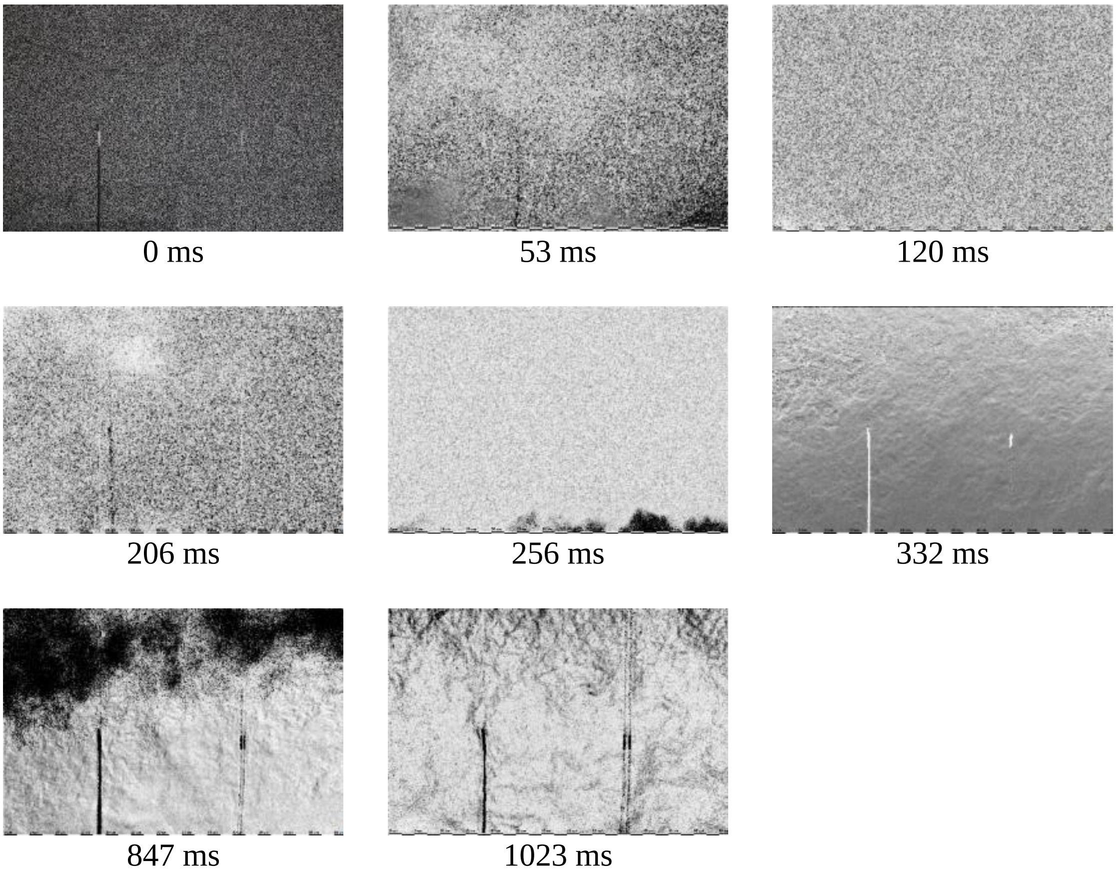


Figure 20: Original photograph series taken from the jet far field (camera 2) of experiment 20190503_140045 (80 K, 200 bar, 4 mm nozzle); time = 0 ms refers to the time of the trigger initiation

6 Some General Observations

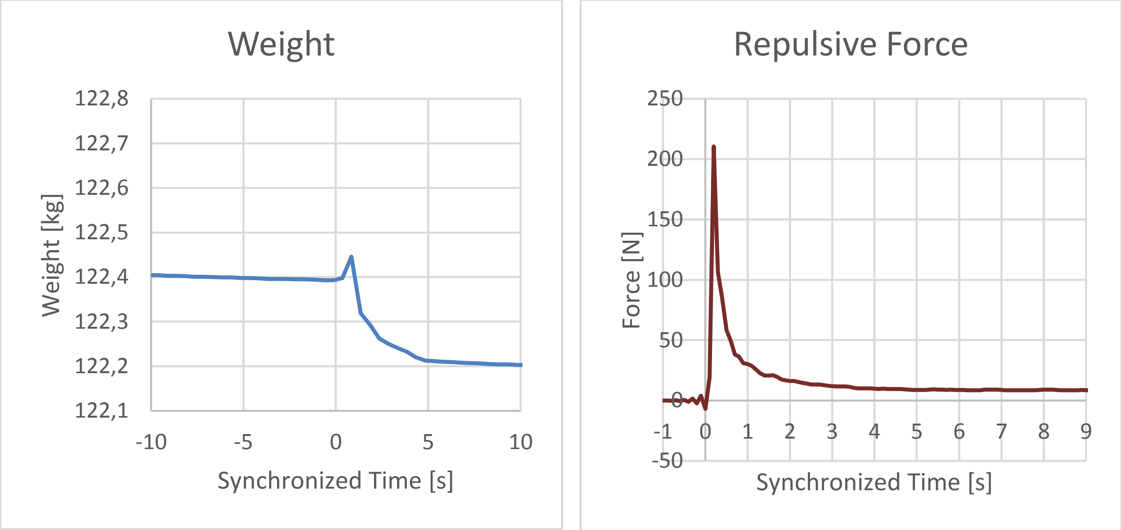
In the frame of the E3.1 Part A test series of the PRESLHY project 224 hydrogen blow-down experiments were made and evaluated using the DisCha-facility of KIT. 98 of the experiments were made at cryogenic temperatures, close to the standard boiling temperature of nitrogen (approximately 80 K) and 126 at ambient temperature (approximately 300 K). The measurement of pressure, temperature and concentrations in the pressure vessel and in the released jet was steadily. After the first two days of experiments, for instance, a fast pressure measurement was added (4^{th} raw data file), since it was found that the frequency used initially was far too slow. Further sensors were added (additional open thermocouples, field mills) and a signal corresponding to the activation of the release valve was added for a more accurate synchronization of the different data files recorded.

The inventories stored in the DisCha pressure vessel for those blow-down experiments vary from about 1,2 g, for the lowest pressure 5 bar and ambient temperature, to about 140 g, for the highest pressure 200 bar and standard boiling temperature of nitrogen. Table 4 contains the densities for the relevant conditions and the corresponding inventories in the DisCha vessel with 2.815 dm^3 free volume. The densities have been derived with real gas factors extracted from [2].

Table 4: Hydrogen inventories of the DisCha experiments

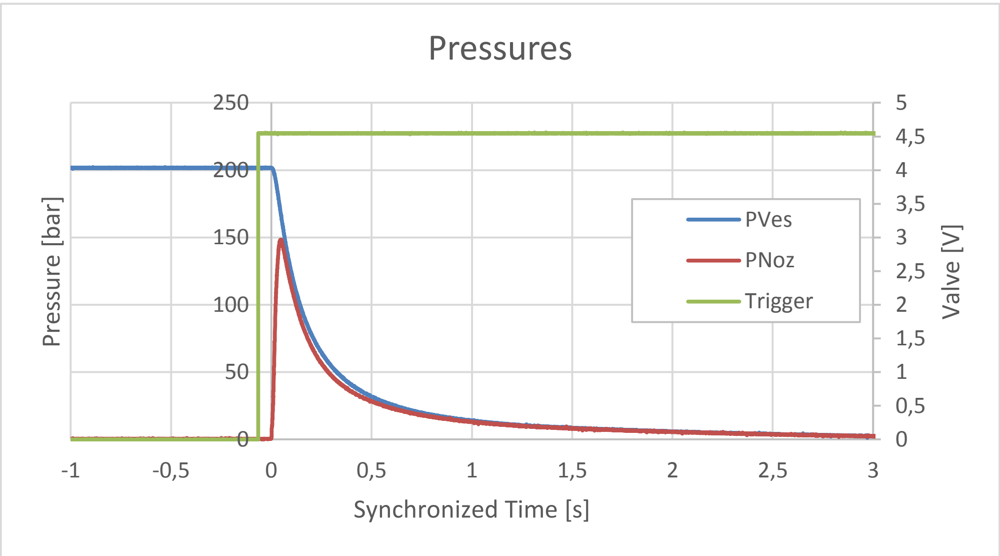
Temperature / K	**Pressure / bar**	1	5	10	20	50	100	150	200
293,15	Ideal Density / (g/l)	0,083	0,414	0,827	1,654	4,136	8,271	12,407	16,542
	Z -factor @ 300 K	1,000	1,000	1,008	1,013	1,030	1,060	1,090	1,120
	Density / (g/l)	0,083	**0,414**	**0,821**	**1,633**	**4,015**	**7,803**	**11,382**	**14,770**
	H2 mass in DisCha / g	0,233	**1,164**	**2,310**	**4,597**	**11,303**	**21,966**	**32,042**	**41,578**
77	Ideal Density / (g/l)	0,315	1,574	3,149	6,298	15,745	31,490	47,235	62,980
	Z -factor @ 80K	1,000	0,990	0,980	0,970	0,960	1,020	1,130	1,260
	Density / (g/l)	0,315	**1,590**	**3,213**	**6,493**	**16,401**	**30,872**	**41,801**	**49,984**
	H2 mass in DisCha / g	0,886	**4,477**	**9,045**	**18,277**	**46,169**	**86,906**	**117,669**	**140,704**

Even for the experiments with highest inventory - e.g. for experiment 20190528_104204, which is used for the further discussions - the weight and the repulsive force measurements show perturbations and limited precisions, see Figure 21. So, these data should be considered rather qualitative than quantitative. Best quality is provided in the pressure recordings.



20190528_104204
(4mm, 200 bar, **T**$_{LN2}$)

Figure 21: Weight and repulsive force measurements of the DisCha set-up for hydrogen blow-down starting with 200 and nitrogen boiling temperature



20190528_104204
(4mm, 200 bar, **T**$_{LN2}$)

Figure 22: Pressure measurements in the vessel and release line before the nozzle and trigger signal for hydrogen blow-down starting with 200 and nitrogen boiling temperature

As explained above all experiments with identical temperature, pressure and nozzle diameter combination have been repeated at least three times (with the only exception of the cold test with 100 bar and 1 mm nozzle diameter). The test series with 4 mm nozzle at ambient temperature with a pressure of 100 bar provide 8 and the 200 bar 7 repetitions and allow for a statistical evaluation of the measured reservoir pressure. The root-mean-square deviation (RMSD) for the two test series was calculated and for 100 bar it is less than +/- 0.5%. For 200 bar it is about +/- 1%. Figure 23 qualitatively demonstrates the good reproducibility of these experiments by plotting all 7 curves and their averages in an overlay mode in the same diagram.

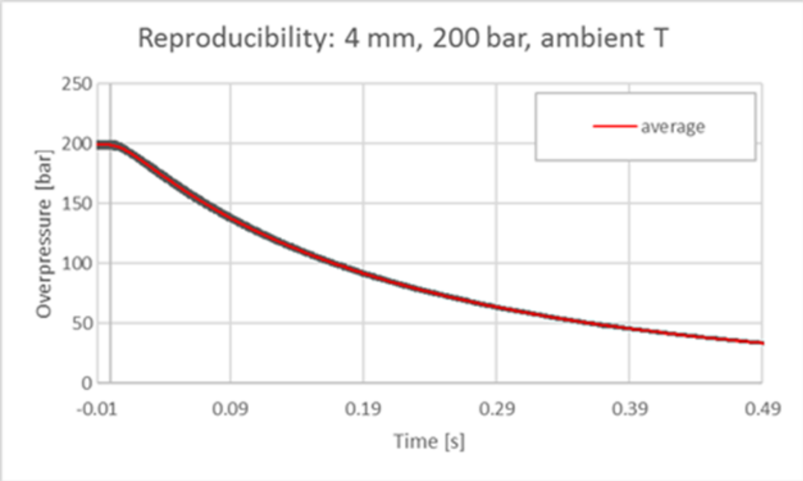


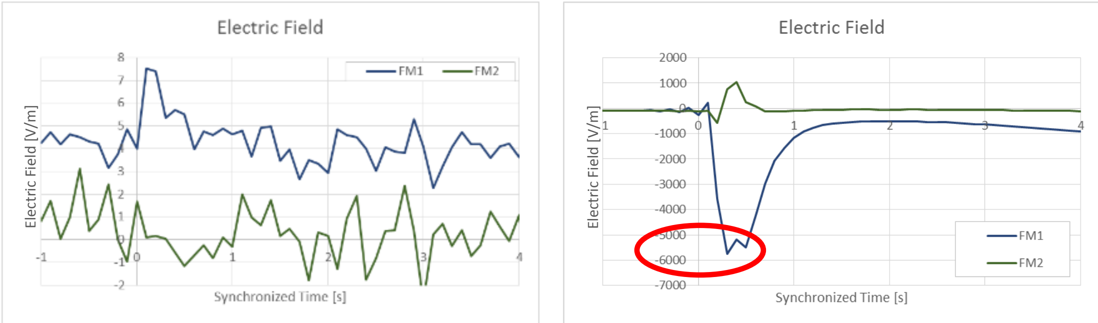
Figure 23: Qualitative demonstration of the reproducibility of the 200 bar blow-down experiments of hydrogen with ambient temperature (RMSD of vessel overpressure 1%)

Although the actual further exploitation of the data, like determination of discharge coefficients and modelling of electrostatic field generation, is left for the further work in the PRESLHY work packages WP3 and WP4, some observations should be presented already here:

- Not a single test showed a spontaneous ignition, although
- The tests done with hydrogen at ambient temperature do not generated any significant electrostatic field, whereas the cold jets generate relative strong static electricity, in the order of 5 kV/m (see Figure 24). This is 100 - 1000 times stronger than the natural electrostatic background field. The strong static electricity seems to be generated by ice crystals (potentially water ice from ambient humidity) which form on the release nozzle before the tests. The jet entrained electric charge is in some cases positive in other cases negative. These findings are supported by similar pre-cursor experiments done in the KIT test cell.
- In all cold tests white fog was generated in the jet domain. It is assumed that this mainly attributed to the ambient humidity, which condensates in the cold entrainment zone. The weather conditions for late April to early June at the experimental site (KIT Campus North) had a minimum relative humidity of 35% at 32°C, experiments in the afternoon of 4 June 2019, and a maximum humidity of almost 100% in the morning of 9 May 2019.
- The cold tests with large diameter and high pressure show strong temperature decay in the reservoir (see Figure 25) and a quite strong fog generation. However, as stated above it is currently assumed, that these particles are water droplets and ice crystals from ambient humidity. The latter originate at least partially from ice crystals formed on the nozzle before the actual test. It may not be excluded that there is involved condensation of other gases, like CO2, oxygen or even hydrogen, as the acceleration during the release might bring down the dynamic temperature even

below the hydrogen boiling point. Only detailed multi-phase simulations accounting for non-equilibrium effects might clarify this issue.

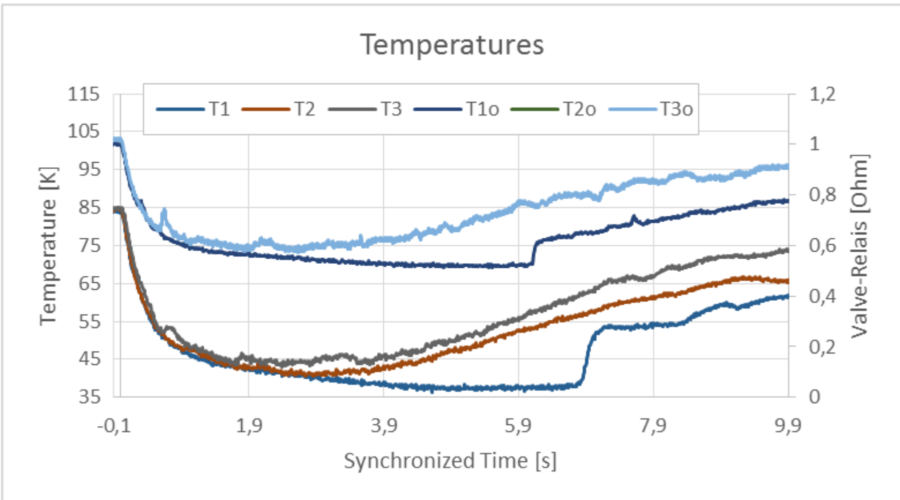
- The fog generated impaired the BOS methodology, in particular in the far field measurements.



20190523_113015
(4mm, 200 bar, **ambient T**)

20190528_104204
(4mm, 200 bar, **T**$_{LN2}$)

Figure 24: Electrostatic field measured with field mills FM1 and FM2 for blow-down of 200 bar hydrogen at ambient temperature (left) and at standard nitrogen boiling temperature (right)



20190528_104204
(4mm, 200 bar, **T**$_{LN2}$)

Figure 25: Temperature measurements in the DisCha vessel for blow-down of 200 bar hydrogen starting from standard nitrogen boiling temperature (measured 84 K on T1, T2 and T3 correspond to 77 K)

7 Summary, Conclusions and Outlook

In the frame of the PRESLHY project more than 200 hydrogen blow-down experiments were made with the DisCha-facility at KIT, about half of them were made at ambient temperature, the other half at cryogenic temperatures, approximately 80 K. The reservoir pressure has been varied from 5 to 200 bar, the tested release nozzle diameter was 0.5, 1, 2 and 4 mm. Extensive equipment was used to measure hydrogen mass, pressure and temperature in the pressure vessel and temperature, hydrogen concentration and electrostatic field in and around the released gas jet. Additionally, all ambient conditions, like temperature, pressure and relative humidity have been recorded. From representative experiments photographs of the near field and far field of the released gas jet were taken and post-processed applying different BOS schemes. From a slightly more remote point movies were recorded.

During the experimental campaign the facility was continuously improved and extended, since several problems with the facility and instrumentation were encountered. The tests have been repeated for each parameter combination 3 to 8 times and the measured variables, in particular the pressure signals show very good reproducibility. The sub-set of the generated experimental data providing best measurement quality and the corresponding series of photographs will be published via KITopen.

The results will be used for discharge coefficient calculations, cryogenic jet and ignition modelling and for proper preparation of the ignited versions of the same tests, representing the combustion/jet fire test series E5.1. However, for those ignited tests the DisCha facility had to be moved to a remote location for safety reasons. The experiments are expected to start this summer.

The discharge tests using a liquid hydrogen container - representing the part B of the E3.1 test program - are under preparation. They will examine the two-phase effects of the discharge at moderate pressures, up to 5 bar. This pressure is the low end of the pressure applied here and therefore there is a good opportunity for comparing and linking the outcomes of part A and part B of the blow-down experiments E3.1.

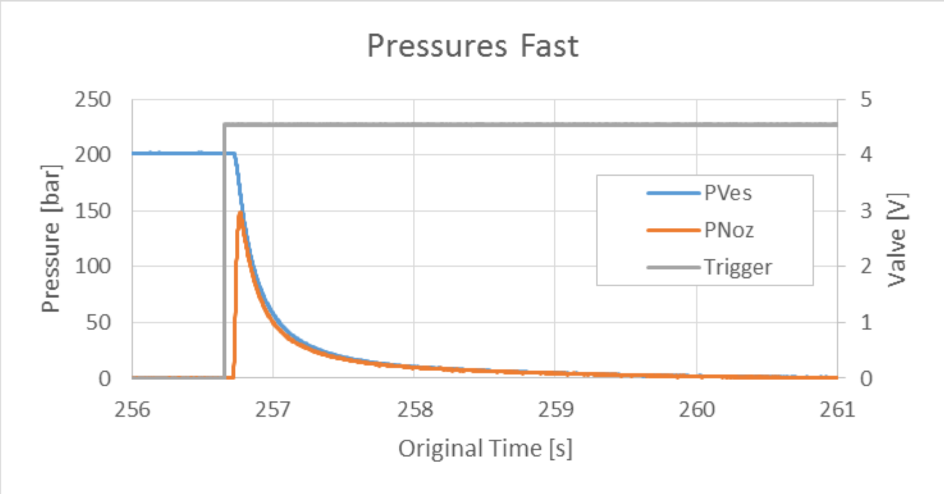
8 References

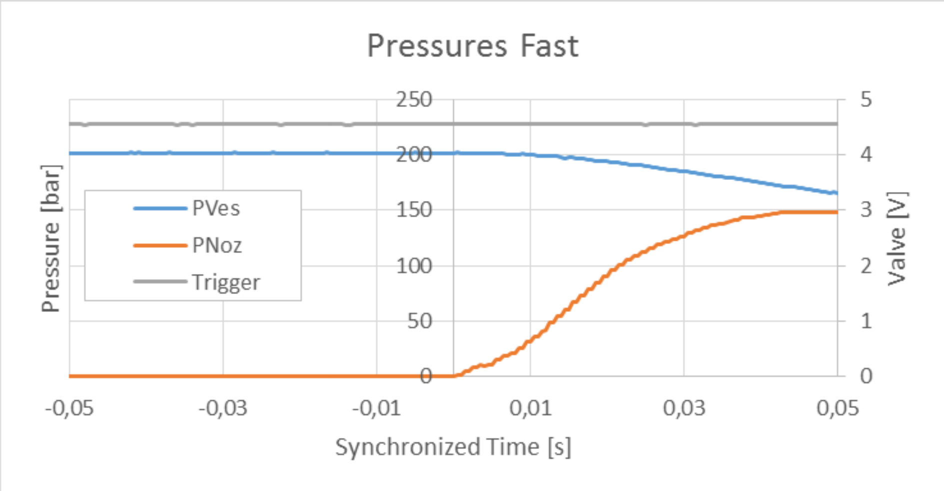
[1] KITopen, public research data repository
https://primo.bibliothek.kit.edu/primo_library/libweb/action/search.do?mode=Basic&vid=KIT&tab=kit_evastar&&srt=date

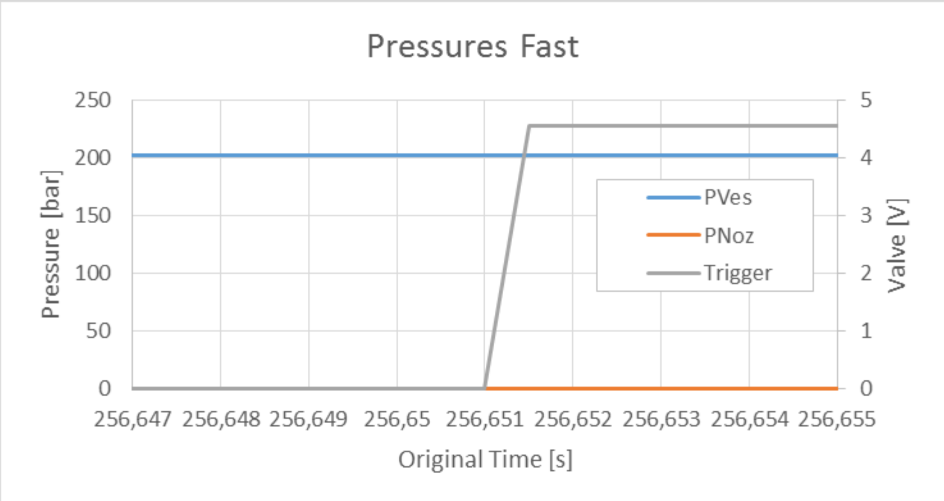
[2] McCarty, R.D., Hord, J., and Roder, H.M. Selected properties of hydrogen (engineering design data). Final report. United States: N. p., 1981. Web.

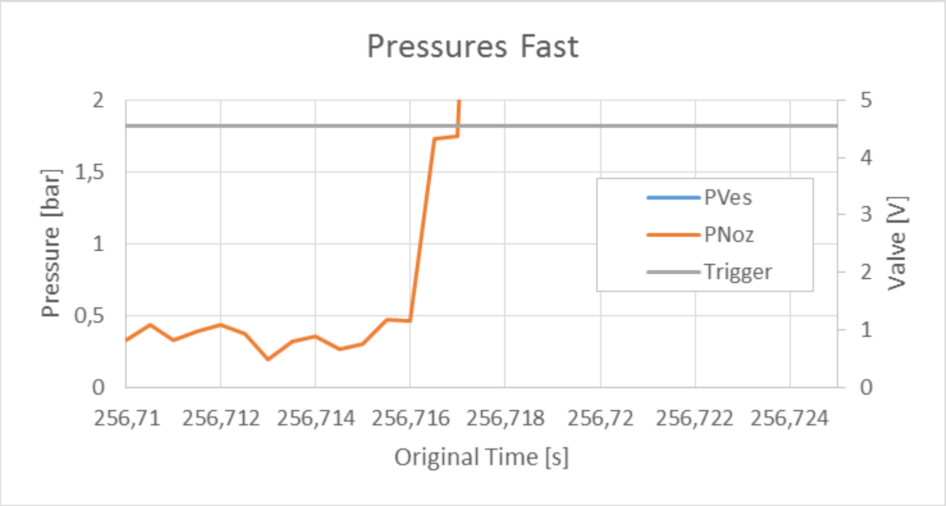
9 Appendix A: Result diagrams of experiment 20190528_104204 (80K, 4mm, 200 bar)

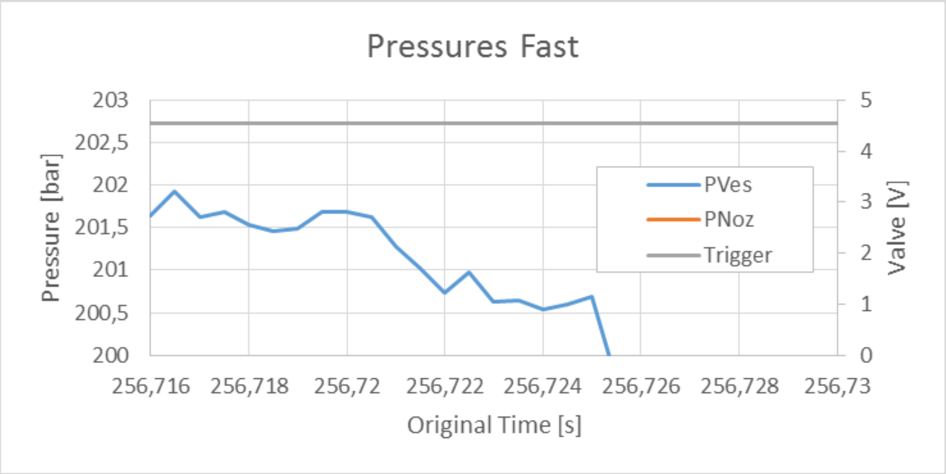
9.1 Diagrams in 20190528_104204-Press

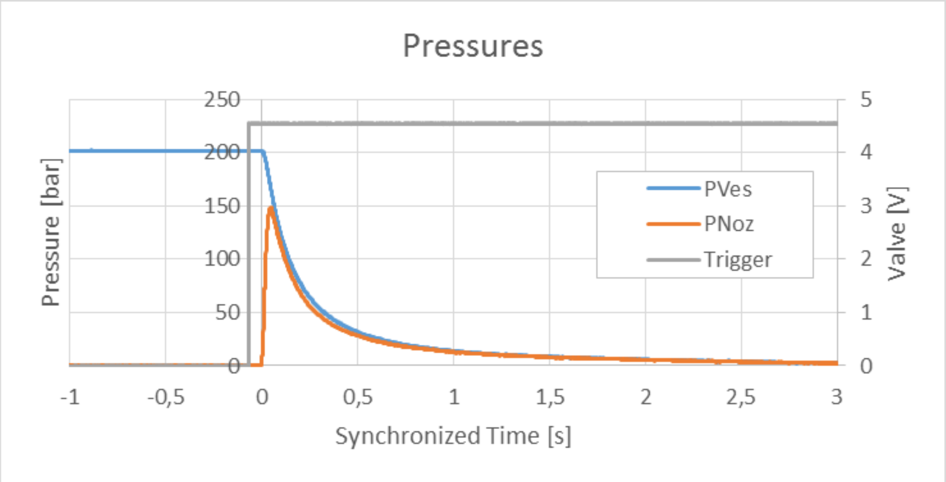




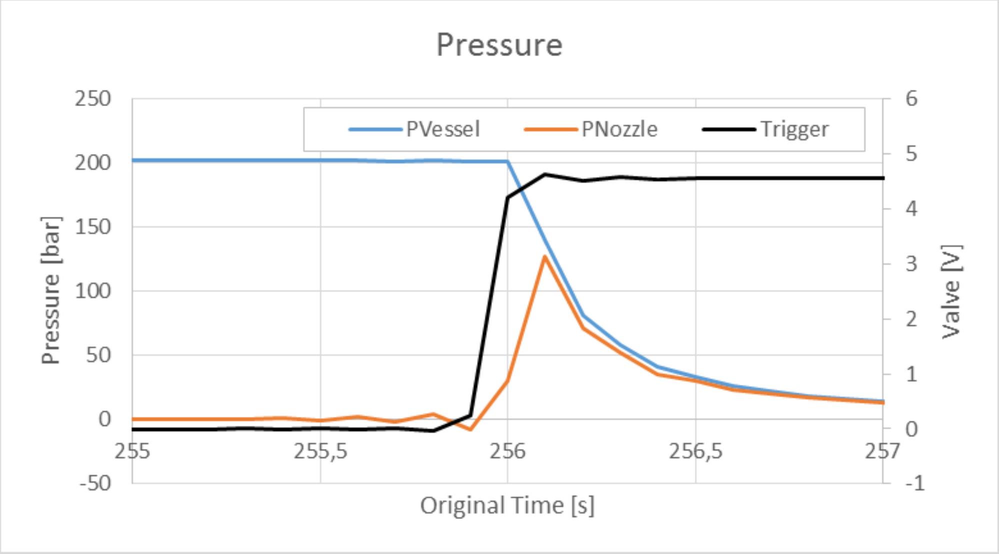


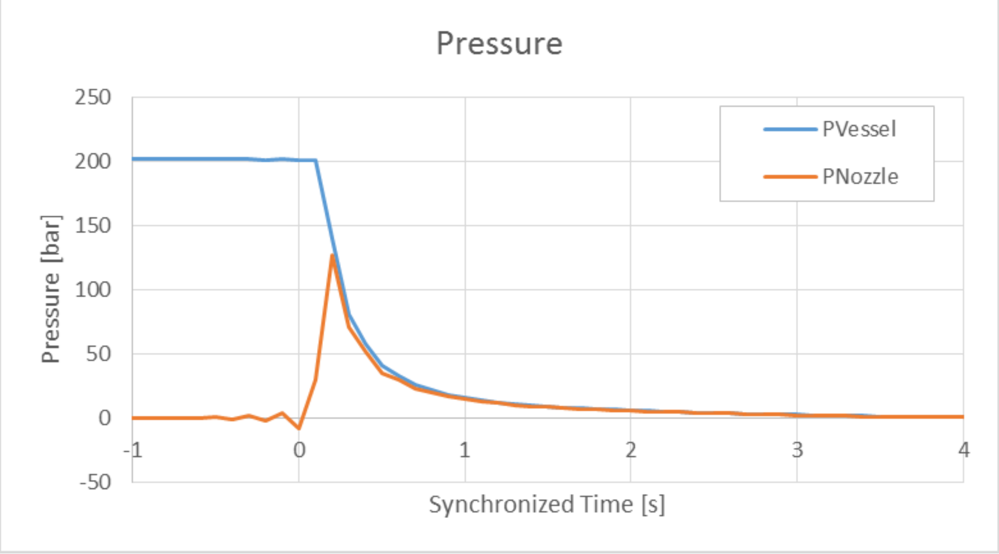

Pressures Fast
Pressure [bar]
Valve [V]
Original Time [s]
PVes
PNoz
Trigger
2
1,5
1
0,5
0
5
4
3
2
1
0
256,71
256,712
256,714
256,716
256,718
256,72
256,722
256,724

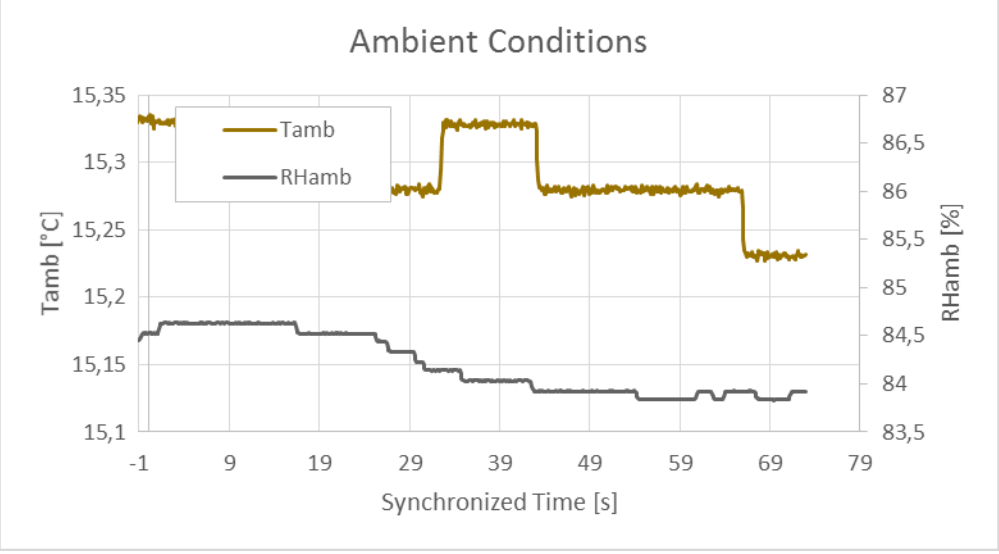

Pressures Fast
Pressure [bar]
Valve [V]
Original Time [s]
PVes
PNoz
Trigger
203
202,5
202
201,5
201
200,5
200
5
4
3
2
1
0
256,716
256,718
256,72
256,722
256,724
256,726
256,728
256,73

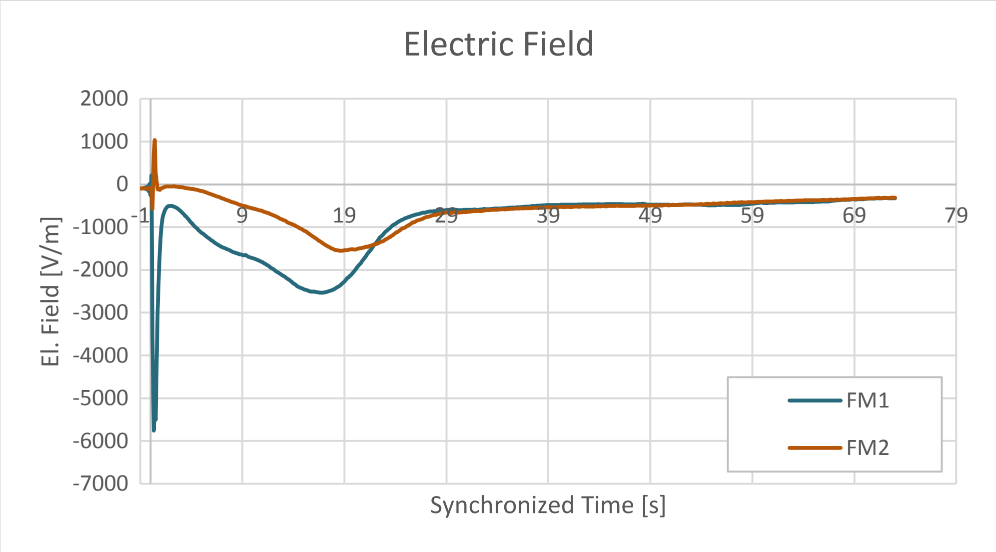

Pressures
Pressure [bar]
Valve [V]
Synchronized Time [s]
PVes
PNoz
Trigger
250
200
150
100
50
0
5
4
3
2
1
0
-1
-0,5
0
0,5
1
1,5
2
2,5
3

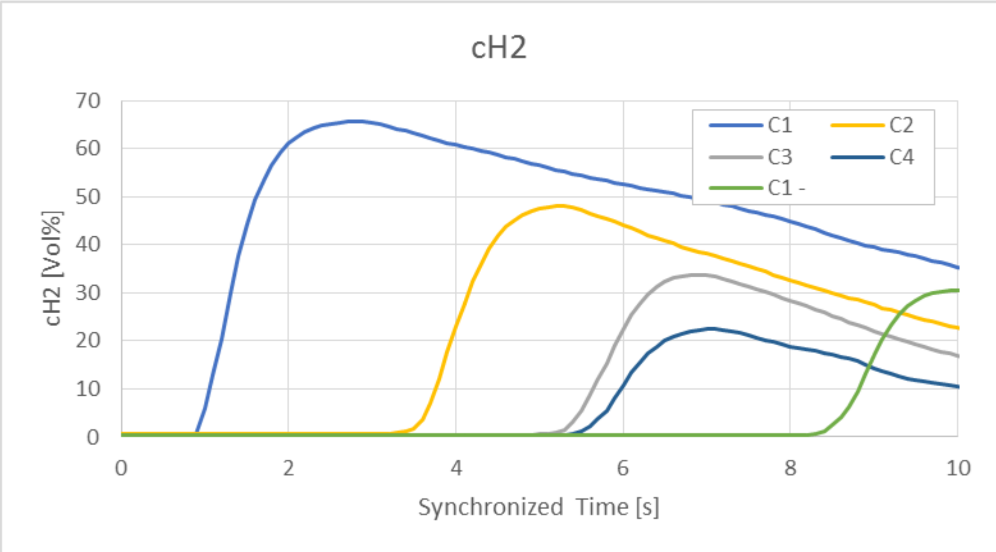
9.2 Diagrams in 20190528_104204-cH2-Amb

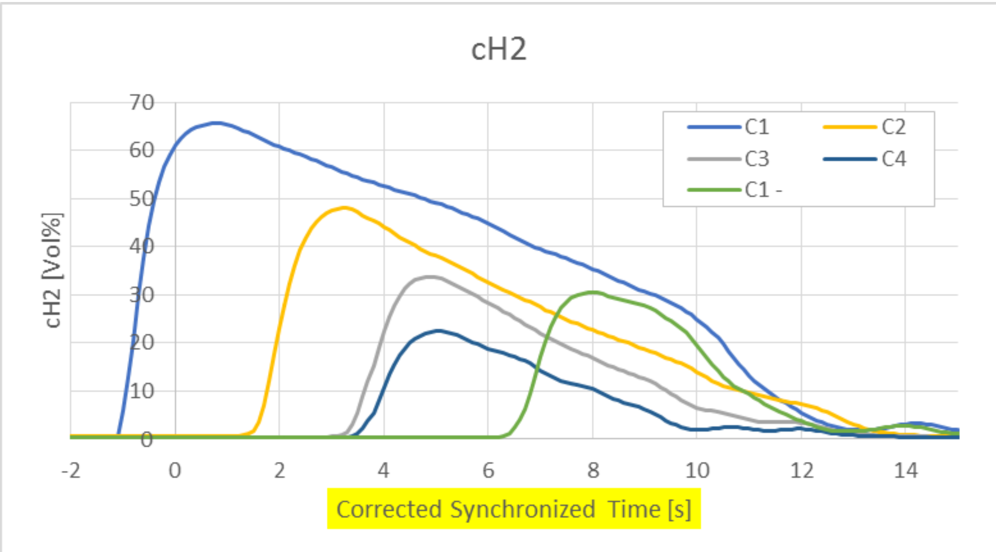


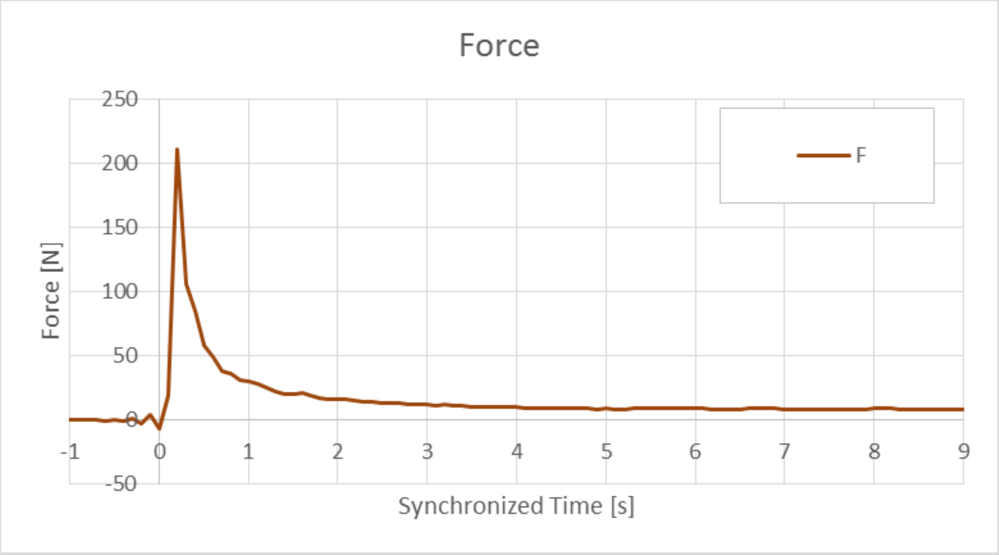




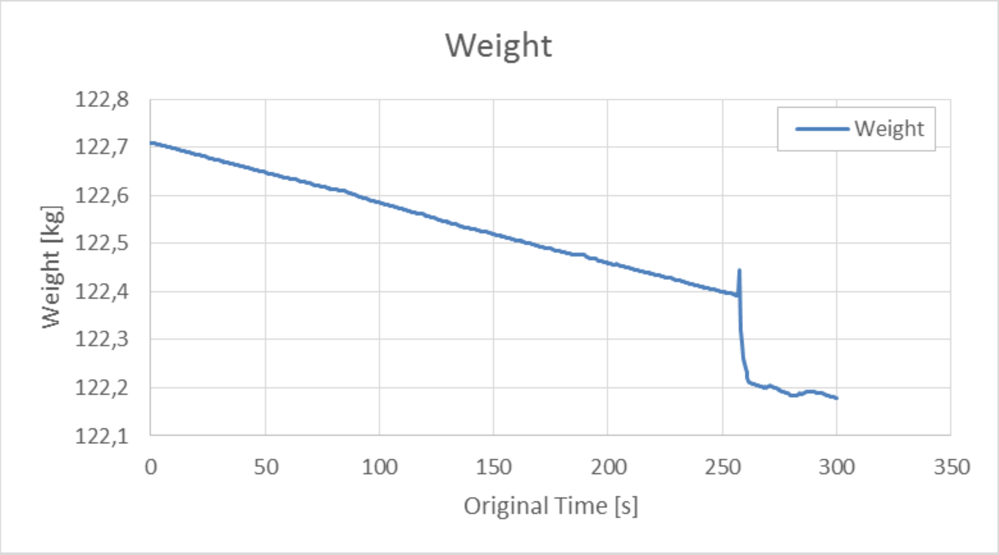

Electric Field
2000
1000
0
-1000
-2000
-3000
-4000
-5000
-6000
-7000
El. Field [V/m]
-1
9
19
29
39
49
59
69
79
Synchronized Time [s]
FM1
FM2

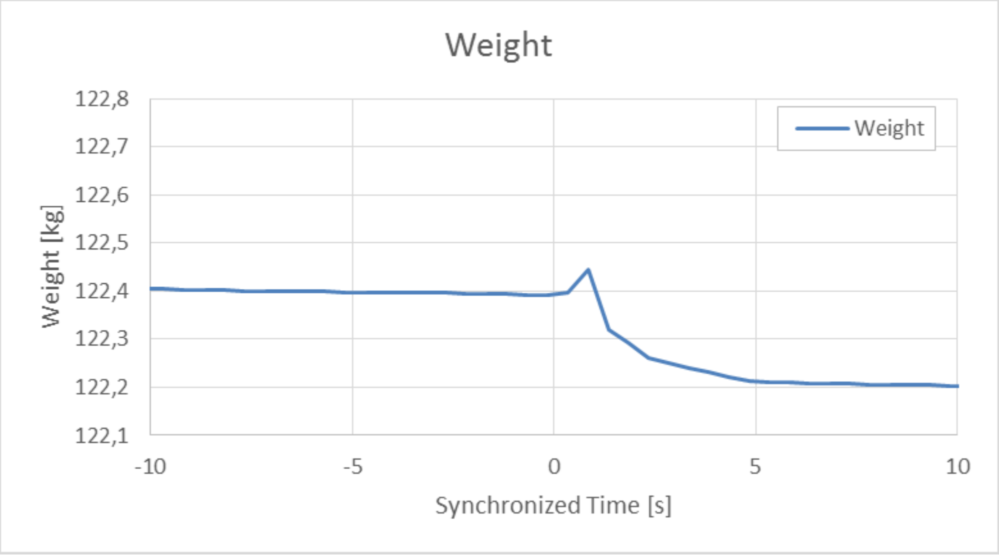

cH2
70
60
50
40
30
20
10
0
cH2 [Vol%]
0
2
4
6
8
10
Synchronized Time [s]
C1
C2
C3
C4
C1 -


cH2
70
60
50
40
30
20
10
0
cH2 [Vol%]
-2
0
2
4
6
8
10
12
14
Corrected Synchronized Time [s]
C1
C2
C3
C4
C1 -

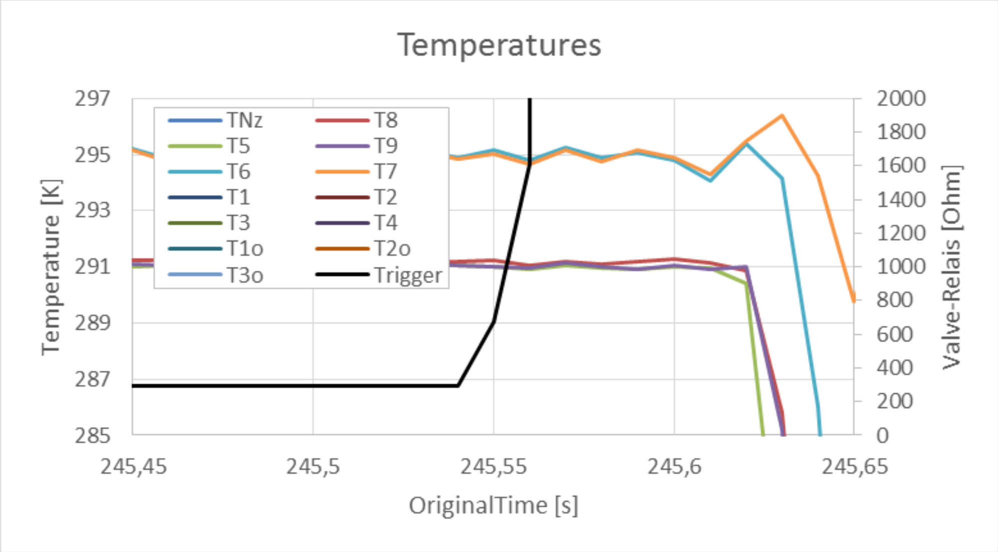

Force
250
200
150
100
50
0
-50
Force [N]
-1
0
1
2
3
4
5
6
7
8
9
Synchronized Time [s]
F

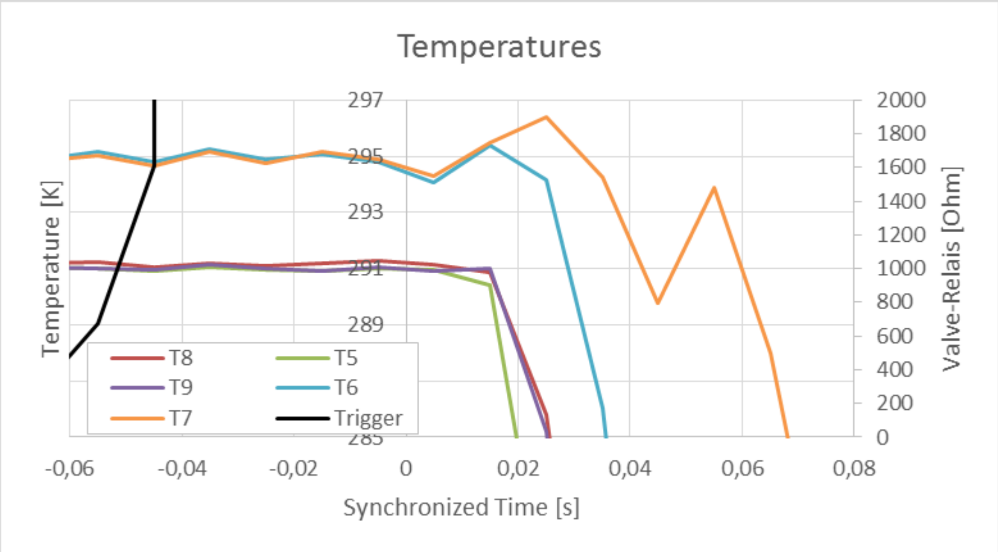
9.3 Diagrams in 20190528_104204-Weight

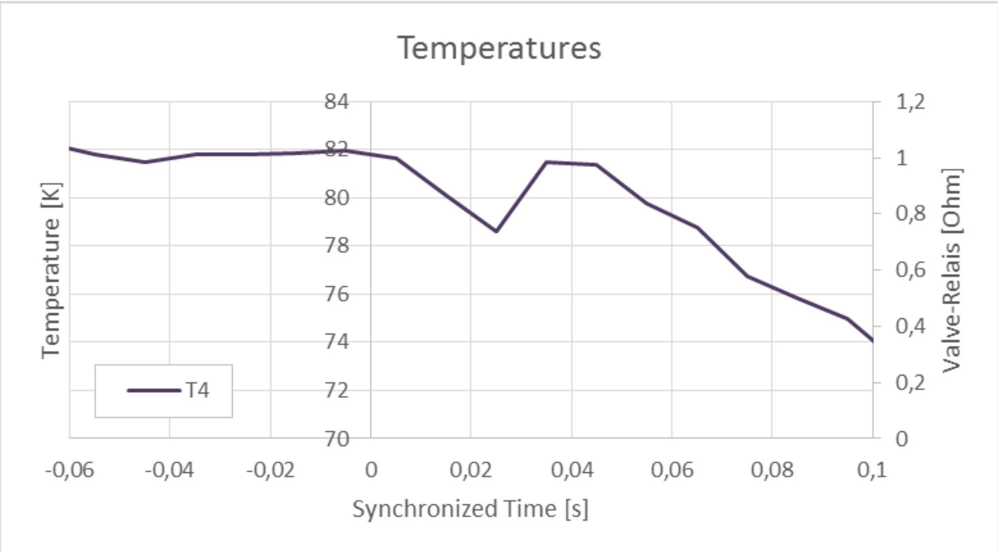


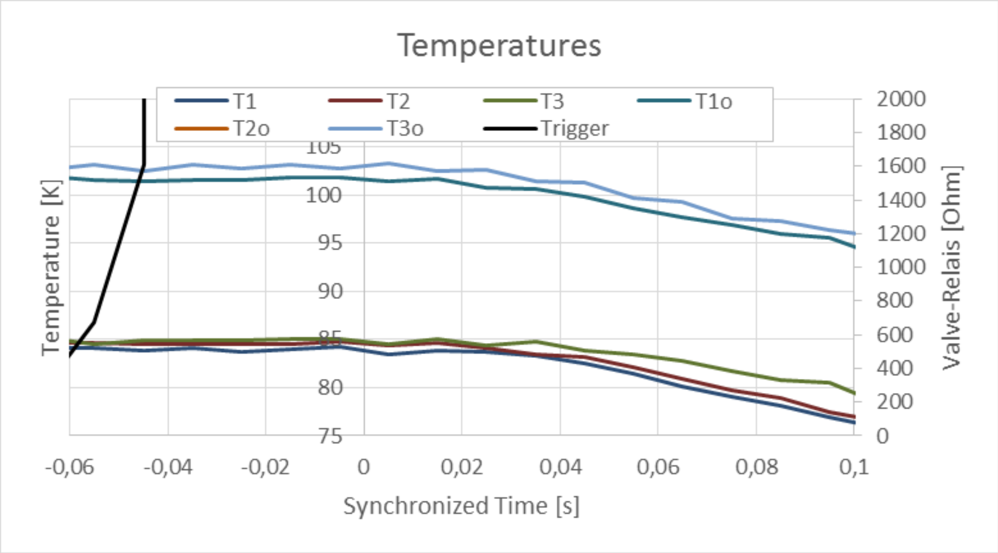


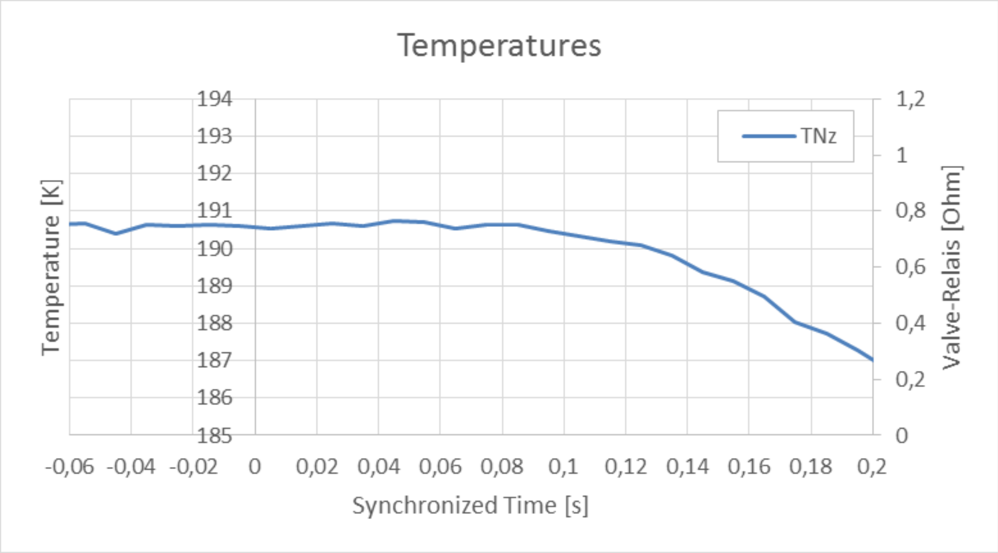
9.4 Diagrams in 20190528_104218-Temp

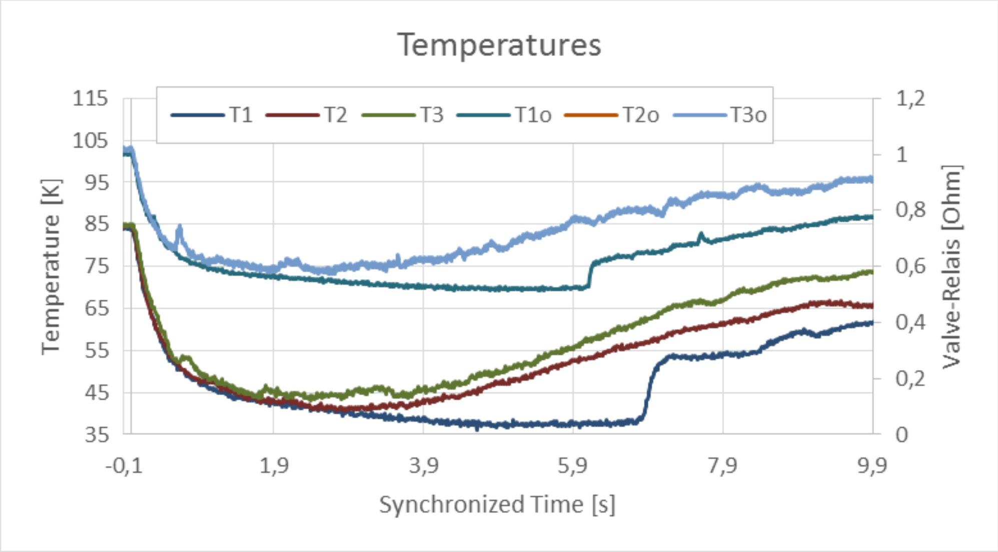







Temperatures
T1
T2
T3
T1o
T2o
T3o
Trigger
Temperature [K]
Valve-Relais [Ohm]
Synchronized Time [s]


Temperatures
TNz
Temperature [K]
Valve-Relais [Ohm]
Synchronized Time [s]


Temperatures
T1
T2
T3
T1o
T2o
T3o
Temperature [K]
Valve-Relais [Ohm]
Synchronized Time [s]

10 Appendix B: All experiments in sequential order

10.1 Table 1: Tests of the 1st DisCha campaign at ambient temperature

Date	Time	dNozz [mm]	pini [bar]	Tini [K]
18.02.2019	13:52:40	4	5	290
18.02.2019	13:58:48	4	5	290
18.02.2019	14:02:23	4	10	290
18.02.2019	14:05:30	4	10	290
18.02.2019	14:08:58	4	20	290
18.02.2019	14:13:05	4	20	290
18.02.2019	14:18:49	3	5	290
18.02.2019	14:21:08	3	5	290
18.02.2019	14:23:18	3	10	290
18.02.2019	14:26:24	3	10	290
18.02.2019	14:29:25	3	20	290
18.02.2019	14:33:36	3	20	290
18.02.2019	14:39:22	2	5	290
18.02.2019	14:41:47	2	5	290
18.02.2019	14:43:58	2	10	290
18.02.2019	14:47:13	2	10	290
18.02.2019	14:50:02	2	20	290
18.02.2019	14:54:11	2	20	290
18.02.2019	14:59:37	1	5	290
18.02.2019	15:02:03	1	5	290
18.02.2019	15:05:28	1	10	290
18.02.2019	15:08:51	1	10	290
18.02.2019	11:11:40	1	20	290
18.02.2019	15:16:21	1	20	290
18.02.2019	15:28:03	0,5	5	290
18.02.2019	15:32:11	0,5	5	290
18.02.2019	15:35:16	0,5	10	290
18.02.2019	15:40:48	0,5	10	290
18.02.2019	15:43:18	0,5	20	290
18.02.2019	15:45:10	0,5	20	290
21.02.2019	10:53:23	4	5	290
21.02.2019	11:02:29	4	10	290
21.02.2019	11:05:11	4	50	290
21.02.2019	11:12:57	4	50	290
21.02.2019	14:03:24	4	100	290
21.02.2019	14:05:17	4	100	290

21.02.2019	14:18:46	4	100	290
21.02.2019	14:24:31	4	150	290
21.02.2019	14:28:19	4	150	290
21.02.2019	14:31:29	4	200	290
21.02.2019	14:34:24	4	200	290
21.02.2019	14:39:34	2	200	290
21.02.2019	14:48:01	2	200	290
21.02.2019	14:56:09	2	200	290
21.02.2019	15:01:10	2	200	290
21.02.2019	15:06:08	2	150	290
21.02.2019	15:09:50	2	150	290
07.03.2019	11:18:16	2	51,51	290
07.03.2019	11:35:13	2	52,158	290
07.03.2019	11:38:15	2	100	290
07.03.2019	11:41:05	2	150	290
07.03.2019	11:49:18	2	200	290
07.03.2019	13:31:59	4	53,8	290
07.03.2019	13:34:54	4	100	290
07.03.2019	13:43:40	4	200	290
07.03.2019	13:53:27	4	151	290
07.03.2019	14:03:03	4	200	290
07.03.2019	14:10:26	1	54	290
07.03.2019	14:13:24	1	104	290
07.03.2019	14:16:56	1	200	290
07.03.2019	14:24:36	1	150	290
07.03.2019	14:37:03	0,5	53,85	290
07.03.2019	14:41:22	0,5	100	290
07.03.2019	14:44:58	0,5	150	290
07.03.2019	14:49:04	0,5	200	290
12.03.2019	14:07:42	0,5	5	290
12.03.2019	14:10:24	0,5	10	290
12.03.2019	14:16:36	1	5	290
12.03.2019	14:19:09	1	10	290
12.03.2019	14:24:44	2	5	290
12.03.2019	14:27:06	2	10	290
12.03.2019	14:32:16	4	5	290
12.03.2019	14:38:46	4	10	290

10.2 Table 2: Tests of the 2st DisCha campaign at ambient temperature

Date	Time	dNozz [mm]	pini [bar]	Tini [K]
22.03.2019	10:06:45	4	200	290
22.03.2019	10:30:08	4	150	290
22.03.2019	10:47:48	4	100	290
26.03.2019	13:47:58	2	200	290
26.03.2019	13:53:13	2	150	290
26.03.2019	13:57:07	2	100	290
26.03.2019	14:00:34	2	100	290
26.03.2019	14:04:41	2	50	290
26.03.2019	14:07:52	2	50	290
26.03.2019	14:19:16	1	200	290
26.03.2019	14:25:23	1	200	290
26.03.2019	14:29:58	1	150	290
26.03.2019	14:34:12	1	150	290
26.03.2019	14:37:50	1	100	290
26.03.2019	14:41:09	1	100	290
26.03.2019	14:45:06	1	50	290
26.03.2019	14:47:55	1	50	290
26.03.2019	14:54:58	0,5	200	290
26.03.2019	15:00:07	0,5	200	290
26.03.2019	15:04:40	0,5	150	290
26.03.2019	15:08:54	0,5	150	290
26.03.2019	15:14:58	0,5	100	290
26.03.2019	15:19:31	0,5	100	290
26.03.2019	15:23:15	0,5	50	290

10.3 Table 2: Tests of the 1st DisCha campaign at LN2-temperature

Date	Time	dNozz [mm]	pini [bar]	Tini [K]
23.04.2019	11:19:03	2	38,3	85
23.04.2019	11:29:01	2	75	87
23.04.2019	11:39:51	2	75	87
23.04.2019	11:49:28	2	76,2	86
23.04.2019	12:03:05	2	110	87
23.04.2019	12:14:41	2	148	86
30.04.2019	10:24:56	2	200	82
30.04.2019	11:06:43	2	200	82
30.04.2019	11:18:36	2	100,8	84
30.04.2019	11:40:28	2	108	84
30.04.2019	13:51:53	2	150	84
30.04.2019	14:07:32	2	150	85
30.04.2019	14:14:45	2	51,9	84
30.04.2019	14:25:46	2	52	84
30.04.2019	14:31:05	2	22,8	84
30.04.2019	14:43:08	2	22,9	84
30.04.2019	14:49:09	2	12,4	84
30.04.2019	15:06:00	2	11,5	84
30.04.2019	15:08:17	2	6	84
30.04.2019	15:11:17	2	5,2	84
03.05.2019	10:01:44	4	151,9	84
03.05.2019	10:26:00	4	150,9	84
03.05.2019	10:41:21	4	101,8	84
03.05.2019	10:52:50	4	101,6	84
03.05.2019	11:02:59	4	22,2	84
03.05.2019	11:09:55	4	11,9	84
03.05.2019	11:15:25	4	10,4	84
03.05.2019	11:20:24	4	5,3	84
03.05.2019	11:24:08	4	5,05	85
03.05.2019	11:53:34	4	50,8	84
03.05.2019	12:07:19	4	48,9	84
03.05.2019	12:16:35	4	20,4	84
03.05.2019	13:45:36	4	201,2	84
03.05.2019	14:00:45	4	200,4	84
07.05.2019	13:56:05	1	153	84
07.05.2019	14:14:57	1	153	84
07.05.2019	14:32:57	1	103	84
07.05.2019	14:46:31	1	99,9	81,9

07.05.2019	15:02:52	1	52,5	84
07.05.2019	15:12:56	1	50	86
07.05.2019	15:23:21	1	20,1	85
07.05.2019	15:30:41	1	20,1	86
07.05.2019	15:37:53	1	10,1	86
07.05.2019	15:46:09	1	10,4	86
07.05.2019	15:53:08	1	5	85
07.05.2019	16:00:47	1	5,2	85
09.05.2019	10:09:55	0,5	200	85
09.05.2019	10:25:57	0,5	201	85
09.05.2019	10:41:38	0,5	150,5	85
09.05.2019	10:53:44	0,5	150	85
09.05.2019	13:27:31	0,5	100	84
09.05.2019	13:45:35	0,5	100	86
09.05.2019	13:57:57	0,5	50,5	85
09.05.2019	14:11:51	0,5	51	85
09.05.2019	14:14:08	0,5	21	85
09.05.2019	14:22:01	0,5	20,9	85
09.05.2019	14:22:54	0,5	10,2	85
09.05.2019	14:32:52	0,5	9,6	85
09.05.2019	14:39:59	0,5	4,9	85
09.05.2019	14:49:55	0,5	4,8	86

10.4 Table 4: Tests of 2nd DisCha campaign at LN2 temperature

Date	Time	dNozz [mm]	pini [bar]	Tini [K]
28.05.2019	10:42:04	4	200	84
28.05.2019	10:54:37	4	50	84
28.05.2019	11:04:41	4	23	83
28.05.2019	11:12:40	4	10	83
28.05.2019	11:19:18	4	5	83
28.05.2019	11:28:37	4	98	86
28.05.2019	14:20:48	4	150	84
28.05.2019	14:36:08	4	100	83
31.05.2019	09:49:51	2	201,5	85
31.05.2019	10:02:57	2	150,14	85
31.05.2019	10:12:49	2	100,09	85
31.05.2019	10:19:48	2	50,03	85
31.05.2019	10:28:10	2	19,95	85
31.05.2019	10:34:08	2	9,59	85
31.05.2019	10:38:28	2	4,99	85
31.05.2019	11:04:40	1	200,07	86
31.05.2019	11:18:08	1	150,11	86
31.05.2019	11:29:44	1	100,08	86
31.05.2019	11:39:40	1	49,86	86
31.05.2019	11:49:03	1	19,31	86
31.05.2019	11:56:03	1	10	86
31.05.2019	12:03:33	1	5,09	86
04.06.2019	13:45:43	0,5	200	84
04.06.2019	14:06:57	0,5	150	84
04.06.2019	14:27:52	0,5	100	83
04.06.2019	14:44:25	0,5	50	83,7
04.06.2019	14:56:38	0,5	20	84,5
04.06.2019	15:05:15	0,5	10	84
04.06.2019	15:11:50	0,5	5	84
04.06.2019	15:22:54	0,5	20	84
04.06.2019	15:29:05	0,5	10	84
04.06.2019	15:35:21	0,5	5	84
24.06.2019	14:30:40	4	200	300
24.06.2019	14:42:45	4	150	300
24.06.2019	14:50:52	4	100	300
24.06.2019	14:56:15	4	50	300
24.06.2019	15:10:45	2	200	300
24.06.2019	15:17:44	2	150	300

24.06.2019	15:25:00	2	100	300