EXPERIMENTAL STUDY OF JET-FORMED HYDROGEN-AIR MIXTURES AND PRESSURE LOADS FROM THEIR DEFLAGRATIONS IN LOW CONFINED SURROUNDINGS

A. Friedrich[1], J. Grune[1], N. Kotchourko[1], A. Kotchourko[2], K. Sempert[1], G. Stern[1], M. Kuznetsov[2]
[1] ProScience GmbH, Parkstr. 9, 76275 Ettlingen, Germany
[2] Research Center Karlsruhe, P.O. Box 3640, 76021 Karlsruhe, Germany
Corresponding author: kuznetsov@iket.fzk.de

ABSTRACT

To provide more practical data for safety assessments, a systematic study of explosion and combustion processes which can take place in mixtures produced by jet releases in realistic environmental conditions is required. The presented work is aimed to make step forward in this direction binding three inter-connected tasks: (i) study of horizontal and vertical jets, (ii) study of the burnable clouds formed by jets in different geometry configurations and (iii) examination of combustion and explosion processes initiated in such mixtures. Test matrix for the jet experiments included variation of the release pressure and nozzle diameter with the aim to study details of the resulting hydrogen concentration and velocity profiles depending on the release conditions. In this study the following parameters were varied: mass flow rate, jet nozzle diameter (to alter gas speed) and geometry of the hood located on top of the jet. The carried out experiments provided data on detailed structure for under-expanded horizontal and buoyant vertical jets and data on pressure loads resulted from deflagration of various mixtures formed by jet releases. The data on pressures waves generated in the conditions under consideration provides conservative estimation of pressure loads for realistic leaks.

1.0 INTRODUCTION

With the growing role of hydrogen as energy carrier in future world economy, safety of hydrogen-related industrial components becomes increasingly important. One of the vital elements of infrastructure in upcoming hydrogen industry are high-pressure storages and pipelines. Any damages or malfunctions of such vessels as well as pressure relieves in normal operation in most cases will lead to formation of hydrogen jets. Widely used approach of evaluation a possible hazard connected with hydrogen leak on the basis of total hydrogen inventory often lead to significant over-estimation of expected damages. To provide more practical data for safety assessments, a systematic study of explosion and combustion processes which can take place in mixtures produced by jet releases in realistic environmental conditions is required. The presented work is aimed to make step forward in this direction binding three inter-connected tasks: (i) study of horizontal and vertical jets, (ii) study of the burnable clouds formed by jets in different geometry configurations and (iii) examination of combustion and explosion processes initiated in such mixtures.

Test matrix for the jet experiments included variation of the release pressure and nozzle diameter with the aim to study details of the resulting hydrogen concentration and velocity profiles depending on the release conditions. The experimental facility for jet release tests consisted of high pressure hydrogen gas system providing hydrogen releases at pressures in the range 20 – 260 bar. The nozzle diameter has been varied in the range 0.16 – 100 mm, and the hydrogen mass flow rate has been altered in the range 0.1 – 8 g/s. Hydrogen concentration profile and flow velocity for horizontal jets were measured in three different cross-sections at distances 0.75, 1.5 and 2.25 meters from the nozzle. For vertical jets the measurements of concentrations were made in more then five cross-sections. “Background oriented schlieren” technique was used as supplementary source of concentration distribution information. In this study the following parameters were varied: mass flow rate, jet nozzle diameter (to alter gas speed) and geometry of the hood located on top of the jet. There were two arrangements: flat plate 100 x 100 cm and hood with 50 cm vertical side walls. In the combustion experiments the mixture was ignited in the stagnation area below the horizontal plate. The ignition was performed using different type of turbulizers with the aim to obtain the most energetic regime of combustion which can be achieved in such conditions.

The carried out experiments provided data on detailed structure for under-expanded horizontal and buoyant vertical jets and data on pressure loads resulted from deflagration of various mixtures formed by jet releases. The data on pressures waves generated in the conditions under consideration provides conservative estimation of pressure loads for realistic leaks.

2.0 EXPERIMENTAL SETUP

Since the process of the jet formation during hydrogen releases typical for the conditions under consideration has a stochastic character therefore the scenarios studied in the current work can include a number of uncertainties and variations that makes very difficult to gain reproducible data. Particularly the nature of the hydrogen release, with a hydrogen reservoir of defined initial conditions being opened to the ambience, leads to countless variations, especially for the ignition experiments. With the aim to reduce the possible experimental uncertainties the experiments were performed using the release with constant exit velocity and mass flow rate during the whole release period of time. For such release the ignition moment with high probability is close to the end of the release, when almost the complete amount of hydrogen was discharged into the test chamber and when still high exit velocity can generate additional turbulence which will promote high-speed combustion.

2.1 Test matrix

Nine hydrogen release scenarios were studied in the experiments, covering three diameters of the circular release nozzle with three different constant hydrogen release rates each. Nozzle diameters and release rates are summarized in Table 1 with the name of the appropriate experimental series.

Table 1: Release scenarios investigated in the experiments

Experimental series	Nozzle-diameter [mm]	Exit velocity [m/s]	Mass flow [$g(H_2)/s$]	Release duration for 10 g H_2 inventory [s]
PlA	100	0.2	0.14	71.3
PlB	100	1	0.7	14.3
PlC	100	5	3.5	2.85
PlD	21	5	0.15	64.7
PlE	21	100	3	3.23
PlF	21	200	6	1.62
PlG	4	100	0.14	71
PlH	4	200	0.29	35
PlI	4	400	0.57	17.5

Experiments for two different configurations were conducted: (i) Square horizontal plate with a side length of 1.00 m in a distance of 1.50 m centrically above the release nozzle; (ii) Same plate in same distance but with four additional vertical sidewalls of 0.50 m height, forming a downward opened hood with a volume of 500 liters above the release nozzle. The two configurations are sketched in Figure 2.

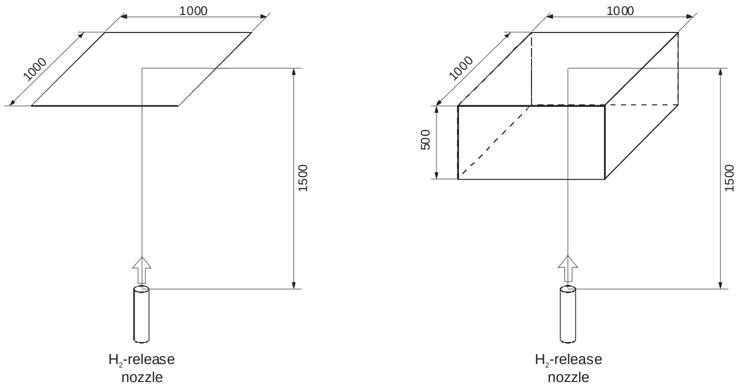


Fig. 2: Configurations used for jet congestion. Left (configuration 1) – horizontal plate; right (configuration 2) – horizontal plate with side walls.

2.2 Hydrogen release system

To adjust the hydrogen release properties, a separate release control system outside the test chamber and a bypass system were used. A sketch of the hydrogen release system is given in Figure 3.

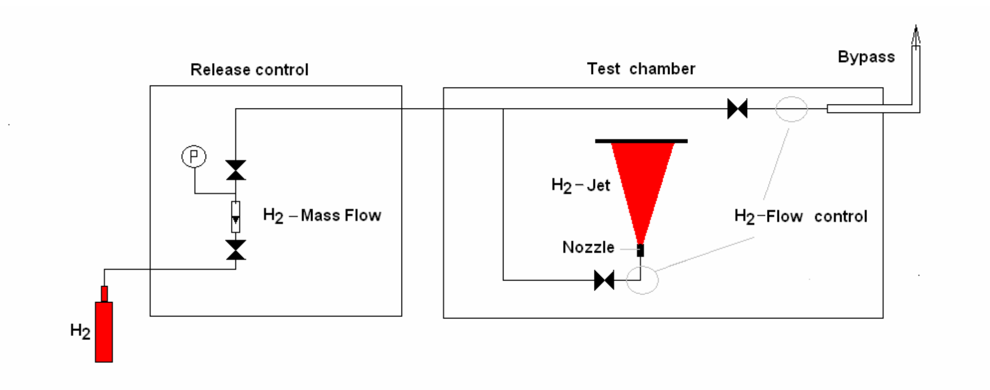


Figure 3: Hydrogen release system.

Gas cylinders were used as the hydrogen source. The hydrogen mass flow in the pipes, that was used to control the exit velocity, was tuned via a hydrogen mass flow controller in the release control system. To provide a constant exit velocity during the release, the hydrogen mass flow had to be adjusted first, while the hydrogen was conducted through a bypass to the outside of the building. This bypass was equipped with the same nozzle as the release and a *Prandtl* probe to measure the exit velocity of the gas. When the required exit velocity had established in the bypass, the valves of bypass and release were switched simultaneously, so that the hydrogen flow was piped through the nozzle inside the test chamber. During the release, the exit velocity in this nozzle was also measured by a *Prandtl* probe. After the release end, the valves were switched again to bypass flow and the valves in the release control system were closed.

Since both, bypass and release, have the same hydraulic resistance, the exit velocity was established very quickly, remains constant throughout the whole release time and decreased to zero very fast after the valves were switched to bypass flow again.

2.3 Hydrogen concentration measurements

In the distribution experiments hydrogen concentrations between nozzle and plate were determined using eight sample cylinders. Since a stable plume needs some time to establish above the release, measurements were performed at times close to the end of the duration of the hydrogen release.

The sample taking cylinders consist of a hollow body with an internal volume of approximately 300 ml that is equipped with two ports. These ports are closed by electrical valves that allow remote opening. One of the valves, the inlet valve, is equipped with a cannula (d_i = 2 mm, l = 500 mm) that was pointed to the gas sampling point in the hydrogen jet, while the outlet valve is equipped with a self sealing coupling.

Before the measurement the sample taking cylinders were evacuated via the outlet valve and then installed to the desired position where a gas sample should be taken. During the experiment, close to the end of the hydrogen release, the inlet valve was opened computer-controlled at a given time for approximately 2 seconds. This rather long opening time is necessary since the sample taking cylinders need some time to be filled to an internal pressure that allows the subsequent analysis of their content using the gas analysis system. No complete charge of the cylinders to ambient pressure is required for a reliable evaluation of the hydrogen concentration. A minimum span of 0.1 m between two sampling points was chosen to avoid side effects due to too much gas being removed from the plume at a certain position.

The concentration measurements were also used to determine promising positions for the ignition source in the subsequent combustion experiments.

2.4 Gas analysis system

To analyse the hydrogen content of the sample taking cylinders a gas analysis system (Fisher-Rosemount, Series MLT) with a measuring range from 0 to 100 Vol.-% H_2 and 0 to 100 Vol.-% O_2 was used.

2.5 Ignition source

A high frequency spark generator was used to ignite the released hydrogen. The spark was generated between two electrodes in a distance of 3 mm to each other. The igniter is equipped with a ceramic tube for heat protection and to make sure that no shortcut of the ignition circuit occurs when flame acceleration devices are used. A stable current and high voltage discharge at 60 kV with a frequency of 20 kHz produces an almost stable electric arc between the electrodes of the ignition device. This spark igniter allows producing spark discharges with energies from 10 to 20 J per second using the control unit.

2.6 Dynamic pressure measurements

Combustion overpressure measurements were performed using ten piezoelectric pressure gauges (PCB, Models 112A21, 113A21 and 113A31). Eight of these sensors were fixed to a bar in a distance of twenty centimetres to each other. The two remaining pressure transducers were installed to the same bar at locations in between these positions. The whole bar was then installed either horizontally or vertically in a given height and distance to the axis of the hydrogen release.

2.7 Sound level measurements

Sound levels were measured during the combustion experiments using a digital sound level meter (roline, model RO-1350) with a measuring range from 90 to 130 dB(A) in a horizontal distance of 3 m to the ignition source. During the experiments the digital output signal of the device was recorded by the data acquisition system.

2.8 Data acquisition

Two independent fast data acquisition systems, based on 12-bit ADC boards (IMTEC, Model T-112-8) with sampling rates of up to 1.25 MHz, installed to two independent IBM PCs were used for data recording during the experiments. The first one recorded the signals of the Prandtl probes of the hydrogen release system while the second one recorded the signals of the pressure transducers and the sound level meter in the combustion experiments. The trigger signal for the first data acquisition system was an electrical impulse provided by the remote control of the release valve when it was opened. The second data acquisition was triggered via a change in one of the pressure signals above or below a threshold value that was defined in advance.

2.9 Flame acceleration devices

With the use of hydrogen flame acceleration devices in some combustion experiments it was attempted to obtain a worst case scenario for the combustion of the released hydrogen. It is known from former experiments, that grid net layers are useful raw materials for the construction of such devices [1]. There are almost infinite possibilities to create flame acceleration devices and due to the different hydrogen release properties every arrangement has its own optimum device. During the experiments, depending on the arrangement chosen, several flame acceleration devices were used. These devices are shown in Figure 5.

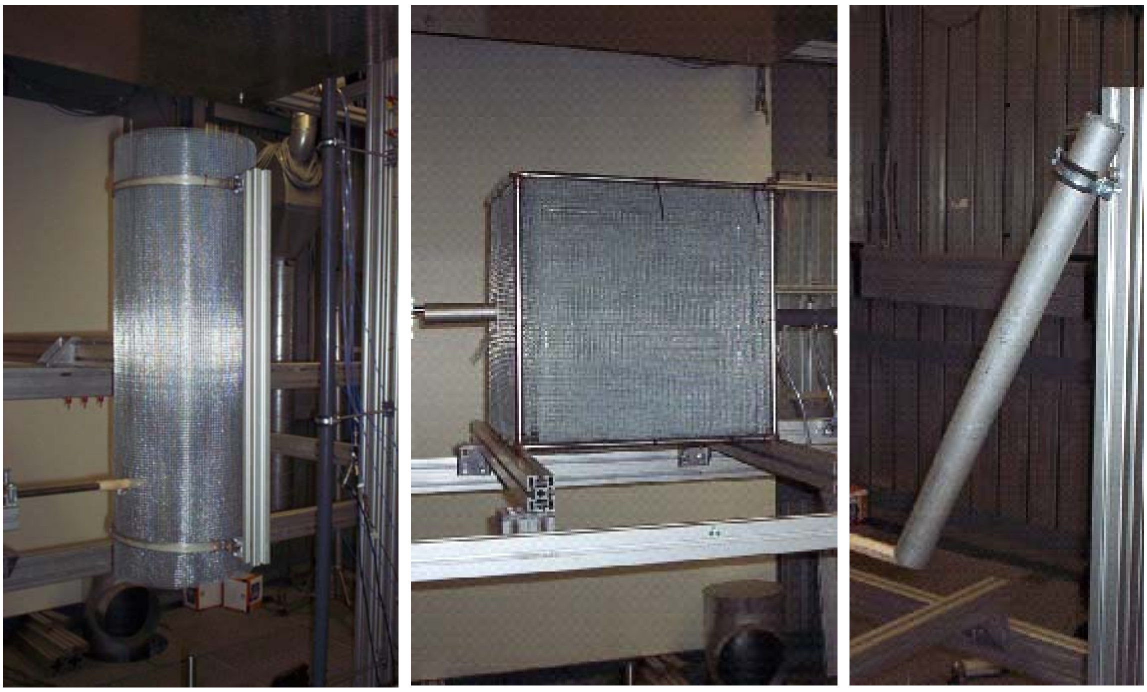


Figure 5: Flame acceleration devices used in the experiments (from left to right: cylinder, cube and tube).

The cylinder (Fig. 5, left), used in the experiments with the two large nozzles, consists of a sheet of net layer grid (grid size: 6.5 x 0.65 mm) with a width of 1 m that is rolled up (22 turns) to form a cylinder of 0.34 m diameter and a height of 1 m. The core of the cylinder has a diameter of 0.1 m and is equipped with vertical grid net layer sheets in a distance of 0.1 m to each other. The cube (Fig. 5, centre), as well used in the experiments with the two large nozzles, has a side length of 0.54 m and is filled with sheets of net layer grids, piled up pyramidally from every face [1]. The tube (Fig. 5, right), only used in the experiments with the small nozzle, has a length of 0.65 m and an inner diameter of 42 mm which is filled with a rolled sheet of net layer grid.

3.0 RESULTS

3.1 Distribution experiments

Concentration measurements inside the cloud of released hydrogen were performed in horizontal and vertical direction using sample taking cylinders that were installed to the bars of the test stand with the tip of their cannula pointing to the position where a gas sample should be taken. Figure 6 gives an impression of the experimental setup for the distribution experiments.

Figure 6: Sketch of the experimental setup for the distribution experiments in configuration 1 with horizontal plate, large release nozzle and the sample taking cylinders.

3.1.1 Free jet distribution experiments in configuration 1 (horizontal plate)

To provide measurements in a stable hydrogen jet, the gas samples were taken towards the end of the release duration. Usually, for a given arrangement, first the vertical concentration profile was measured, with the eight gas sampling positions in the axis of the hydrogen release at different heights from 0.1 to 1.5 m (directly below the plate) above the nozzle.

In Figure 7 the results of the concentration measurements are along the axis of the release are presented. There are the data for three different nozzle sizes and with different release rates.

All experiments with nozzle diameter 100 mm were performed with release durations that correspond to a hydrogen inventory of 10 g inside the test chamber. Samples were taken after 40 s (PlA) or as close as possible before the end of the release duration (PlB and PlC). The measured hydrogen concentrations in every experiment decrease with increasing distance from the release nozzle. For increasing release rates the hydrogen concentrations measured along the release axis do also increase. When the sampling points are shifted to positions 5 cm beside the release axis (PlC02), the measured hydrogen concentrations become lower, especially for positions close to the nozzle.

For the experiments with the medium nozzle (d = 21 mm), an increase in the measured hydrogen concentrations is observable when the release rate is increased from 0.15 g/s to 3 g/s. A further increase of the release rate to 6 g/s does not produce a significant rise in the measured hydrogen concentrations although an even higher inventory of 15.6 g H_2 was released into the test chamber during experiment PlF01, compared to an inventory of 10 g H_2 in experiment PlE01. This minor effect of the hydrogen inventory on the measured concentrations can also be observed for the experiments with a release rate of m = 0.15 g/s: In experiment PlD01 an inventory of 3 g H_2 leads to slightly lower concentrations than in the similar experiments PlD02 and PlD03 with an inventory of 10 g H_2. For the experiments with the small nozzle (d = 4 mm), the measured hydrogen concentrations remain almost unchanged for release rates from 0.14 g/s to 0.57 g/s and inventories of 3 g H_2.

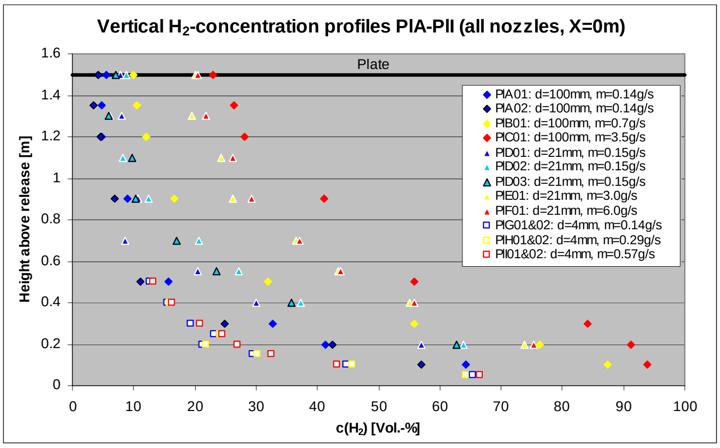


Figure 7: Vertical hydrogen concentration profiles along the axis of the release for experiments with all nozzles at different release rates.

In accordance with *Birch et al* [2], the diagram in Figure 8 (left) demonstrates an almost linear dependence of the reciprocal hydrogen concentration from the ratio of nozzle diameter d and distance from the release Z (height) for the experiments with high exit velocities (v_{exit} = 100 – 400 m/s). For low exit velocities, another linear dependence can be derived from Figure 8 (right), where the reciprocal hydrogen concentration is plotted against the product of distance (height) from the release Z and the square root of the ratio of nozzle diameter d and hydrogen mass flow m.

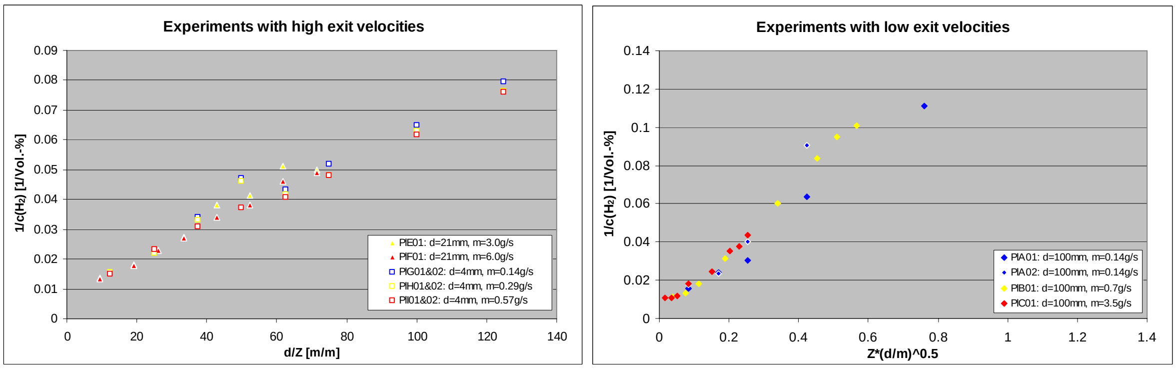


Figure 8: Reciprocal hydrogen concentration versus ratio of nozzle diameter (d) and distance (height, Z) for experiments with high exit velocities (v_{exit} = 100 – 400 m/s) (left) and with low exit velocities (v_{exit} = 0.2 – 5 m/s) (right).

The vertical hydrogen concentration profiles also give useful indications to promising ignition source positions for the subsequent combustion experiments. Since the ignition of a stoichiometric hydrogen-air mixture (about 30% H_2 in air) produces the highest combustion pressures, the location along the axis of the release where this concentration was measured in the vertical distribution experiments was chosen to be the ignition point for the combustion experiments. Before a combustion experiment was conducted, the horizontal hydrogen concentration profile in this height was measured with the eight sample taking cylinders.

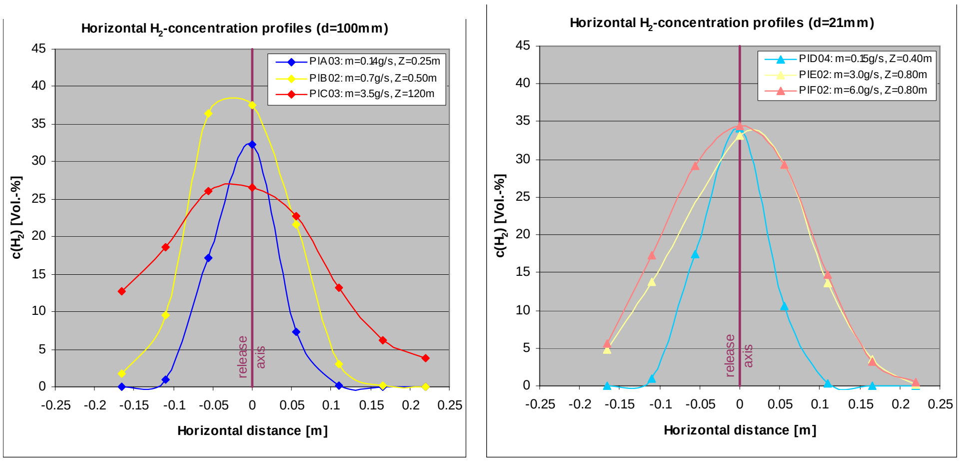


Figure 9: Horizontal hydrogen concentration profiles in the height of the ignition source for the experiments with nozzles d = 100 mm (PlA-PlC, left) and d = 21 mm (PlD-PlE, right) for different release rates (Z: height above the release nozzle).

The horizontal hydrogen concentration profiles depicted in Figure 9 show, that in the position of the ignition source hydrogen concentrations of approximately 30 Vol.-% were measured for the experiments with the two large nozzles (d = 100 and 21 mm). Furthermore a shape of the hydrogen concentrations similar to Gaussian profile was observed, with their maximum close to the axis of the release.

For two experiments Background-Oriented-Schlieren (BOS) -photography was used to visualize the released hydrogen inside the test chamber. Figure 10 shows photographs taken during an experiment with the medium nozzle (d = 21 mm) and a release rate of 3 g/s for 3.23 s, leading to a hydrogen inventory of ca. 10 g H_2, which is comparable to the experiments PlE01 and PlE02 with the same settings. Figure 10 shows that after an opening time of ca. 1.3 s a stable plume had established above the release nozzle. After the release valve was closed (3.23 s), the visible amount of hydrogen decreases rapidly, with some hydrogen still accumulated below the plate.

In the experiment with the small nozzle (d = 4 mm) and a release rate of 0.14 g/s injection during 21 s resulted in an inventory of 3 g H_2 inside the test chamber, which is comparable to the experiments PlG01 and PlG02 with the same settings. In this case, a stable plume had established after ca. 2 s, remaining practically unchanged until the release is closed after 21 s. Soon after closing the release valve only very little hydrogen is visible directly below the plate.

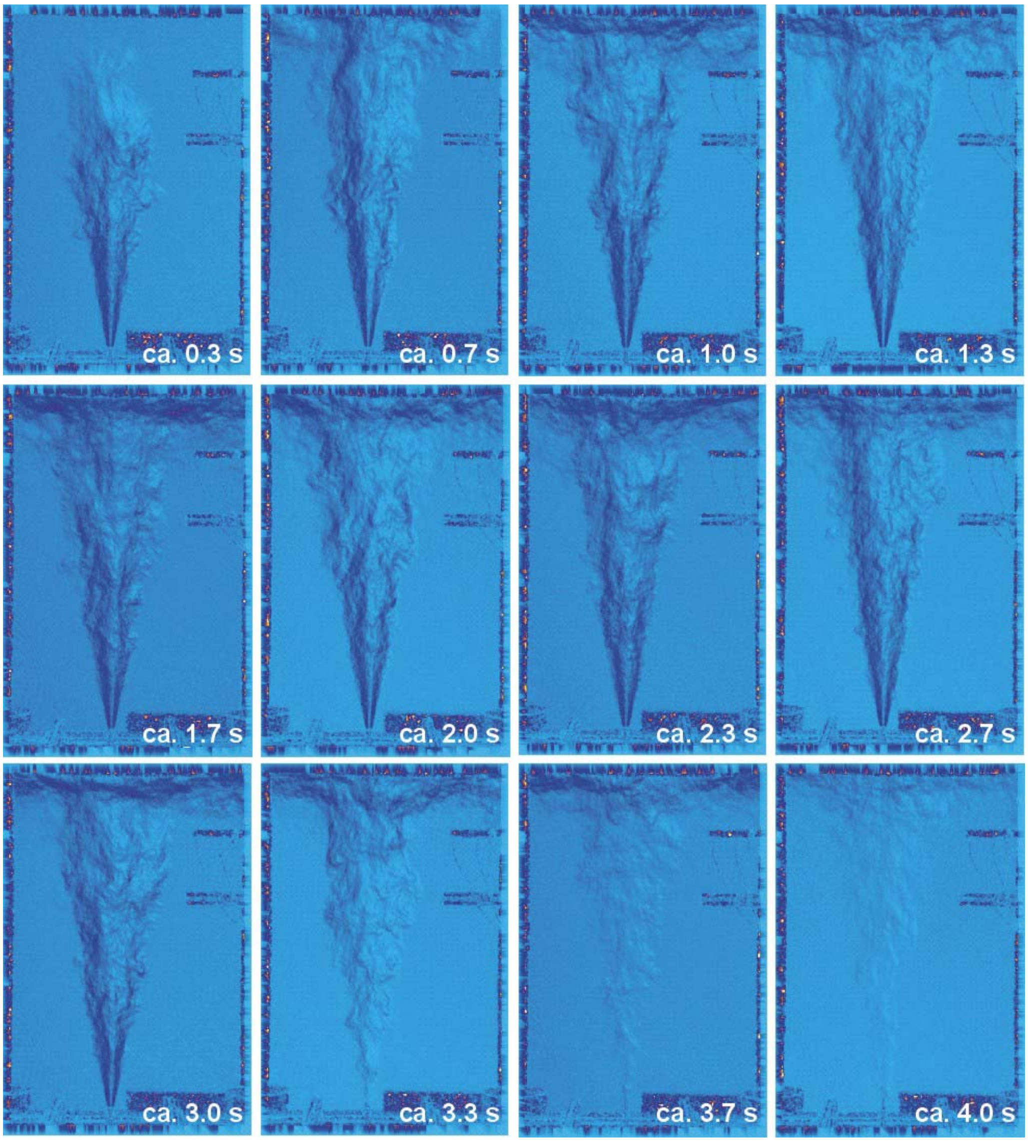


Figure 10: Background-Oriented-Schlieren (BOS) -photographs taken during an experiment with the medium nozzle (d = 21 mm) and a release rate of 3 g/s for 3.23 s, leading to a hydrogen inventory of 10 g H_2.

As mentioned above, the experiments in which the BOS-technique was used are comparable to experiments with concentration measurements via sample taking cylinders. Figure 11 compares the photographs with these concentration measurements, represented by colored dots at approximately the position where the sample had been taken. The white numbers besides the dots give the hydrogen concentration measured in this position. Since the cylinders need an opening time of several seconds to be filled to an internal pressure that allows a subsequent analysis of the gas sample, a photograph taken at about half of the opening time of the cylinders was used for this comparison.

The comparison of the experiments PlE01 and PlE02 with the appropriate photograph in Figure 11 (left) shows, that the border of the plume in horizontal direction was well resolved by the measurements with the sample taking cylinders. From the comparison of the experiments PlG01 and PlG02 with the corresponding photograph (Fig. 11, right) can be derived, that for the small nozzle (d = 4mm) with a release rate of 0.14 g/s, the hydrogen concentration above the nozzle decreases very fast to concentrations of about 10 Vol.-% H_2.

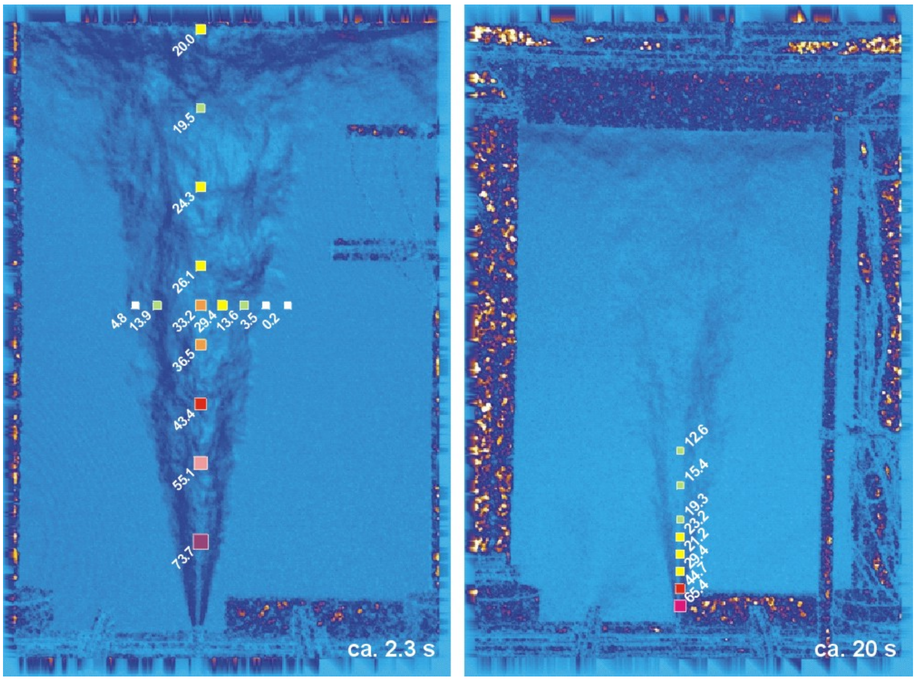


Figure 11: Comparison of concentration measurements via sample taking cylinders (colored dots) with BOS photographs of similar experiments.

3.1.2 Free jet distribution experiments in configuration 2 (horizontal plate with sidewalls)

In these distribution experiments the plate and the additional sidewalls formed a downward opened hood with a volume of 500 liters above the release nozzle. Assuming the complete amount of released hydrogen being distributed homogenously in this volume leads to concentrations of 2.24 Vol.-% H_2 for the release of 1 g hydrogen, 6.72 Vol.-% H_2 (3 g) and 22.4 Vol.-% H_2 (10 g). Due to the low mean concentrations for the release of 1 and 3 g H_2 only experiments with an amount of 10 g hydrogen were performed. The experiments were conducted with the positions of the sample taking cylinders oriented horizontally inside the downward opened hood.

The height of the sample taking positions was 1.25 m above the nozzle for the cylinders above and to the left of the release and 1.05 m above the nozzle for the cylinders to the right of the release. This arrangement was chosen because a symmetrical distribution of the hydrogen was assumed in this symmetrical configuration. With this arrangement it was possible to measure horizontal concentration profiles during the release in two different heights with one experiment. Figure 12 summarizes all concentration measurements performed with an inventory of 10 g H_2 for the configuration with the additional sidewalls.

All measurements referred to in Figure 12 show a similar distribution of the hydrogen inside the hood: In the middle, above the release, the highest concentrations were measured. With increasing distance from the release axis on either side the measured hydrogen concentrations decrease to a minimum in a distance between 0.25 and 0.375 m. A further increase of the distance to the release axis leads to an increase of the measured hydrogen concentrations with a maximum reached at the sampling point close to the sidewall. With increasing release rate, nozzle diameter and amount of hydrogen this behaviour becomes more distinct. Despite the sampling points are located in different heights, the measured concentration profiles on both sides of the release axis are almost symmetrical, with the concentrations measured at the lower sampling points being a bit lower. The shape of these concentration profiles can be explained on the basis of BOS-photographs taken during an experiment comparable to experiment PlD13 (Figure 13).

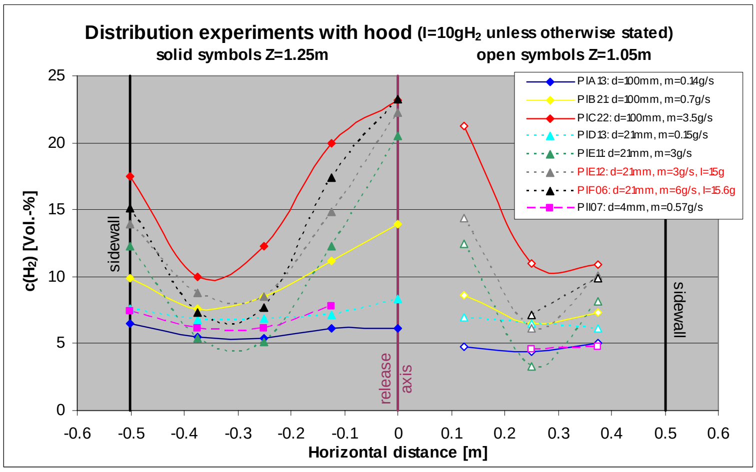


Figure 12: Hydrogen concentrations measured during the experiments with the additional sidewalls.

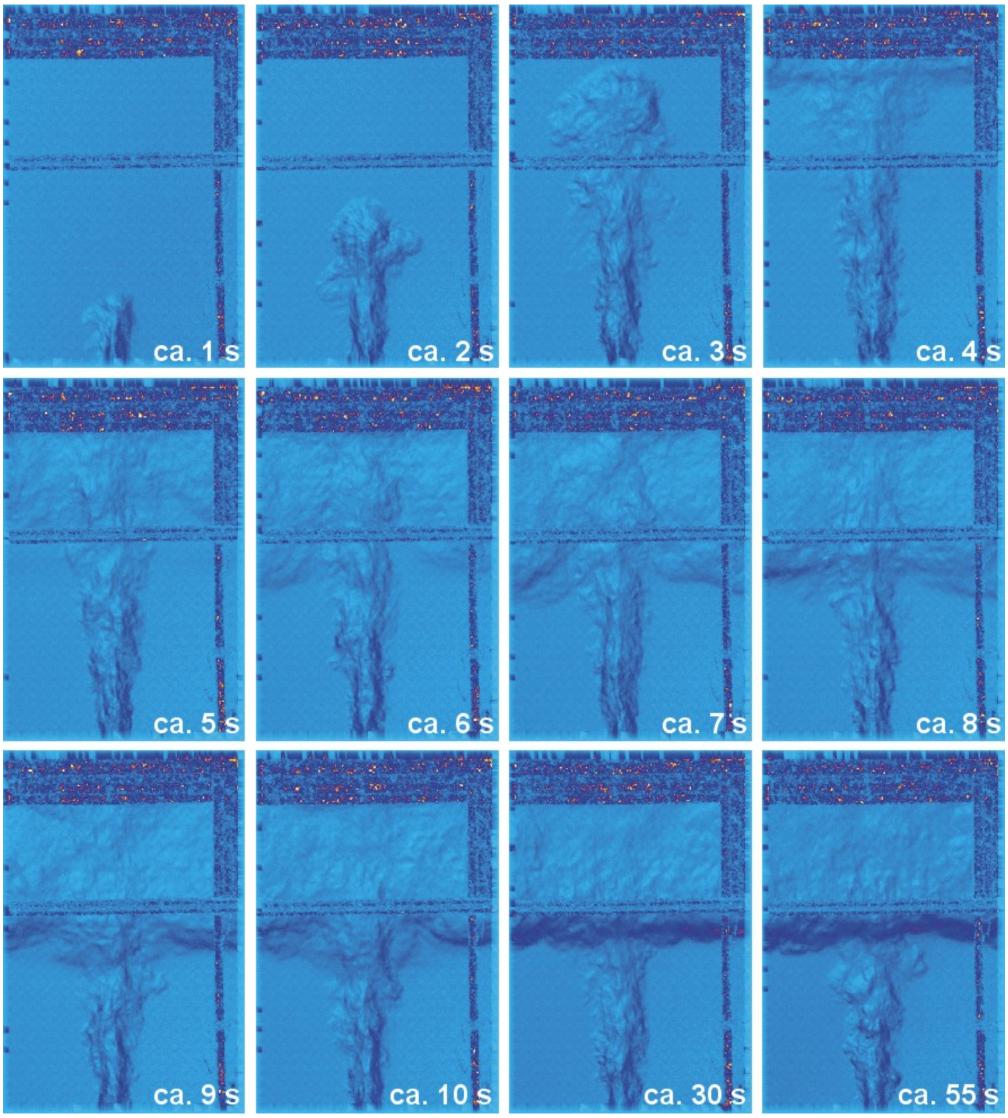


Figure 13: Series of BOS-photographs of a distribution experiment with the medium nozzle (d = 21 mm) and a release rate of 0.15 $g(H_2)/s$ for 64.67 s, leading to an inventory of 10 g H_2.

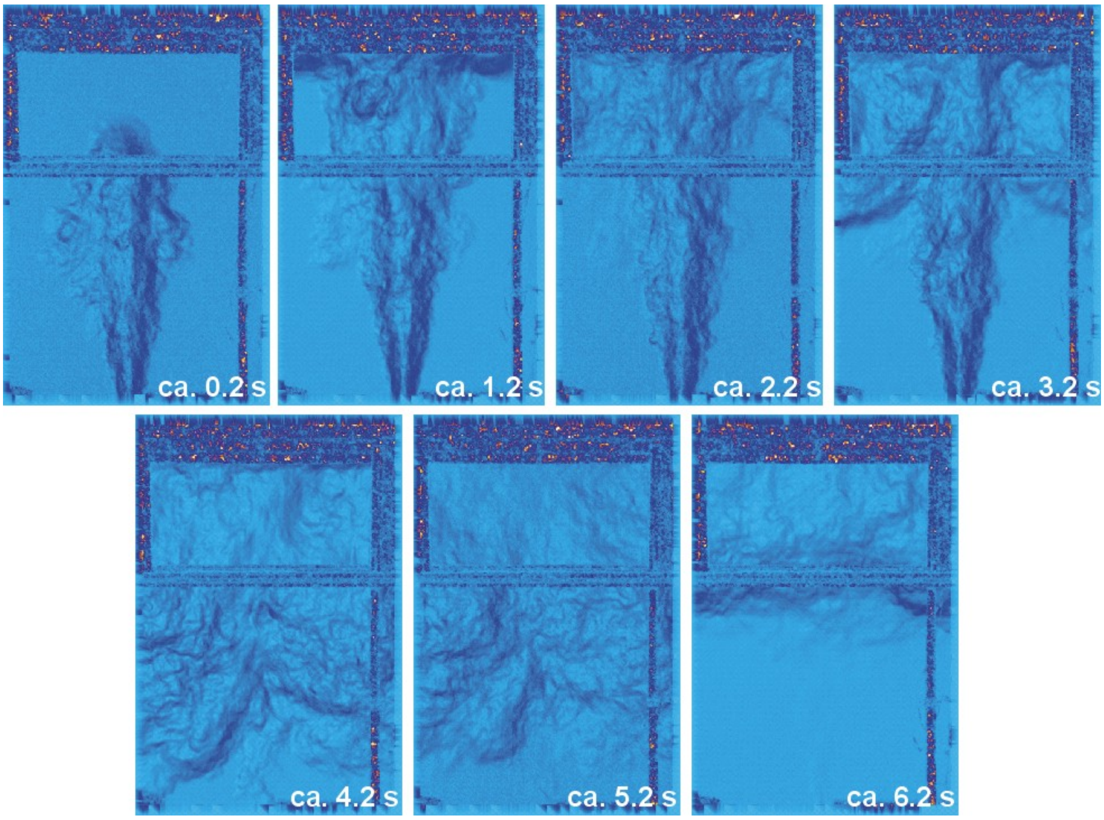


Figure 14: Series of BOS-photographs of a distribution experiment with the medium nozzle (d = 21 mm), a release rate of 3.0 g(H_2)/s for 3.23 s, leading to an inventory of 10 g H_2.

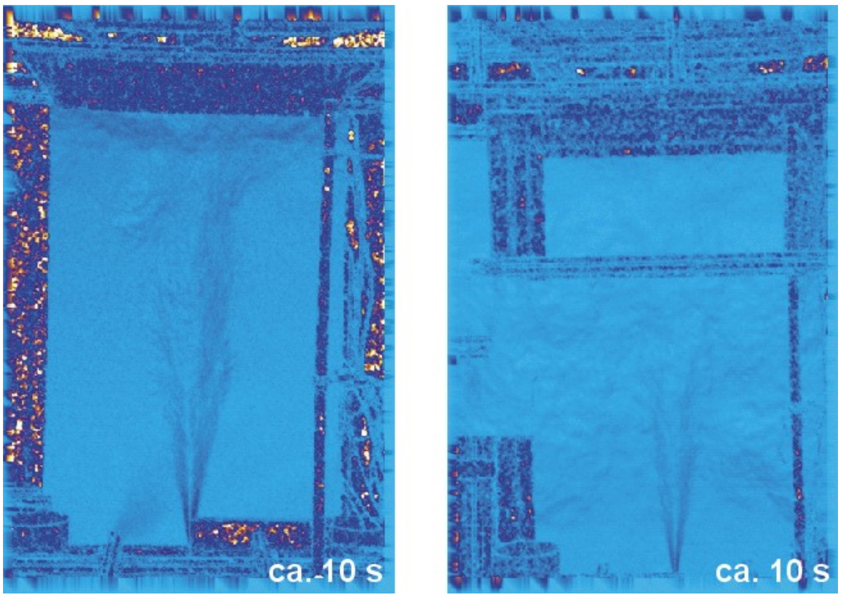


Figure 15: Comparison of BOS-photographs of two distribution experiments with the small nozzle (d = 4 mm) and release rates of 0.14 g(H_2)/s without (left) and with (right) the additional sidewalls.

As depicted in Figure 13, the released hydrogen travels upwards forming a plume until it reaches the horizontal plate, where it is diverted in horizontal direction. When reaching the sidewalls, the direction of the flow is changed to downwards, leading to a concentration profile as shown in Figure 12. With increasing exit velocities the release duration time decreases, allowing less mixing inside the hood and therefore the concentration profile becomes more distinct. Figures 14 show series of BOS-photographs of distribution experiments with the medium nozzle (d = 21 mm) and release rates (3 g/s) resulting in the inventory of 10 g H_2. Figure 21 compares the concentrations measured via the sample taking cylinders with the BOS-photographs. Again a photograph taken at about half of the opening time of the cylinders was used for this comparison.

The Figures 13-14 show, that the hydrogen cloud has roughly the same shape during the release time in all three experiments. Especially the last picture in Figure 14 demonstrates that after the release duration time is over, a large amount of hydrogen remains inside the hood.

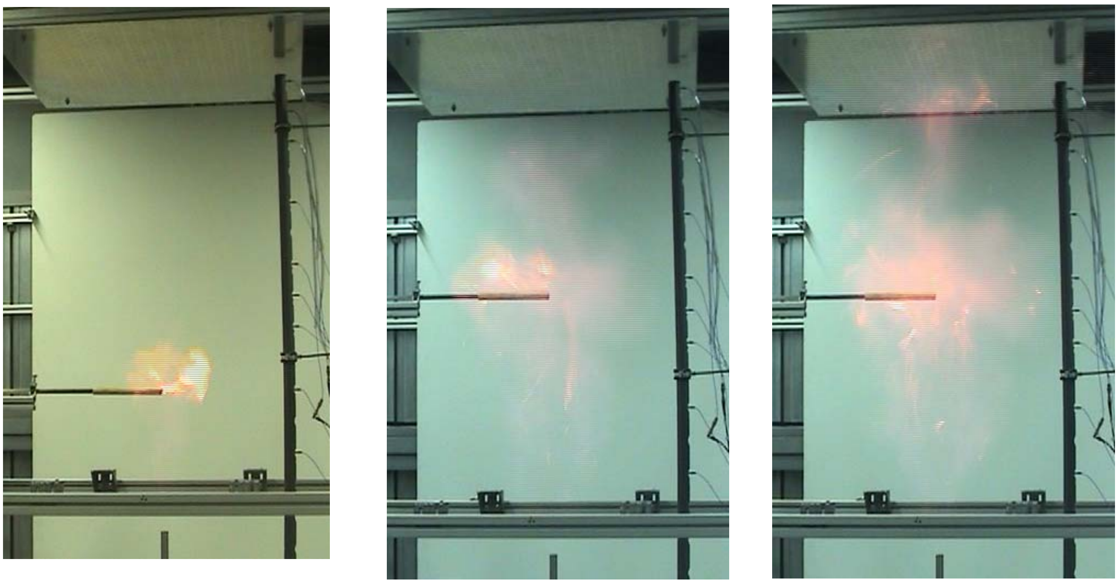
Figure 15 compares two similar experiments (d = 4mm, m = 0.14 g/s) with and without sidewalls to demonstrate a further effect of the sidewalls: Due to the downward diversion of the hydrogen flow generated by the sidewalls an accumulation of the released hydrogen can also be observed between hood and nozzle.

3.2 Combustion experiments

Combustion experiments in configuration 1 (horizontal plate). After promising positions for the ignition source were determined, combustion experiments were performed for the nine scenarios. The hydrogen cloud was ignited less than one second before the end of the release to provide maximum turbulence and maximum hydrogen inventory inside the test chamber to achieve maximum combustion pressures. The first measurements were done without any flame acceleration devices between nozzle and plate to measure the pure combustion pressure generated by the ignition of the released hydrogen.

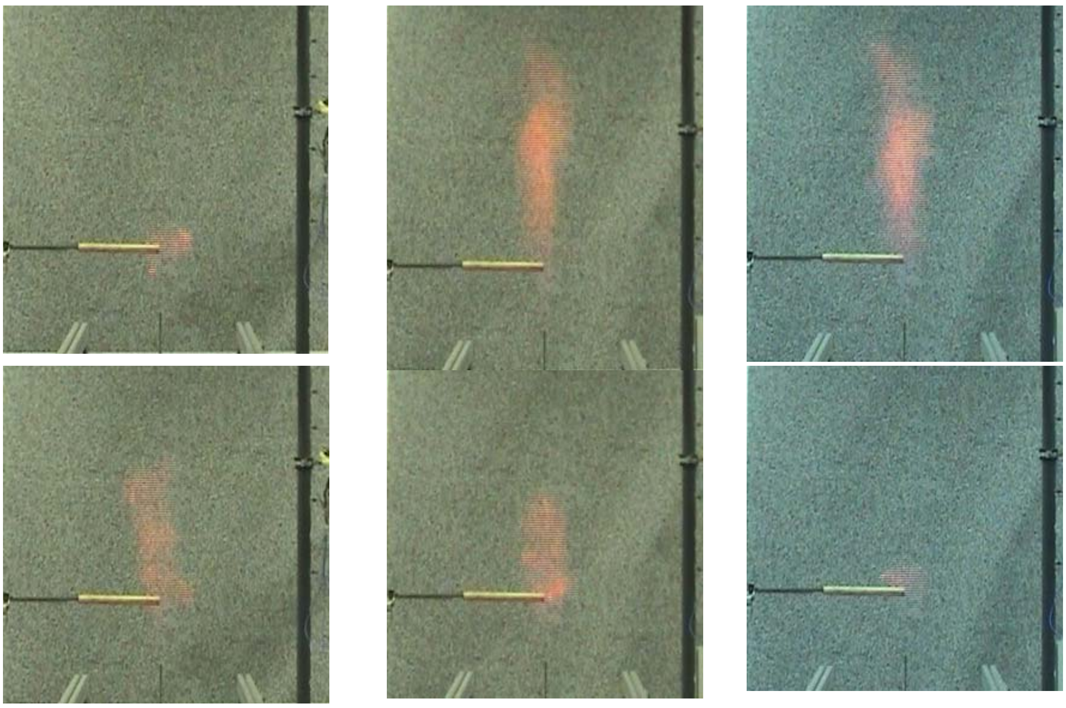
PlA09	PlB07	PlC04
m = 0.14 g/s, H_{ign} = 0.25 m,	m = 0.7 g/s, H_{ign} = 0.5 m,	m = 3.5 g/s, H_{ign} = 1.2 m,
Inventory (H_2): ca. 10 g	Inventory (H_2): ca. 10 g	Inventory (H_2): ca. 10 g

Figure 16: Photographs of the ignition sequence from movies recorded during the combustion experiments with the large nozzle (d = 100 mm).



PlD08	PlE04	PlF03
m = 0.15 g/s, H_{ign} = 0.45 m,	m = 3.0 g/s, H_{ign} = 0.8 m,	m = 6.0 g/s, H_{ign} = 0.8 m,
Inventory (H_2): ca. 10 g	Inventory (H_2): ca. 10 g	Inventory (H_2): ca. 10 g

Figure 17: Photographs of the ignition sequence from movies recorded during the combustion experiments with the medium nozzle (d = 21 mm).



PlG05	PlH05	PlI05
m = 0.14 g/s, H_{ign} = 0.17 m,	m = 0.29 g/s, H_{ign} = 0.17 m,	m = 0.57 g/s, H_{ign} = 0.17 m,
Inventory (H_2): ca. 10 g	Inventory (H_2): ca. 10 g	Inventory (H_2): ca. 10 g

Figure 18: Photographs of the ignition sequence from movies recorded during the combustion experiments with the small nozzle (d = 4 mm).

The experiments were observed by a video camera to record the ignition sequence of the released hydrogen. Some photographs demonstrating typical behavior for the different nozzle diameters and different release rates are presented in the Figures 16-18. After the hydrogen jet was ignited, in some experiments a diffusion flame, comparable to a burner was observed.

Simultaneously sound level measurements were performed in a horizontal distance of three meters from the ignition point. In Figure 19 the sound level is plotted against the logarithmic axis of the mass flow for all combustion experiments without flame acceleration devices.

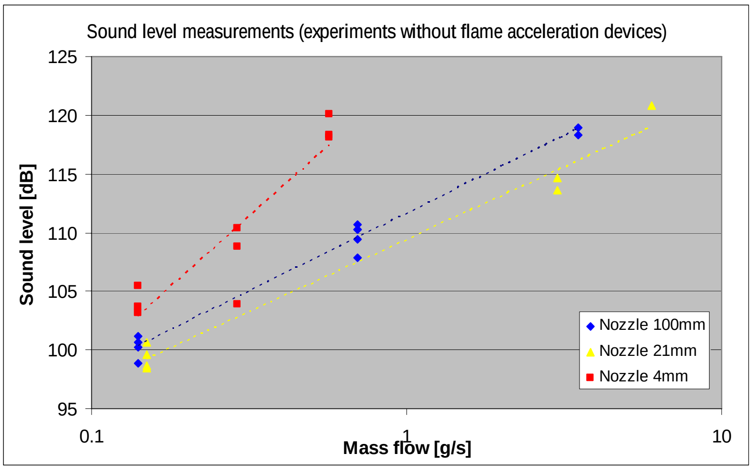


Figure 19: Sound level versus logarithmic mass flow for combustion experiments without flame acceleration devices.

All three curves show an almost linear shape. For a given mass flow, the ignition of the hydrogen released through the smallest nozzle leads to the loudest combustion. For the two larger nozzles similar sound levels were measured at a given release rate.

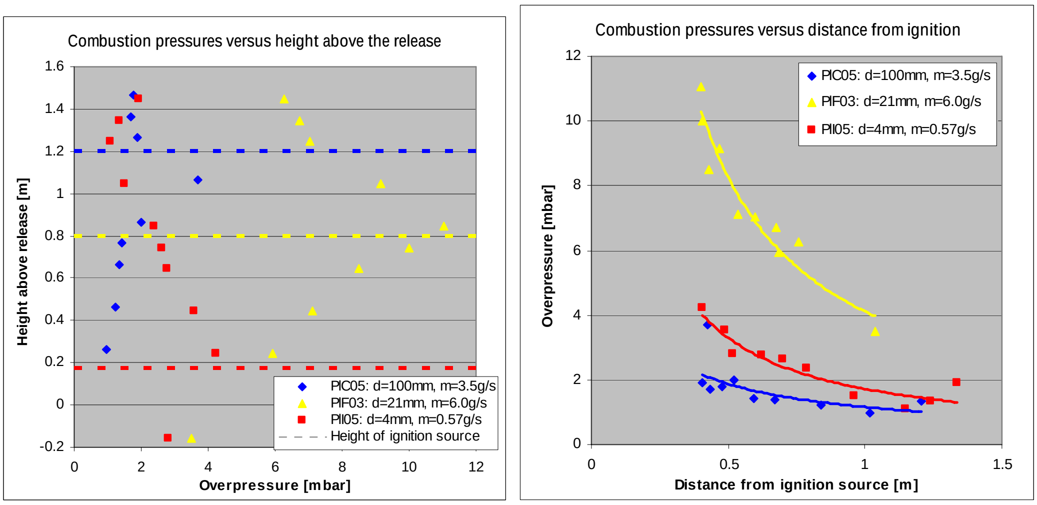


Figure 20: Combustion overpressures for experiments with three nozzles with their maximum release rates but same inventory (ca. 10 g(H_2)). Left: referred to the height above the release in a horizontal distance of 0.4 m from its axis; right: referred to the distance from the ignition source.

For the combustion pressure measurements, pressure sensors were installed along a vertical line with a horizontal distance of 0.4 m to the axis of the release. Figure 20 shows the measured maximum overpressure at different heights above the release (left) and distances from the ignition source (right) for three experiments with three nozzles with their maximum mass flow but same inventory of about 10 g. All curves in the left part of Figure 20 show their maximum at a pressure sensor located in a height close to the height of the ignition. The ignition of ≈ 10 g H_2 released through the large nozzle (d = 100 mm) with a release rate of 3.5 g/s produces similar overpressure as the ignition of the same amount of hydrogen released through the small nozzle (d = 4 mm) with a release rate of 0.57 g/s (ca. 4 mbar). The highest combustion overpressure of ca. 12 mbar in this comparison was measured for the release of 10 g H_2 through the medium nozzle (d = 21 mm) with a release rate of 6.0 g/s.

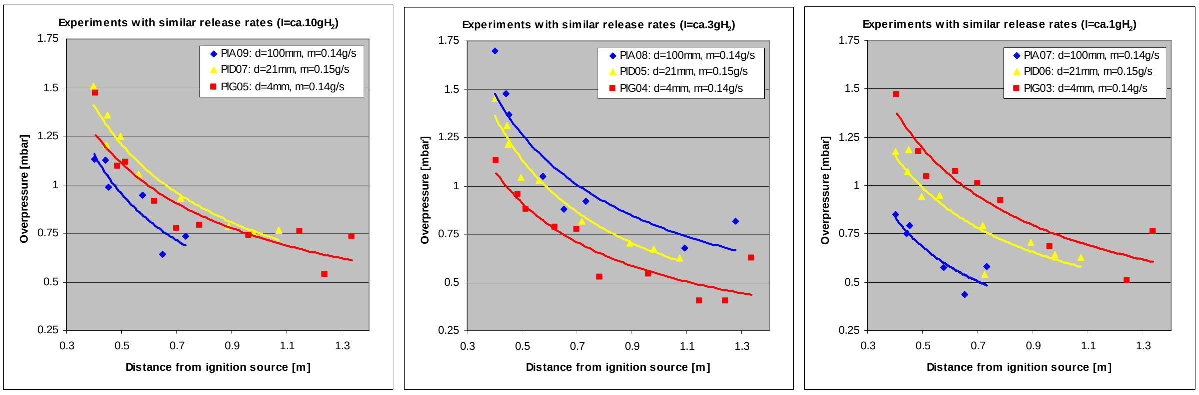
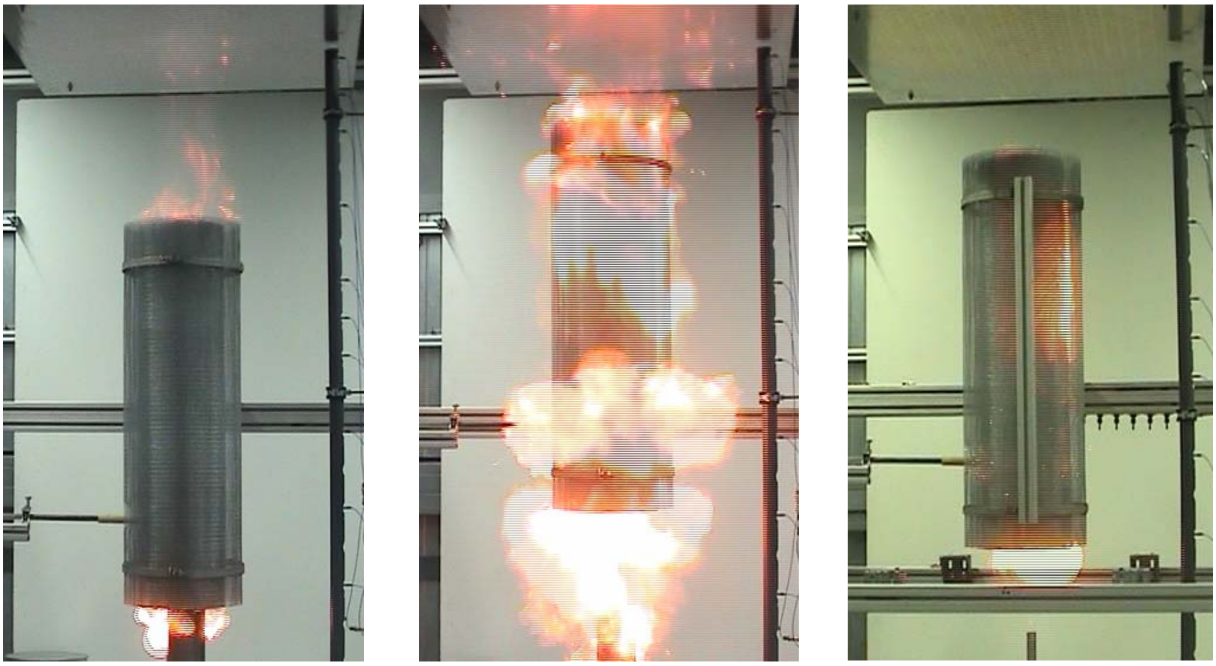


Figure 21: Combustion overpressures for experiments with similar release rates but different nozzle diameters and a H_2 inventory of ca. 1 g (left), ca. 3 g (middle) and ca.10 g (right).

Combustion overpressures for experiments with the same inventory, similar release rates but different nozzle diameters are summarized in Figure 21. For all these experiments the small combustion pressures of less than 2 mbar were measured. While for the experiments with an inventory of ≈ 1 g H_2 the combustion overpressures seem to increase with increasing nozzle diameter, the inverse relation between nozzle diameter and overpressure is apparent in the experiments with an inventory of ca. 3 g H_2. For the experiments with an inventory of ca. 10 g H_2, all experiments show almost similar pressures, with the small nozzle producing slightly lower values than the others.

Combustion experiments in configuration 1 (horizontal plate) with flame acceleration devices. To obtain maximum overpressures (worst case scenario) during the combustion of the released H_2 cloud, hydrogen flame acceleration devices were used in some of the combustion experiments. When used, the flame acceleration devices were installed centrically (cylinder, cube) or tilted (tube) with the bottom of the device above the axis of the release. The ignition source was placed on the axis of the cylinder, in the centre of the cube or directly below the lower end of the tube. The pressure measurement positions, release and ignition properties and the measured maximum overpressures for all experiments with flame acceleration devices can be extracted from Appendix D at the end of this report.

Some photographs, taken from movies recorded during the experiments with the cylinder as flame acceleration device are shown in Figure 22. Compared to the photographs of the experiments without the flame acceleration device, a much larger flame is visible. In all such experiments due to the flame acceleration device a larger burnable cloud was generated and a faster combustion process takes place. This conclusion can also be confirmed by comparing the pressure records of experiments with and without the cylinder as flame acceleration device. Figure 23 gives examples for the increasing effect of the cylindrical device on the combustion pressure achieved during the experiments. The solid symbols in this figure correspond to the maximum pressure measured for experiments without flame acceleration devices, while the open data points stand for the measured maximum pressure in similar experiments with the lower end of the cylinder in a height of 0.27 m above the nozzle.



PIA10 (d = 100 mm)	PIB10 (d = 100 mm)	PID09 (d = 21 mm)
m = 0.14 g/s, H_{ign} = 0.25 m,	m = 0.7 g/s, H_{ign} = 0.5 m,	m = 0.15 g/s, H_{ign} = 0.45 m,
Inventory (H_2): ca. 1 g	Inventory (H_2): ca. 3 g	Inventory (H_2): ca. 1 g

Figure 22: Photographs of the ignition sequence in experiments with the cylinder as flame acceleration device.

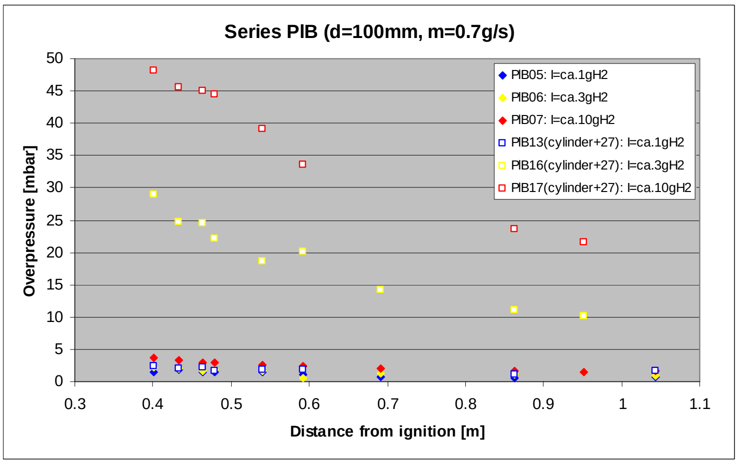


Figure 23: Measured combustion overpressures for experiments (large nozzle, same release rates but three different H_2 inventories) without and with the cylinder as flame acceleration device in a height of 0.27 m above the nozzle.

For small hydrogen inventories (I = ca. 1 g(H_2)) similar combustion pressures were measured with and without the flame acceleration cylinder. The reason possibly is that due to the large nozzle the hydrogen is not directed properly into the acceleration device, which was placed 0.27 m above the nozzle. So it is already diluted to low concentrations before it reaches the cylinder. For the larger inventories of ca. 3 and 10 g(H_2), combustion overpressures of more than 25 and 45 mbar were measured, corresponding to an increase with a factor of 7 and 20 compared to the measurements without the acceleration device.

For the medium nozzle, similar conclusions can be taken, but even for the minimum inventory of ca. 1 g(H_2) a clear increase of the measured combustion overpressure due to the flame acceleration device can be distinguished. In this case, due to the smaller nozzle, the hydrogen is directed more proper into the cylinder. Figure 24 shows the combustion overpressures measured in the experiments with this nozzle for a mass flow of 0.15 g(H_2)/s with varying inventories.

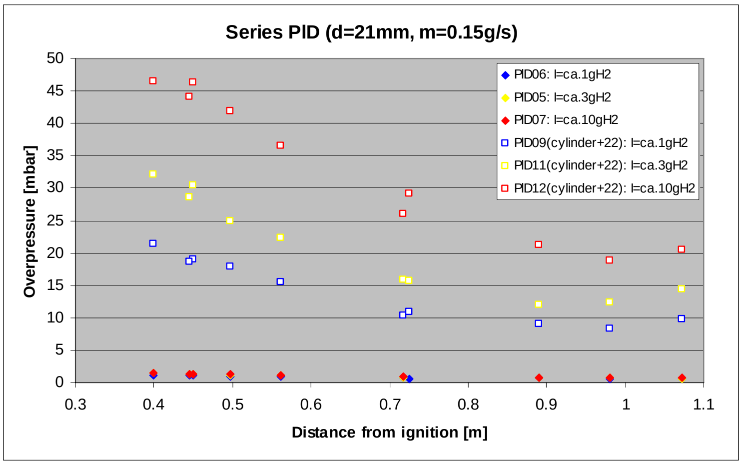


Figure 24: Measured combustion overpressures for experiments (medium nozzle, same release rates but three different H_2 inventories) without and with the cylinder as flame acceleration device.

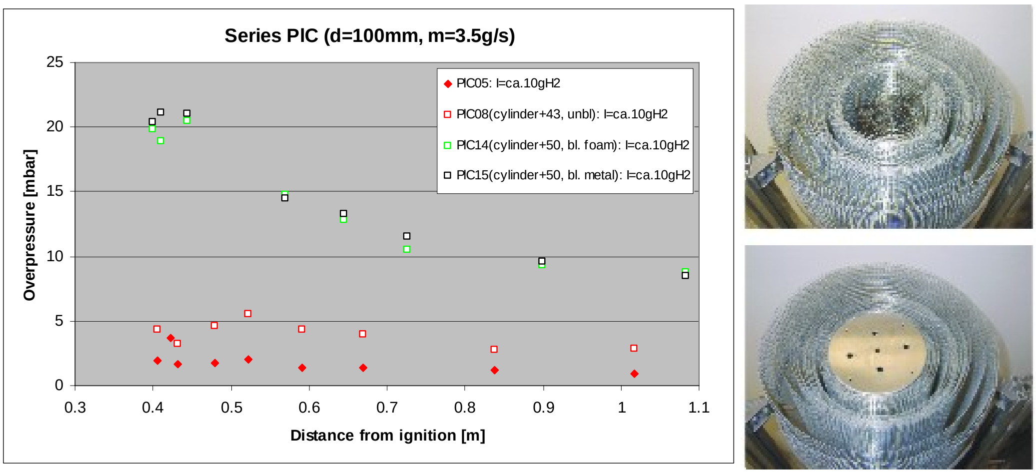


Figure 25: Measured combustion overpressures for experiments without and with the cylinder as flame acceleration device (large nozzle, same release rates and same H_2 inventories, blocked and unblocked cylinder) and photographs of the unblocked and blocked cylinder.

For the large nozzle with high release rates (m = 3.5 g/s) an other behavior can be observed: With the maximum inventory of 10 g(H_2) only a small difference between measurements with and without flame acceleration device can be observed. Due to the high exit velocity the released hydrogen possibly travels through the almost unblocked centre of the cylinder without being mixed or accumulated in the device. When this chimney inside the cylinder is blocked either by some foam plastic or metal sheet at its bottom (Fig. 25, right), turbulence is generated, leading to much higher combustion pressures. Figure 25 (left) shows the combustion overpressures measured in the experiments with this configuration.

Due to the high exit velocity and the blockage at the bottom of the cylinder directly above the nozzle, much hydrogen is reflected and diluted to a non flammable concentration. So in the experiments with the high release rate of 3.5 g(H_2)/s and the blocked cylinder smaller maximum overpressures of ≈ 20 mbar, compared to ≈ 45 mbar for lower release rates, were measured for the same hydrogen inventory.

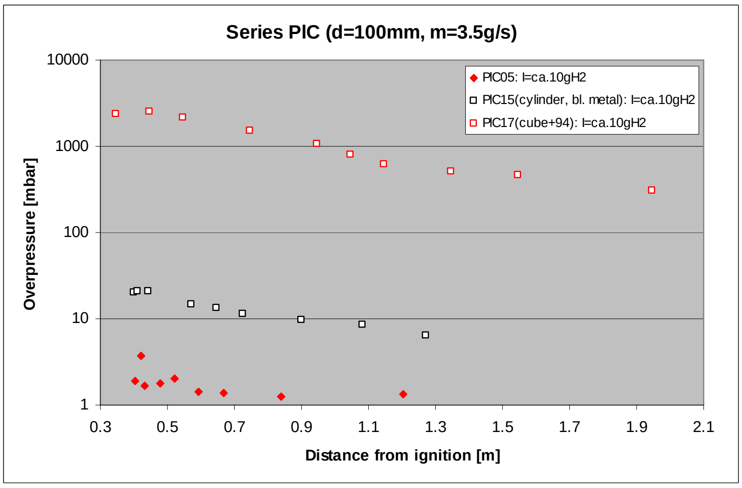


Figure 26: Comparison of maximum overpressures measured in experiments (large nozzle, release rate: 3.5 g(H_2)/s, inventory: ca. 10 g H_2) without and with different flame acceleration devices (logarithmic pressure scale).

To achieve higher combustion pressures with this experimental setup another flame acceleration device was used. Figure 26 compares the maximum overpressures measured in experiments with the large nozzle, a release rate of 3.5 g/s and an inventory of ca. 10 g H_2, without and with different flame acceleration devices. In experiment PIC15 the cube flame acceleration device was positioned centrically above the release nozzle with its upper face directly below the plate (lower face in a height of 0.94 m above the nozzle).

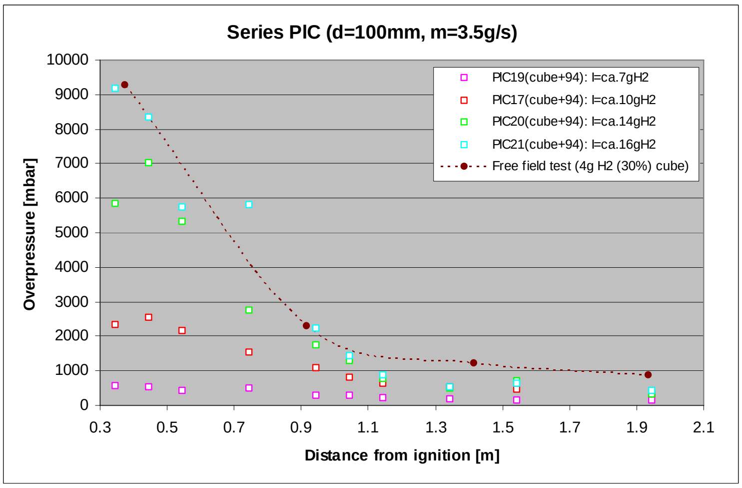


Figure 27: Comparison of maximum overpressures measured in current experiments (large nozzle, release rate 3.5 g(H_2)/s, different inventories, cube as flame acceleration device) with a free field experiment with the same cube, filled with a stoichiometric H_2-air mixture of 4 g H_2.

In the experiment with the cube as flame acceleration device, a maximum overpressure of ca. 2.5 bar was measured. This corresponds to an increase of the maximum pressure with a factor of 1000 compared to the configuration without obstacles and a factor of 100 compared to the experiment with the blocked cylinder. In further experiments with the cube the amount of hydrogen released into the test chamber was increased close to the maximum amount the chamber is allowed to contain (16 g H_2). Figure 27 compares all these data with the data measured during a free field experiment, where the same cube was filled with a stoichiometric hydrogen-air mixture of 4 g H_2 (ca. 30% H_2 in air).

Similar maximum overpressures were also reached in experiments with the medium nozzle as Figure 28 demonstrates. In these cases the maximum H_2-inventory was ca. 10 g, but nevertheless maximum pressures of more than 5 bar were measured, when the cube was placed directly below the plate. When it was placed 0.4 m lower, much lower maximum combustion pressures were measured. This indicates that large part of the hydrogen is accumulated directly below the plate.

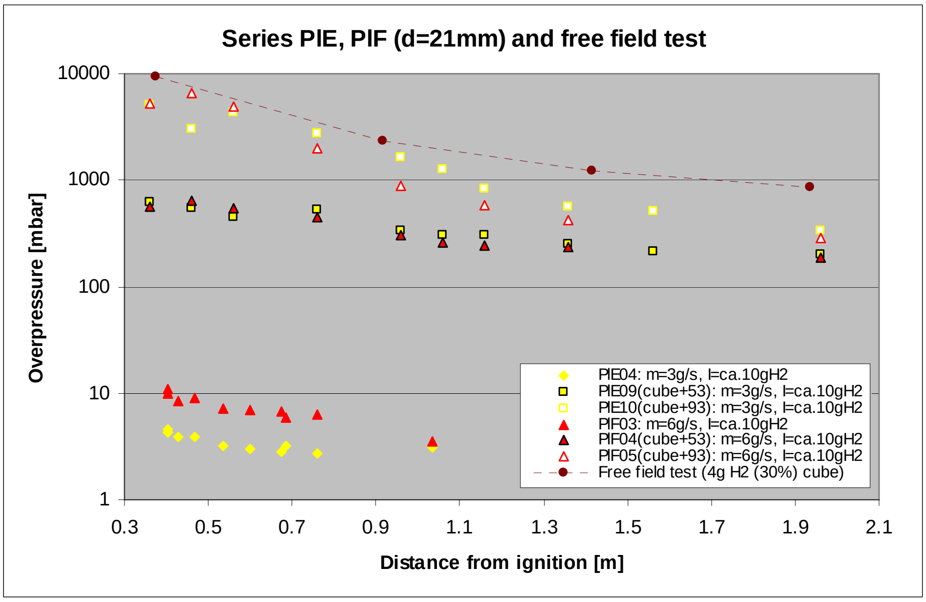
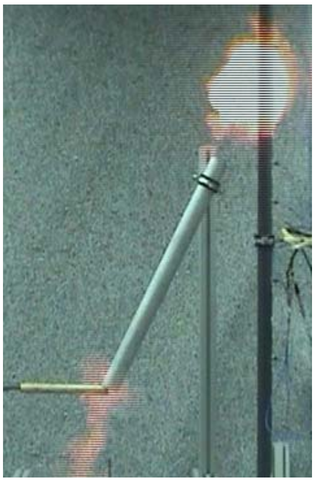


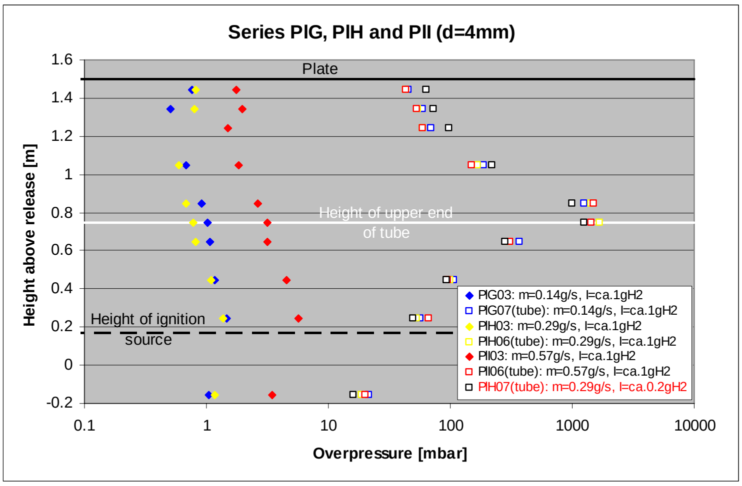
Figure 28: Comparison of maximum overpressures measured in current experiments (medium nozzle, different release rates, inventory: ca. 10 g H_2, cube as flame acceleration device at different heights) with a free field experiment with the same cube, filled with a stoichiometric H_2-air mixture of 4 g H_2 (logarithmic pressure scale).

As the figures 27 and 28 show, the ignition of ca. 10 to 16 g H_2 released into a geometry, which is obstructed by a cube with grid net layers, produces similar combustion pressures as they were measured in a free field experiment, where same the cube was filled with a stoichiometric hydrogen-air mixture of 4 g H_2.

In the experiments with the small nozzle, the tube flame acceleration device was used. The left side of Figure 29 shows a photograph of the ignition of the released hydrogen in experiment PlI6, with a release rate of 0.57 g(H_2)/s and an inventory of ca. 1 g H_2. The right side of this figure shows a comparison of pressure measurements in experiments with and without the tube as flame acceleration device. Due to the small volume of the tube (ca. 900 ml), only experiments with low inventories (≤ 1 g H_2) were performed.

In the experiments without the tube, the maximum combustion overpressure was measured by the pressure transducer in the closest distance to the ignition source. Due to the use of the flame acceleration device, this maximum is shifted to the pressure transducer which has the closest distance to the upper end of the tube. Maximum pressures of more than 1 bar were measured in the experiments with the flame acceleration device. These maximum pressures are more than 100 times higher than those measured without the tube and show only little variation. This leads to the conclusion, that no matter which release rate is used, the tube is filled with similar hydrogen concentrations.





PlI06
m = 0.57 g/s, H_{ign} = 0.17 m,
Inventory (H_2): ca. 1 g

Figure 29: Photograph of the ignition sequence of an experiment with the tube as flame acceleration device (left) and comparison of pressure measurements with and without the tube as flame acceleration device (logarithmic pressure scale)(right).

As the pressure values of the experiment PlH07 with a hydrogen inventory of ca. 0.2 g show, even smaller amounts of released hydrogen do not change the value of the maximum pressure significantly. Under normal conditions the inventory of 0.2 g H_2 corresponds to a volume of more than 2 liters which is more than twice as much as the volume of the tube. With respect to the fact that the highest combustion pressures are achieved in the ignition of a stoichiometric hydrogen-air mixture that contains only about 30 Vol.-% H_2, it can be assumed, that even lower hydrogen amounts of less than 0.1 g (corresponding to volumes of less than ca. 1 liter), are capable of producing combustion pressures of about 1 bar under these conditions.

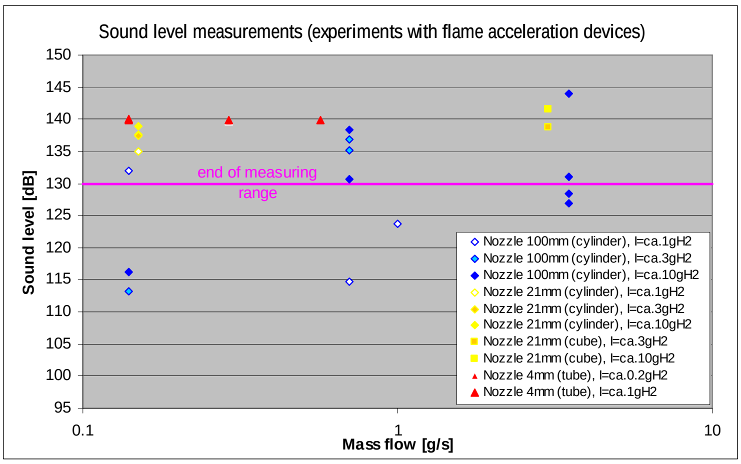


Figure 30: Sound level measurements for the experiments with flame acceleration devices (values of more than 130 dB(A) are not reliable due to limited measuring range; they are only included to demonstrate that this value was exceeded).

Sound level measurements in a horizontal distance of 3 m from the ignition source were also performed for the experiments with the flame acceleration devices. To protect the sound level meter, no measurements were conducted in experiments where very high pressures were expected in advance. Since the sound level meter has a limited measuring range that ends at 130 dB(A), values above this margin are not reliable but clearly show that this value was exceeded. Figure 30 shows the results of these measurements.

As expected, by far the most of the measured sound levels are higher than those for the experiments without flame acceleration devices, where maximum sound levels of about 120 dB(A) were measured. Comparable values below 130 dB(A) were only measured for experiments with the cylinder as flame acceleration device with low inventories or low mass flows.

Combustion experiments in configuration 2 (horizontal plate with sidewalls). For the configuration with additional sidewalls also combustion experiments were conducted. Due to the reasons mentioned above only experiments with an inventory of 10 g hydrogen were performed. The number of these combustion experiments is limited and no flame acceleration devices were used, since the construction of the sidewalls is not stable enough to withstand larger combustion events.

The combustion experiments performed in configuration 2 are summarized in Figure 31. Two different ignition positions were used in these experiments: one within the hood in a height of 1.2 m above the release nozzle (Fig. 31, left), and one below the hood in a height of 0.8 m above the release nozzle (Fig. 31, right). Additionally, if possible, measurements with similar settings without additional sidewalls are also depicted for comparison.

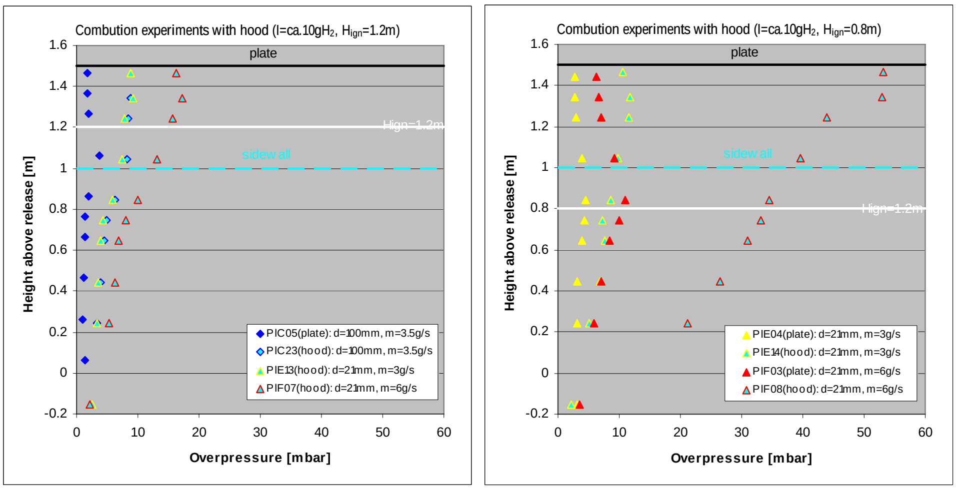


Figure 31: Maximum overpressures measured in the combustion experiments with additional sidewalls with a height of ignition of 1.2 m (left) and 0.8 m (right).

The vertical pressure profiles for the measurements with the additional sidewalls show a different shape than the ones with the plate only. In the experiments without the sidewalls, the maximum pressures were measured in a height close to the height of the ignition by the pressure sensor in the closest distance to the ignition. In the experiments with the sidewalls, the highest maximum pressures were recorded at positions close to the plate inside the hood, independent of the position of the ignition. The reason for this behavior is that a larger amount of hydrogen is retained in burnable concentration inside the hood.

4.0 SUMMARY

In the scenarios analyzed, a limited amount of hydrogen, possibly enclosed in the pipes and the engine of a faulty hydrogen powered vehicle, is accidentally released. The study investigates the hazard potential of this limited amount of hydrogen when it is released into an almost open geometry with no additional venting, traveling upwards as free jet until it either reaches a horizontal plate, is accumulated in a hood above the release or penetrates a porous system on its way upwards.

Based on the discussion of possible realistic hydrogen release scenarios a test matrix was developed, covering a wide range of release rates and exit velocities. Hydrogen release scenarios of up to 10 g hydrogen through one of three different nozzles with release times from 1 to 70 s into a low confined ambience were investigated.

In 33 experiments the concentration distribution and the shape of the free jet H_2 cloud was determined via concentration measurements. The hydrogen concentrations measured in vertical direction along the axis of the jet can be described by mathematical functions, the measured horizontal hydrogen concentration profiles of the jet exhibit the shape of Gaussian distribution functions. Furthermore the possibility of an accumulation of the released hydrogen in a hood above the jet was investigated. Additionally the experiments concerning the hydrogen distribution behavior were supplemented by Background-Oriented-Schlieren (BOS) photography.

In 81 combustion experiments pressure and sound level measurements were performed for the scenarios described. The ignition of the released hydrogen was initiated in positions along the axis of the release, where concentrations of about 30 Vol.-% H_2 (almost stoichiometric concentration) were determined in the distribution experiments. Due to the ignition of the undisturbed free jet a maximum overpressure of 11.1 mbar was detected by the pressure gauge in the closest distance (0.403 m) to the ignition source, with a maximum sound level of 121 dB(A) in a distance of three meters from the ignition (experiment PlF03). In the experiments where a hydrogen accumulation in a hood above the release was investigated, a maximum overpressure of 53.2 mbar was measured by the pressure gauge at the highest position inside the hood in a distance of 0.78 m to the ignition, with a maximum sound level that exceeded the measuring range of the sound level meter (130 dB(A)) in a distance of three meters from the ignition (experiment PlF08).

In the experiments, where grid net layer structures were used as flame acceleration devices to simulate porous materials in the vicinity of the hydrogen source, a maximum overpressure of 9176 mbar was recorded by the pressure sensor in the closest distance (0.345 m) to the ignition, while a maximum overpressure of 410 mbar was measured by the pressure sensor in the largest distance of 1.945 m to the ignition (experiment PlC22). In this experiment no sound level measurements were performed to protect the sound level meter.

The current work provides an extensive data base for the validation of numerical codes, used to simulate the distribution behavior and combustion loads of hydrogen free jets. It is intended to help evaluating the hazard potential of hydrogen free jets in the safety assessment of future hydrogen applications.

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