

# **HYDROGEN BLOWDOWN RELEASE EXPERIMENTS AT DIFFERENT TEMPERATURES IN THE DISCHA-FACILITY**

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## **ABSTRACT**

In this work experiments on horizontal hydrogen jet releases from a 2.815 dm<sup>3</sup> volume tank to the ambience are described. For the main experimental series, tank, valve and release line were cooled down to a temperature of approx. 80 K in a bath of liquid nitrogen. As a reference, similar experiments were also performed with the uncooled tank at ambient temperature. The releases were carried out through four nozzles with different circular orifice diameters from 0.5 to 4 mm and started from initial tank pressures from 0.5 to 20 MPa (rel.). During the releases pressures and temperatures inside the vessel as well as inside the release line were measured. Outside the nozzle further temperature and hydrogen concentration measurements were performed along and besides the jet axis. The electrostatic field built-up in the jet was monitored using two field meters in different distances from the release nozzle and optical observation via photo and video-cameras was performed for the visualization of the H<sub>2</sub>-jet via the BOS-method. The experiments were performed in the frame of the EU-funded project PRESPLY, in which several tests of this program were selected for a comparative computational study, the results of which will also be presented at this conference. So, on the one hand the paper gives a comprehensive description of the facility, on the other hands it also describes the experimental procedure and the main findings.

## **1.0 INTRODUCTION**

Hydrogen is one of the most promising options as energy carrier in a future economy that has to rely increasingly on renewable energies. Hydrogen has the potential to integrate renewable energies very efficiently against the background of a growing worldwide energy need and the diversification of the energy sources. But in its gaseous state hydrogen has a rather low volumetric energy content compared to the fossil fuels that are currently used worldwide, which makes its acceptance as energy carrier in daily use more difficult. This disadvantage can be largely compensated when H<sub>2</sub> is stored in its liquid state, but this requires cryogenic temperatures, since the critical temperature of hydrogen lies at 33.18 K. Another aspect for its rather reluctant introduction in economy is connected with safety considerations, which are mainly due to its different properties compared to the commonly used fuels. Both problems are targeted by PRESPLY, an EU FCH JU 2.0 co-funded research and innovation activity (Project ID 779613) that addresses pre-normative work for the safe use of liquid or cryogenic hydrogen as an energy carrier [1]. The work reported here is part of the PRESPLY-program and addresses the scenario of a sudden release of cryogenic hydrogen from a reservoir and its dispersion in the surrounding ambient air. A potential sequel to this scenario, the combustion of the released hydrogen after an ignition of the premixed cloud, is addressed in a separate experimental investigation with the same facility but slightly changed equipment.

As a kind of preliminary work with the same facility similar experiments were conducted with nitrogen instead of hydrogen [2], but in the current work the improved DISCHA-facility is utilized to investigate releases of hydrogen at cryogenic temperatures and pressures up to 20 MPa, and to compare this behavior with similar releases at ambient temperature. Due to specific limitations of facility and infrastructure with respect to LH<sub>2</sub> a storage temperature of approx. 80 K (boiling temperature of liquid nitrogen, LN<sub>2</sub>) had to be used in the tests. Transient releases from a tank with pressurized gaseous hydrogen have been investigated experimentally and theoretically already earlier [e.g. 3,4,5], and in the frame of the PRESPLY-project also theoretical modelling work by various partners is performed, for which the results of the unignited DISCHA-experiments act as input data. So apart from defining the initial conditions of the subsequent explosion tests in which the released H<sub>2</sub> will be ignited, the main

purpose of the tests is to provide validation or reference data for models defining or using a discharge coefficient and to gain information on the electrostatic field excitation and the associated ignition potential of high-pressure hydrogen gas jets at cryogenic temperatures.

## 2.0 EXPERIMENTAL DETAILS

### 2.1 Test Facility

The DISCHA-facility mainly consists of a stainless-steel pressure vessel with an internal free volume of 2.815 dm<sup>3</sup> and a weight of roughly 28 kg, which is fastened in an insulated box for an external cooling of the vessel with LN<sub>2</sub> to a temperature of approx. 80 K. Initially it was considered to cool down the pressure vessel with LH<sub>2</sub> to a temperature of approx. 30 K in a second stage of the experiments, but this plan was discarded due to the limited availability of LH<sub>2</sub>, and also because of the vigorous boiling behavior expected for the cooling process that would produce enormous clouds of cold gaseous H<sub>2</sub> that have to be disposed of safely. A safe disposal seemed problematic due to the location of the facility in a tent at the hydrogen test site at KIT with office buildings and laboratories in rather close vicinity. The final reason for the refusal of a LH<sub>2</sub>-cooling was that the pressure vessel was designed only for a temperature of 80 K.

The cooling box with the pressure vessel is fastened on a sledge that is mounted on a balance. The total experimental set-up with a weight of approx. 120 kg is placed on a table to provide for a nozzle height of 113 cm above the ground. Photographs of the facility and a sketch of the facility are shown in Figure 1 and Figure 2.

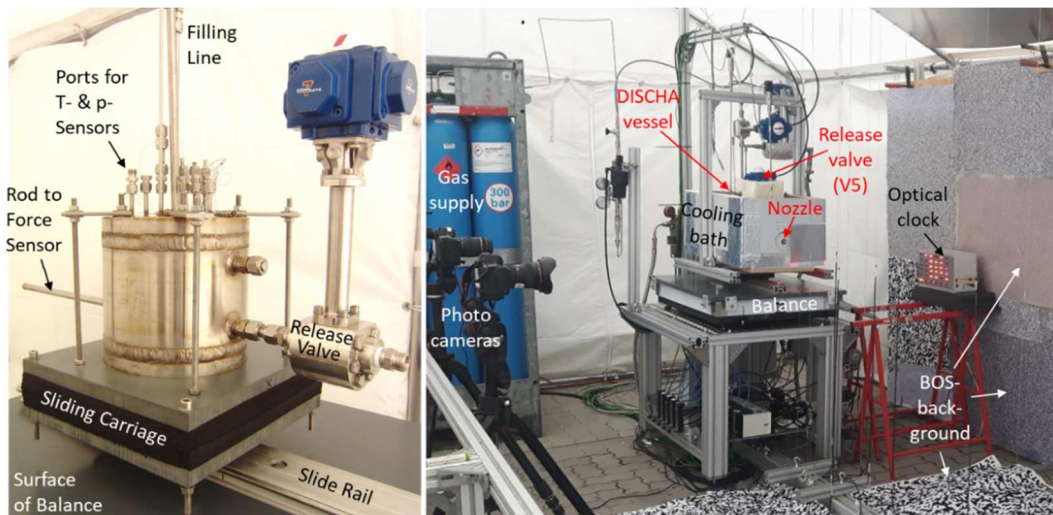


Figure 1. Photographs of the DISCHA-facility without (left) and with cooling box and additional equipment (right).

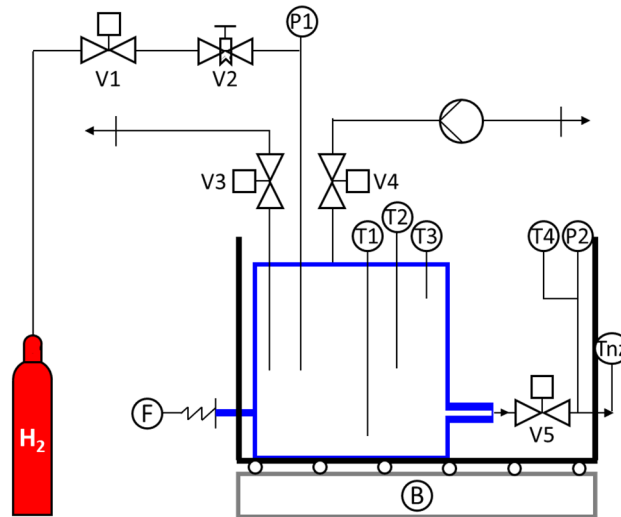


Figure 2. Sketch of the DISCHA-facility with main components and pipework.

Through the filling line and the valves V1 and V2 the test vessel can be filled with hydrogen up to pressures of 20 MPa 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 (F in Figure 2). Opposite to the force sensor a tubular exhaust pipe is welded to the vessel, where the release valve (V5 in Figure 2) with release nozzles of different nozzle diameters can be connected. 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 3). Another connection, which is kept as short as possible, is mounted in between the release valve and the vessel exhaust.

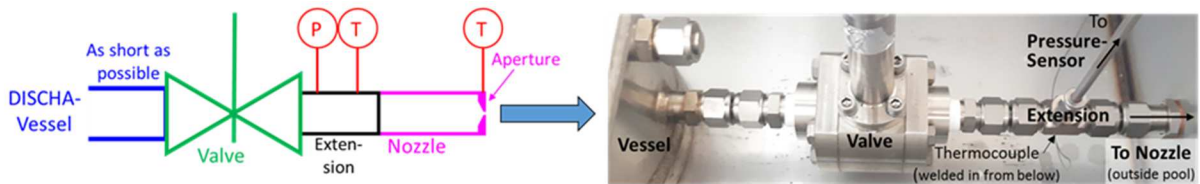


Figure 3. Sketch and photo of the release pipework of the DISCHA-facility.

## 2.2 Instrumentation of the Test Facility

In the experiments it is aimed to get as many information as possible on the release parameters and the effusing hydrogen without disturbing neither the flow in the release line nor the expansion behavior outside the nozzle. Therefore, several strategies were followed that might allow the characterization of the release process and the jet expansion in different ways.

### Instrumentation attached to the vessel for determination of the release rate

The release rate of the gas leaving the vessel can be determined in different ways, but each has a drawback. Measuring the flow rate directly with e.g. Coriolis flow meters in the release branch seems to be the smartest way, but due to the vast test matrix (ambient temperature, 80 K and initially 30 K) this is not possible since no device working at the low cryogenic temperatures is commercially available. Furthermore, the wide range of initial pressures (20 MPa to 0.5 MPa) leads to a wide range of release rates that cannot be covered by one sensor. So other ways for determining the release rate were sought. One way is to determine impulse and mass of the effusing gas, another possibility is to measure accurately pressure and gas temperature in the pressure vessel. Both ways were followed by installing a system comprising of a force sensor (for measuring the impulse) and a balance (for measuring the mass of the effused gas) as well as a pressure sensor and several thermocouples to the facility.

Force sensor: The sledge in between the balance and the box with the pressure vessel provides an almost slip free movement of the complete setup for the measurement of the repulsive forces that act on the vessel during the release experiments. The force is transferred to the plate of the force sensor (Althen, Type ALF318CPR0K0, 0 - 2 kN, F in Figure 2) by a rod at the sidewall of the pressure vessel which is located in the opposite position to the release branch.

Balance: To monitor the mass of the released gas a balance (Mettler Toledo, type PBA430x, range: 0 – 150 kg, B in Figure 2) is used to measure the loss of weight caused by the effusing gas in the hydrogen release experiments. To avoid influence of other measurement and control equipment on the weight signal all lines and joints are hanging from the crossbar at the top of the frame structure around the facility that is attached directly to the supporting table below the balance.

Pressure sensors: Two static pressor sensors (WIKA, type: S-20, range: 0 - 25 MPa (rel.)) are used in the facility. One sensor (P1 in Figure 2) in the filling line is used to control the initial pressure inside the vessel during the filling procedure and also during the release experiment, while the second one (P2) 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): Two sets of thermocouples (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 closed standard TCs (diameter 0.33 mm, sensitive tip covered by thin stainless steel shell, T1 to T3 in Figure 2) with a second set of three thinner but older open TCs (diameter 0.25 mm, stainless steel shell of sensitive tip removed, T1o to T3o in Figure 2) that are no longer available at the KIT-workshop. Both sets are installed in comparable positions inside the vessel. In the release line two further closed TCs (diameter 1 mm, sensitive tip covered by thin stainless steel shell, T4 and Tnz in Figure 2) are positioned: T4 is welded into the line to measure the temperature inside it, while Tnz 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.

#### **Instrumentation outside the vessel for determination of the distribution behavior**

To capture information on the distribution behavior of the released H<sub>2</sub> again several methods that were kept as non-intrusive as possible, are used. A set of thermocouples in combination with five H<sub>2</sub>-concentration measurement positions is used to gain information on the temperature field and the concentration distribution in the region of the jet. Simultaneously two field meters were installed besides the jet to measure electrical field excitation during the release. Furthermore, optical observation using the BOS-technique (Background-Oriented-Schlieren) was applied to get indications about the overall distribution of the hydrogen as well as about its behavior close to the nozzle. Apart from the task of being as non-intrusive as possible during the measurements the risk of an unintended ignition of the released hydrogen was the reason for the remote positioning of all sensitive and expensive measuring equipment that was used in the experiments.

Thermocouples (TCs): Five closed standard thermocouples (diameter 0.33 mm, sensitive tip covered by thin stainless-steel shell, T5 - T9 in Figure 4) were distributed outside the cooling box in the jet region. 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 below and above the nozzle centerline (see Figure 4).

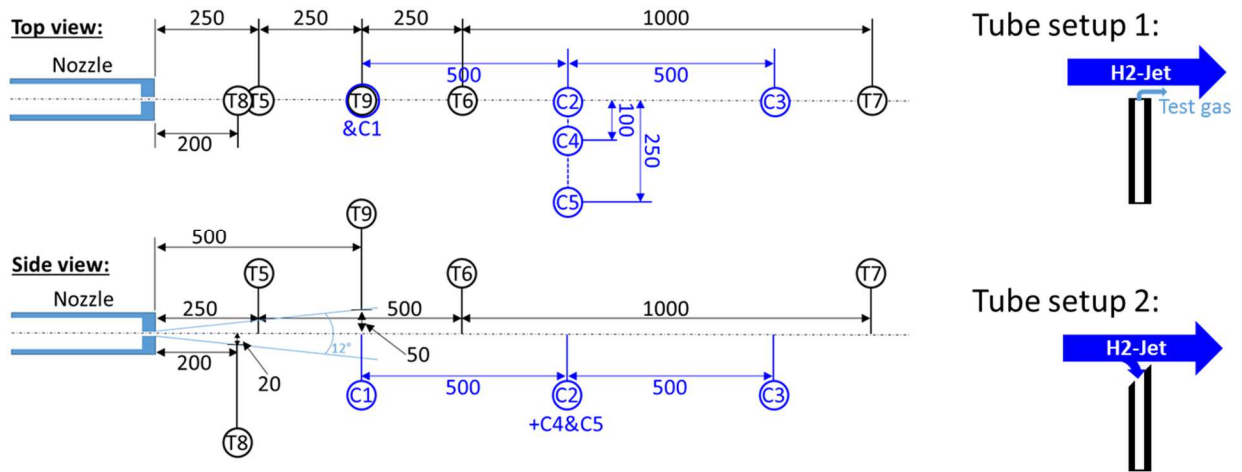


Figure 4. Sketches of the ex-vessel instrumentation of the DISCHA-facility and configurations of the plastic tubes for the H<sub>2</sub>-concentration measurements

**Concentration measurements:** Five H<sub>2</sub>-sensors (Messkonzept, type: FTC300, range: 0 - 100 Vol% H<sub>2</sub>) are utilized to determine the H<sub>2</sub>-concentration in different positions in the H<sub>2</sub> jets. Three of these positions lie on the jet axis, while the remaining two positions are in different horizontal distances to the jet centerline (see Figure 4). Since these sensors are rather bulky and require a constant gas flow they were not mounted physically to the positions shown in Figure 4, but were connected to these positions via thin plastic tubes of 3.0 m length. One single pump is used to supply all sensors with the same volume flow of test atmosphere during the measurements.

**Field meters:** Two field meters (Kleinwächter, model EFM 113B, range: 0 - 10 kV/m) were positioned in the height of the jet centerline in axial distances of 0.5 and 1.5 m from it and with horizontal distances of 0.9 m to the jet axis (see Figure 5).

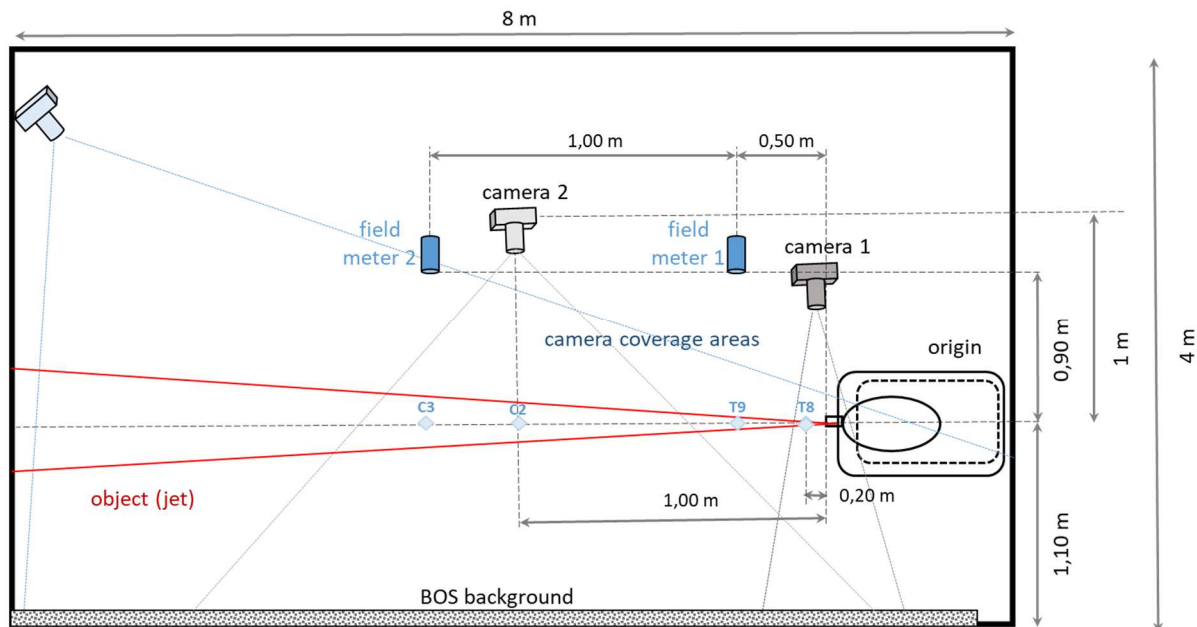


Figure 5. Sketch of the DISCHA-facility with positions of field meters and cameras including view field.

**Cameras:** Two photo-cameras were positioned to the right of the jet in the height of its centerline to capture the region close to the nozzle (camera 1 in Figure 5) and, in a larger angle, the first 1-2 m of the

jet release (camera 2). The photos were synchronized with the release time by utilizing an optical clock, which shows changing LED-signals to indicate the time that has passed after the release 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 left 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 H<sub>2</sub>-jet releases in various application fields. In the part close to the nozzle a fine random black and white box-pattern was used (see also Figure 1), while in farther distances "natural" backgrounds (branches and shrubs) were tested.

## 2.3 Test Matrix

The DISCHA-experiments were performed in several series since several sensors were added during the campaign and the experimental setup became more and more elaborated to overcome difficulties of the instrumentation. The whole test campaign with more than 200 tests lasted almost 4 months with several interruptions for adapting the set-up or because of delays in the LN<sub>2</sub> supply. For the reference tests done first with hydrogen at ambient temperature, typically at least three repetitions of one pressure/nozzle diameter combination were conducted, but in many cases the tests have been repeated even more often to provide an estimate for the reproducibility of the measurements. Due to the more complicated set-up the repetitions of the cold experiments done with LN<sub>2</sub> cooling concentrated on higher initial pressures and larger nozzle diameters. The test matrix for the experiments is shown in Table 1.

Table 1. Test matrix of unignited DISCHA-experiments (A = ambient, C = cryogenic temperature).

		Nozzle diameter [mm]			
		0.5	1	2	4
P <sub>ini</sub> [MPa]	0.5	A/C	A/C	A/C	A/C
	1	A/C	A/C	A/C	A/C
	2	A/C	A/C	A/C	A/C
	5	A/C	A/C	A/C	A/C
	10	A/C	A/C	A/C	A/C
	15	A/C	A/C	A/C	A/C
	20	A/C	A/C	A/C	A/C

## 2.4 Improvements of the facility

During the course of the DISCHA-experiments problems with the facility and the instrumentation were encountered and so several attempts to improve facility and instrumentation were made. However, not all attempts really showed an impact, but with the last and most elaborated set-up two final series with all experiments listed in the test matrix were performed.

### Valve operation

The first problem with the facility was the reaction time the pneumatic ball valve (Habonim, Type 05 HC27C-66MMCT/NPT-6.0, D = 15 mm) needs to open its full cross section after the trigger signal was sent by the control computer. To gain information on the opening behavior separate tests were performed, in which the orientation of the indicator disc at the top of the valve was filmed together with the optical clock at a frame rate of 240 fps. Selected frames of one of these movies together with yellow auxiliary lines that were added during evaluation are shown Figure 6.

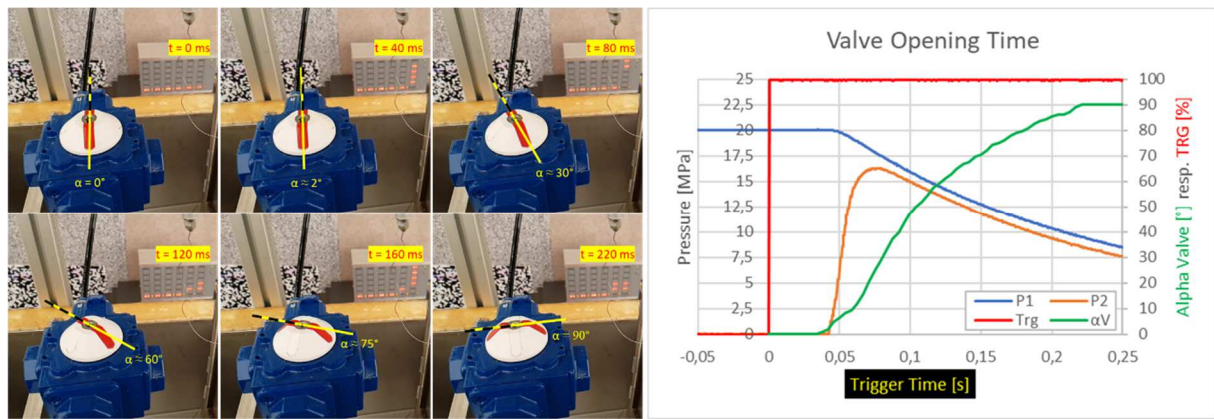


Figure 6. Selected frames from a movie taken during valve opening and synchronization with the pressure records.

The photos in Figure 6 demonstrate, that a reaction time of approx. 40 ms elapses before the ball in the pneumatic valve starts to rotate to open the cross section of the valve. To open the full cross section of the valve further approx. 180 ms are needed. These findings correspond very well with the records of the fast pressure sensors that were connected to the pressure vessel (P1) and the release line (P2) that are shown in the right part of Figure 6. The first pressure increase in the signal of the pressure sensor in the release line (P2) occurs at a ball valve rotation of approx. 2°. So for all further synchronization efforts the time of the first pressure increase in the record of P2 was set as  $t = 0$  s for the experiment.

### Synchronization

In the experiments a large number of different sensors with different output formats were used that could not be recorded simultaneously in the same file. So in total four data-files were generated by the automated LabVIEW-routine, which all have a different time basis and also different measuring frequencies.

- The most precise record contains the signals of the pressure sensors (P1 and P2) together with the trigger signal that was sent by the control computer. This file was recorded with a measuring frequency of 2 kHz.
- The second file again contains the pressure signals, but this time at a lower measuring frequency of 10 Hz, together with the signals of the field meters and the force sensor, as well as the H<sub>2</sub>-concentrations and the ambient conditions.
- The third file had to be generated due to the unique output format of the balance, which did not allow faster output than 2 Hz.
- The fourth data file was generated for the records of all thermocouples used in the facility at a measurement frequency of 100 Hz.

A synchronization of the different data files is possible since either the pressure signals (2<sup>nd</sup> file) or the trigger signal (4<sup>th</sup> file) were recorded together with the other data. A synchronization using the absolute time stamp of the files (i.e. when the file was generated) proved to be not accurate enough. Solely in case of the balance the addition of an extra signal was not possible, but due to the very low measuring frequency this uncertainty was thought to be acceptable.

### Concentration measurements

As Figure 4 shows, H<sub>2</sub>-concentration measurements were performed in five positions on and besides the jet axis. To minimize disturbances in the flow field it was decided to use five thin plastic tubes (inner diameter 2.5 mm, length 3.0 m) and one pump to extract constantly samples from the flow field that were analyzed continuously by fast acting H<sub>2</sub>-sensors (Messkonzept, Type: FTC300, Range: 0 - 100 Vol% H<sub>2</sub>). Besides the rather bulky dimensions of the sensors their vulnerability against temperatures

lower than  $-20^{\circ}\text{C}$  led to the decision to keep a rather long distance between sampling position and sensor to allow the samples to be warmed during the transportation time.

To determine the duration of this transportation time pre-experiments were performed with a balloon and a remote-controlled valve. In these tests  $\text{H}_2$  or  $\text{H}_2\text{-N}_2$ -mixtures were slowly released at one measuring position close to the tip of the plastic tube and the time in between valve opening and the detection of  $\text{H}_2$  by the sensor was measured. For all five sensors identical transportation times of  $t_{\text{react}} = 2\text{ s}$  from valve opening to the first reaction of the sensor were determined. Further  $1.75\text{ s}$  were needed by all sensors to reach a displayed concentration value that corresponds to 95% of the  $\text{H}_2$ -concentration in the balloon. So a total time delay of  $3.75\text{ s}$  was accounted for in the evaluation of the  $\text{H}_2$ -concentration measurements.

### **Temperature measurements**

In the sketches of Figure 2 and Figure 4 the positions of the 13 thermocouples used in the experiments are given. All sensors of the same diameter were freshly made from the same batch (except for T1o – T3o, see above) and most of them (all except for T4, T1o – T3o) were calibrated in a bath of  $\text{LN}_2$  (approx.  $80\text{ K}$ ) prior to the start of the experimental series. Most of the sensors were furthermore exposed to  $\text{LH}_2$  (approx.  $20\text{ K}$ ) in a later experimental series. So a calibration of the sensors in the range from  $20\text{ K}$  to  $300\text{ K}$  is possible. Using this calibration all temperature values measured during the experiments were corrected.

## **3.0 RESULTS AND DISCUSSION**

The unignited DISCHA-experiments were part of a larger research program, in which also the combustion behaviour of the released hydrogen is evaluated by igniting the  $\text{H}_2$ -jet in different positions at different points in time. The ignited experiments were performed later in a separate series, since the explosions induced by the ignition of the  $\text{H}_2$ -jet might severely damage the ex-vessel instrumentation used in the current series. Furthermore, in the ignited tests the focus of the instrumentation lies on the consequences of the explosion, and thus for the ignited series the current ex-vessel instrumentation is replaced by additional fast pressure sensors and acoustic equipment. Main aims of the current set of unignited DISCHA-experiments are to describe the flow-field and distribution of the released hydrogen, which then acts as input for the ignited tests. Furthermore, experimental data for the evaluation of computational models for the simulation of cryogenic hydrogen releases should be provided with the in-vessel instrumentation. And finally the electrostatic field built-up that is generated during the release should be quantified.

### **Release rate determination**

To determine the hydrogen release rate from the reservoir two independent ways were followed. In the first method the records of the balance (loss of weight) and the force sensor (impulse of released gas) can be utilized, while for the second the pressure and the temperature measurements inside the reservoir can be used. Unfortunately, the first method proved to be unsuccessful, since the measuring rate of both devices is too low to resolve the fast phenomena occurring after the release valve opening. Furthermore, in most experiments either of the two signals (weight or force) was disturbed by the valve action and thus the most interesting part of the record is spoiled. It is assumed that even slightest deviations from an exactly horizontal alignment of the release vessel will lead to an additional load on the scale or to an oblique loading of the force sensor, which will make the measurements unusable during the valve opening period. So for the determination of the release rates only the second method, using pressure and temperature in the vessel could be used. In this method the density of the content of the reservoir can be calculated using the pressure and temperature records, and the actual release rate can then be calculated using the reservoir pressure loss over time. Pressure decrease and release rates were subject to simulation efforts of several PRESLHY-partners. For further information on the release rates it is referred to the respective presentations at this conference [6,7], in which the results of the current measurements were used.

## H2-concentration distribution

Information on the hydrogen distribution outside the nozzle was gained via five H<sub>2</sub>-concentration measurement positions outside the vessel. To minimize the influence of the bulky sensors on the flow field these sensors were supplied with samples through thin plastic tubes, whose open end was positioned at the desired measurement position. In pre-experiments the time delay due to the sample transport through the pipes was measured, but when the first concentration measurements were evaluated severe problems with the time scale were encountered, since the first sampling position in a distance of only 50 mm to the nozzle detected H<sub>2</sub> with a strong time delay compared to the other sensors in more remote positions. The reason for this behavior actually was the high velocity jet that passed the upper horizontal rim of the tube (tube set-up 1 in Figure 4) which produced a sucking effect (comparable to a water jet pump) on the gas column inside the tube and thus caused a strong delay in the transport of the gas to the H<sub>2</sub>-sensor. To improve the situation a tilted cut (tube set-up 2 in Figure 4) was used in the subsequent experiments, but this orientation resulted in an acceleration of the gas sample inside the tube due to the pushing effect of the jet in this configuration, especially in the position close to the nozzle. The whole system turned out to be not suitable for measuring the exact transient concentration progression, since the effects of the jet on the gas columns in the tubes are dependent on the velocity of the jet in the respective position, which is in turn changing with the reservoir pressure. So for further evaluations mainly the maximum concentrations measured in the three positions on the jet axis (C1 to C3 in Figure 4) with tube set-up 2 were used. Two examples for the H<sub>2</sub>-concentrations measured in these positions in experiments with different initial pressures are given in Figure 7 for two nozzle diameters.

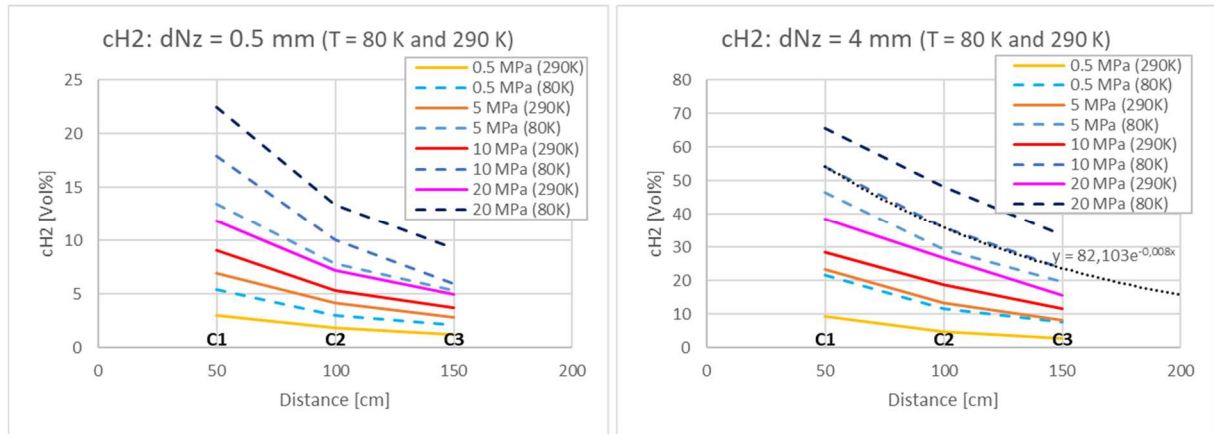


Figure 7. Examples for measured maximum H<sub>2</sub>-concentration in positions C1 to C3 for different nozzle diameters, initial temperatures and reservoir pressures.

The curves in the diagrams show that the concentrations in the three measurement positions increase with decreasing distance to the nozzle, decreasing temperature, increasing nozzle diameter and increasing reservoir pressure. Each curve can be approximated by an exponential function in the form

$$cH_2 = Ae^{-Bd} \quad (1)$$

in which A and B are specific constants for the respective nozzle/temperature case and d being the distance to the nozzle. Using these equations, the H<sub>2</sub>-concentrations downstream the measured values can be estimated and they were already used successfully to plan and evaluate the later ignited DISCHA-experiments.

The second method used to gain information on the H<sub>2</sub>-distribution was the optical observation using the BOS-method [8,9,10]. In this method the photographs/movies taken during the experiments are compared with a reference image of the set-up taken prior to the experiment from exactly the same position. In the photos taken during the release density gradients due to the hydrogen in the jet cause a displacement of the background pattern glued to the walls besides the jet opposite to the camera positions

(see Figure 5). With an algorithm similar to the ones used for Particle Image Velocimetry (PIV) it is possible to quantify this displacement and thus to visualize the regions that are more or less strongly influenced by the jet. Examples for the capabilities of the method are shown in Figure 8 for both photo-cameras in a test with the 4 mm nozzle ( $p_{\text{ini}} = 10 \text{ MPa}$ ,  $T_{\text{ini}} = 84 \text{ K}$ ), where different processing methods that were developed during the PRESLHY-project are applied.

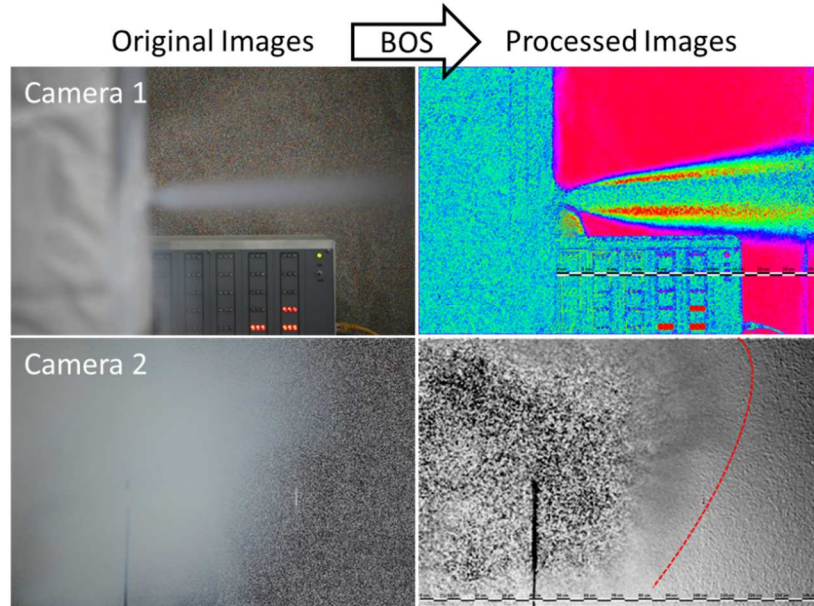


Figure 8. Examples for BOS-photographs of the H<sub>2</sub>-jet.

The top left image in Figure 8, taken with camera 1, shows the original photo with details of the release close to the nozzle, while the top right image shows the processed image using the seven color procedure (the scale below the jet was added after processing). In the bottom row of Figure 8 original and processed images of the tip of the jet, taken with camera 2, are shown. This time the original image was processed using a procedure optimized for black-white representations (red line for tip of jet and scale added after processing).

### Electrostatic field measurements

The discharge of an electrostatic field built-up could act as a possible source for the ignition of cryogenic hydrogen jets. To gain information on the order of magnitude of electric fields generated during the release of hydrogen at different temperatures two field meters were added to the experimental set-up (see Figure 5). Although added rather late in the campaign at least one measurement was performed for every case of the test matrix. Selected results of the campaign are shown in Figure 9. In the top left graph of Figure 9 the most extremal (highest positive and lowest negative) electric field values measured in several experiments with the same nozzle diameter at ambient temperature are plotted. Despite the fact that all field values are lower than 300 V/m, the tendency can be observed that higher field values are measured for larger nozzle diameters. The highest positive field values were always measured by the field meter closer to the nozzle (FM1) in an experiment with the highest initial pressure ( $p_{\text{ini}} = 20 \text{ MPa}$ ), while the lowest negative values have their origin in the records of both sensors, mostly in experiments with lower initial pressures of 10 MPa or less.

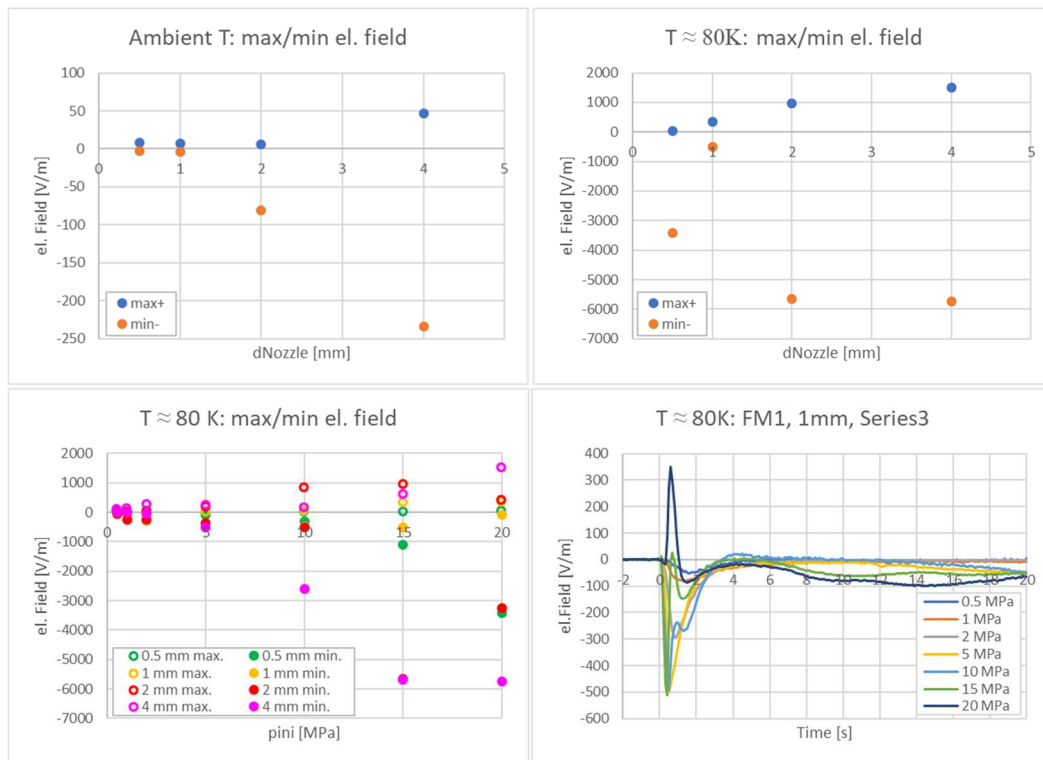


Figure 9. Selected results for electric field measurements during the DISCHA-experiments at ambient initial temperature (top left) and at an initial temperature of approx. 80 K (top right and bottom).

Much higher electric fields were measured under cryogenic reservoir conditions as the top right graph in Figure 9 shows, in which the most extremal electric field values measured in several experiments with all nozzle diameters at a temperature of approx. 80 K are plotted. In the lower left graph the most extremal electric field values measured in several experiments at the same initial pressure are plotted for the four nozzle diameters investigated. Both graphs indicate that the most extreme values are measured in experiments with the highest initial pressures and the largest nozzle diameter. The bottom right graph of Figure 9 shows the electric field records measured in a series with the 1-mm-nozzle at approx. 80 K. The graph expresses that in one series performed within a few hours on the same day as well dominant positive as dominant negative fields were measured (also valid for FM2) and that the highest field values were measured always in the first second after the release valve was opened. The latter fact and the observation of significantly higher fields at cryogenic temperatures coincide well with the assumption that the main reason for the built-up of electric fields during the release of cryogenic hydrogen is connected with ice crystals that form due to frozen ambient humidity at the cold nozzle prior to the release. When the release valve is opened these crystals are blown away and generate the electric field by friction and rupture of the crystals.

According to the German Technical Regulations for Hazardous Substances (TRGS) spark discharges at potential differences of  $U < 300$  V do not have an ignition effect against explosive atmospheres caused by flammable gases/vapors and dusts and at potential differences  $U < 100$  V also not against explosive substances [11]. Although in the experiments much higher field strengths were measured no spark discharge and no ignition of the released hydrogen was observed.

#### 4.0 CONCLUSIONS

In the frame of the EC funded project PRESLHY more than 200 release experiments from a vessel with a volume of  $2.8 \text{ dm}^3$  were performed. In the tests two different initial temperatures, four nozzle diameters and seven initial pressure stages were investigated. Several methods for the determination of the hydrogen release rate, the concentration distribution and the electrostatic field built-up were applied that

did not all yield the desired results. But despite all draw-backs a determination of the hydrogen release rate is possible for all experiments conducted using the fast pressure and thermocouple signals recorded during the experiments. A part of the data is already used by PRESLHY project partners for the validation of their modelling tools and a comparative study which is also presented in the frame of this conference [6,7].

The H<sub>2</sub>-concentration distribution in the region of the jet was investigated using H<sub>2</sub>-sensors, which mainly gave the maximum concentrations measured in the sensing position. For all cases investigated equations could be formulated to estimate the maximum concentrations to be expected on the jet axis in distances higher than 40 cm from the release nozzle. These results, together with the optical observations using the BOS-technique, were used to plan the ignited DISCHA-experiments performed later in a separate experimental series.

Finally, electrostatic measurements along the jet were performed to get an impression of the electrostatic field built-up that can be expected in the vicinity of cryogenic H<sub>2</sub>-releases. Despite large scatter in the measured field values trends could be observed that larger fields can be expected for lower reservoir temperatures, higher initial reservoir pressures and larger nozzle diameters. These findings are in good agreement with the assumption that the main reason for the field built-up is connected with ice crystals that form at the cold nozzle prior to the release and that are blown away in the initial phase of the release.

With the unignited DISCHA-experiments performed within the EC-funded project PRESLHY a huge basis of experimental data on the release of hydrogen at ambient and cryogenic conditions was generated that is publicly available and might be used for code validation.

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