A New Technology for Hydrogen Safety: Glass Structures as a Storage System

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ABSTRACT

The storage of hydrogen poses inherent weight, volume and safety obstacles. An innovative technology which allows for the storage of hydrogen in thin sealed glass capillaries ensures the safe infusion, storage and controlled release of hydrogen gas, under pressures up to 100 MPa. Glass is a non-flammable material which also guarantees high burst pressures. The pressure resistance of single and multiple capillaries has been determined for different glass materials. Borosilicate capillaries have been proven to have the highest pressure resistance and have therefore been selected for further series of advanced testing. The innovative storage system is finally composed of a variable number of modules. As such, in the case of the release of hydrogen this modular arrangement allows potential hazards to be reduced to a minimum. Further advantage of a modular system is the arrangement of single modules in every shape and volume dependent on the final application. Therefore the typical locations of storage systems, e.g. the rear of cars, can be modified or shifted to places of higher safety and not directly involved in crashes. The various methods of refilling and releasing capillaries with compressed hydrogen, the increase of burst pressures through pre-treatment, as well as the theoretical analysis and experimental results of the resistance of glass capillaries will further be discussed in detail.

1.0 INTRODUCTION

Hydrogen is one of the most promising fuel sources of all alternative fuels. Technologies are currently being developed which produces hydrogen with high efficiency, e.g. high pressure water electrolysis or extraction from air. Thereby the largest disadvantage of hydrogen is its gaseousness. As one of the lightest chemical elements its power density is very low at natural conditions. In order to use hydrogen as efficient source of energy, the gas must therefore be compressed, chemically bound or liquefied at very low temperatures. But a crucial problem of new hydrogen technologies is the lightweight and also safe storage for portable, mobile or stationary applications in reasonable amounts to assure consumers acceptance of this energy source. An innovative and new technology is the storage of hydrogen in thin sealed glass capillaries which ensures the safe infusion, storage and controlled release of hydrogen gas at pressures up to 100 MPa. The capillaries are molten at one end, the other one will be closed in a specialized storing procedure with an alloy for long time storage. For the release of hydrogen this end has to be heated up to the melting point of the alloy. Another method to close the open end of the capillaries is a connection to a micro valve to enable also in-situ filling and release procedures in mobile applications and short time storage.

The principle is also valid for a bundle of a varied number of capillaries. There is no limitation in number or length of the capillaries as well as the dimension of the whole storage system. Therefore the storage system is useable for any kind of mobile, portable or stationary application.

The great advantage of glass is the higher strength and the lower weight compared to steel. So there is only a low wall thickness necessary to reach a high pressure resistance and less material is needed. This is especially important by using this system for mobile applications.

The safety aspects are also of great interest because an unwanted release of a fuel can lead to dangerous situations. The same applies in case of hydrogen use. A release can be caused by diffusion through the wall material of the storage system or a mechanical impact from outside. Also heat or fire

are critical for each kind of storage system and may cause a danger. For a first basic safety study these situations have been examined or theoretically evaluated for this new storage system.

2.0 STORAGE PRINCIPLE

Storing hydrogen in glass capillaries can be realized by two different filling and closing procedures dependent on the application or the planed storage period. In both cases, the capillaries are closed at one end by melting.

The first method is especially for short time storage and applications where hydrogen has to be provided quickly and/or alternating. The glass structure made of a various number of capillaries is connected to an adapter with a special micro valve. This micro valve is a commercial available component, which is driven electro-magnetic with very short opening and closing times. A small pre-volume connected to a pressure sensor guarantees the necessary operating pressure and volume flow to the application. The release of hydrogen can be realized very fast with different flows and pressure ratios and can be stopped immediately. By using this method of closing it is also possible to realize an in-situ filling without disconnection from the application. The first step of storage procedure is the connection of the micro valve to the filling station. After evacuation of the system the hydrogen is filled into the glass structure up to the desired storage pressure. The micro valve is closed and the storage system disconnected it from the filling station. The storage procedure is finished and the application ready for use.

The second closing method is realized by using a special low-melting alloy to close the open end. Single capillaries or already bundled capillaries (arrays) are placed in a larger pressure resistant vessel made of stainless steel. The setup is pressure resistant up to pressures of more than 200 MPa. The first step is to evacuate the setup. Afterwards the hydrogen is filled into the vessel and the capillaries till the storage pressure is reached. This storage pressure is a flexible parameter and can be changed. After heating up the system to a specific temperature the alloy is melting and closing the open end of the capillaries. In a specialized procedure the alloy is slightly pressed into the capillaries. By cooling the system the alloy is solidified and hydrogen stored in capillaries. The release procedure is carried out vice versa. Heat is applied to the alloy-closed end of capillaries till it melts. Due to the high pressure inside of the glass capillaries the alloy is pushed out and hydrogen is released. Pressure control will be realized by opening only specific areas of the arrays and by volume specifications. The heating rate is also a parameter influencing the opening of the arrays.

3.0 PRESSURE RESISTANCE

There are already material properties of glasses to find in the literature [2, 3, 4], but necessary properties to evaluate the resistance of glasses when pressure is applied to the inside of small glass tubes are scarcely to find. Therefore many examinations have been carried out to determine the pressure resistance of various glass capillaries made from different glass materials. In a first test phase the outer and inner diameter, the wall thickness, the type of glass and the length were varied (Table 1).

The second test phase was attended to different wall thicknesses by having fixed ratios of outer and inner diameter. The thinner the capillaries the thinner is the wall thickness. In theory the defects in glass will be reduced with the reduction of the wall thickness and therefore the strength should be increased. Three different diameter ratios were tested with a high number of various diameters. The length was fixed to 200 mm and only capillaries made of borosilicate were tested (Table 2).

In the third test phase the pressure resistance of glass capillaries with different pre-treatments was determined. The main interest was the influence of various numbers of pressure applications on the pressure resistance of glass structures. Furthermore the influence of the duration of a pressure application was also important with regard to long time storage of hydrogen.

In a final test phase pre-treatments of the glass capillaries with different gases and their influence to the pressure resistance was determined.

Table 1: Glass capillaries used for first pressure resistance tests

No.	Material	outer diameter [μm]	inner diameter [μm]	wall thickness [μm]	length [mm]
1	soda	400	300	50	100
2	soda	340	300	20	100
3	borosilicate	400	360	20	100
4	borosilicate	340	300	20	100
5	borosilicate	400	360	20	200
6	borosilicate	340	300	20	200
7	alumosilicate	400	300	50	100
8	alumosilicate	340	300	20	100
9	alumosilicate	400	300	50	200
10	alumosilicate	340	300	20	200
11	quartz	400	300	50	100
12	quartz	340	300	20	100
13	quartz	400	300	50	200
14	quartz	340	300	20	200

Table 2: Glass capillaries with different diameter ratios used for pressure resistance tests

No.	Diameter Ratio	outer diameter [μm]	inner diameter [μm]	wall thickness [μm]
1	1.33	300	225	37.5
2		350	263	43.5
3		400	300	50
4		450	338	56
5		750	563	93.5
6		1400	1050	175
7		1650	1236	207
8		2300	1725	287.5
9	1.25	150	120	15
10		200	160	20
11		250	200	25
12		300	240	30
13		370	296	37
14		500	400	50
15		750	600	75
16		950	760	95
17		1500	1200	150
18	1.15	300	263	18.5
19		350	303	23.5
20		600	520	40
21		650	563	43.5
22		860	745	57.5
23		100	867	66.5
24		2000	1730	135
25		3750	3250	250

In difference to the first four test phases where single capillaries were examined another test series with bundled capillaries (arrays) were carried out, too. Main focus was again the pressure resistance of these systems and the determination of possible interactions between the capillaries during pressure load. Different types of arrays made of borosilicate were tested. The number of capillaries was varied and, for optimization of weight and strength, different arrays with and without interspaces between the capillaries were manufactured.

3.1 Experimental Set-up

The single capillaries were glued into small 1/16“ stainless steel tubes in order to connect them to the high pressure set-up. The set-up is consisting mainly of a gas supply, a vacuum pump, an air-driven compressor with downstream buffer volume and the connectors to the capillaries. Figure 1 presents a schematically view of the used set-up.

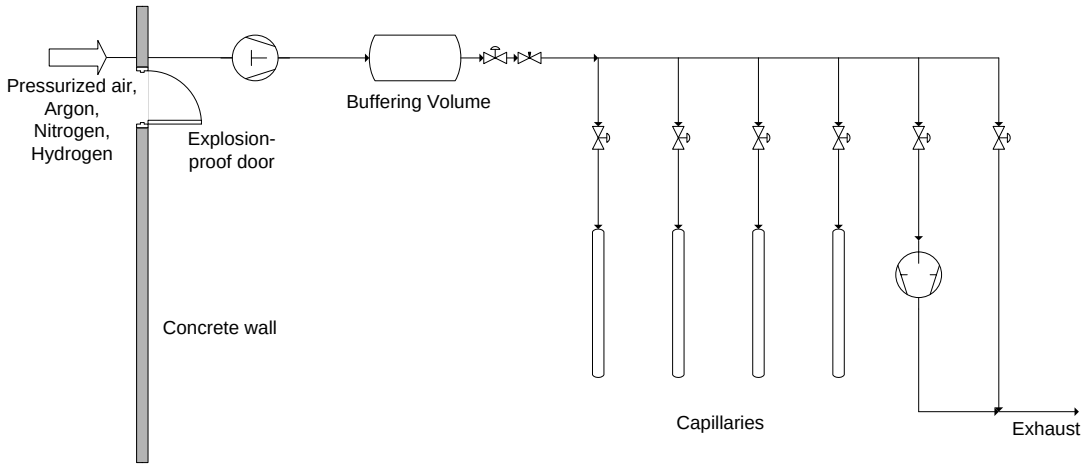

Figure 1: Schematically view of the set-up for the for glass capillaries pre-treatment and pressure resistance tests

For safety reasons the set-up was arranged into two parts each located in a separate room. Especially the high-pressure equipment like compressor, buffering volume as well as the capillaries were installed in the safety room and could be evacuated, filled and vented separately by remote control. The device for handling the different gases and the data acquisition system were arranged with a test stand in the pre-room.

The first step for every test was to evacuate the experimental set-up. Afterwards the desired gas was filled into the capillary by using the two stage compressor, capable for pressures up to 150 MPa. For dumping each cylinder stroke of the compressor the buffer volume was installed between the compressor and the capillaries. Therefore it was possible to fill the buffer up to a specific pressure first and to lead over the gas to the capillary afterwards with a constant flow. Next to the capillaries a pressure transducer was installed connected to an A/D-converter (company Jet Systemtechnik GmbH, Typ MCL-USB, 16 channels 16 Bit A/D, sampling frequency 500 kHz) and a computer. All pressure-time histories were measured and stored digitally. Furthermore a heating device and a corresponding thermocouple were installed to guarantee constant and reproducible temperature conditions during the experiments. The signals were recorded with the same data acquisition system, too.

The main interest in test phase one and two was the pressure resistance of the single capillaries determined by their burst pressures. Different filling speeds were realized and the compressed gas was varied in a huge number of examinations. The gas was filled to the capillaries till they broke.

Test phase three was attended to the increasing of the pressure resistance of single capillaries. Therefore different pre-treatments were carried out by using types of capillaries with known pressure resistance and burst pressures. Compressed air, free from oil and moisture, was filled repeatedly in the capillaries up to a pressure of 50 MPa. After reaching different numbers of pressure applications the burst pressures were determined. In addition to that, also tests with variable durations of pressure load were carried out. Therefore the described procedure was used, but gas was not filled up repeatedly but for different residence times. After achieving this time the burst pressures were determined, too.

3.2 Results

The burst pressures of the single capillaries tested in the first phase are summarized in Table 3. The highest and the lowest burst pressure of every tested type of capillary are shown as well as the average values determined from at least five pressure tests for each type of capillary.

The results did not show any clear dependency and led to the impression that the material and the wall thickness did not influence to the pressure resistance of single capillaries. According to the tensile strength of the tested materials the highest burst pressure was to expect for quartz glass. But capillaries made from borosilicate glass respectively soda glass have also been able to withstand pressures of more than 100 MPa. The highest burst pressure (124.2 MPa) and the highest average value was determined for borosilicate capillaries with a wall thicknesses of 20 µm. The dispersion about the average value is much smaller than for any other glass capillaries.

Table 3: Burst pressures of capillaries made from different materials with different length, diameters and wall thickness (test phase one, determined at 20 °C)

No.	Material	burst pressure in MPa		
		average value	highest value	lowest value
1	soda 100 mm; 400x300	82.7	114.7	25
2	soda 100 mm; 340x300	44.1	54.3	34.1
3	borosilicate 100 mm; 400x360	36	49	27.3
4	borosilicate 100 mm; 340x300	33.9	49.7	24
5	borosilicate 200 mm; 400x360	100.2	124.2	73.7
6	borosilicate 200 mm; 340x300	29.3	40.1	22.3
7	alumosilicate 100 mm; 400x300	48.4	59.1	35.1
8	alumosilicate 100 mm; 340x300	32.8	44.1	19.5
9	alumosilicate 200 mm; 400x300	46	53.5	42.1
10	alumosilicate 200 mm; 340x400	44.3	62.7	32.6
11	quartz 100 mm; 400x300	84.2	98.9	69.4
12	quartz 100 mm; 340x300	49.6	61.4	39.3
13	quartz 200 mm; 400x300	89	109.1	39.4
14	quartz 200 mm; 340x300	38.2	56.2	14.6

The variation of the wall thicknesses by fixing the ratio of outer to inner diameter was determined in test phase two. Only capillaries made of borosilicate were used due to the results of test phase one. Capillaries with three different outer to inner diameter ratios of 1.33, 1.25 and 1.15 were tested, whereby the dimensions were varied and therefore the wall thickness varied, too. The tests were carried out ten times for every type of capillary. Table 4 summarizes the used capillaries and the corresponding pressure values.

In theory, the tensile strength of glass fibers will increase with decreasing diameter [5]. This assumption is based on the fact that with decreasing diameter the probability of defects is reduced

severely. The effect should also be verifiable at capillaries due to the fact that capillaries are hollow fibers and should show similar characteristics also at pressure resistance tests.

Table 4: Burst pressures of borosilicate capillaries with three different outer to inner diameter ratios and different wall thicknesses (determined at 20 °C)

No.	Diameter ratio	Dimension in µm	burst pressure in MPa		
			average value	highest value	lowest value
1	1.33	300x225	42	49.4	30
2		350x263	106	120	89.7
3		400x300	100	116	78.3
4		450x338	82	108	52
5		750x563	59	78.4	37.7
6		1400x1050	51	64.2	33.7
7		1650x1236	42	53.8	33.8
8		2300x1725	36	50	26.1
9	1.25	150x120	65	86	52
10		200x160	70	78	61
11		250x200	79	94	54
12		300x240	88	101	77
13		370x296	70	83	52.4
14		500x400	69	81.2	34.5
15		750x600	46	64.2	25.2
16		950x760	41	55.9	27.3
17		1500x1200	37	52.1	27.3
18	1.15	300x263	44	48.9	40.1
19		350x303	58	69.3	40.2
20		600x520	31	41.4	20.9
21		650x563	64	81.5	51.3
22		860x745	27	33	21.8
23		1000x867	31	40.2	24.7
24		2000x1730	19	23.4	14.1
25		3750x3250	16	20.8	12

In Figure 2 the average burst pressures in dependence of the final wall thickness for the three different outer to inner diameter ratios are plotted. With decreasing wall thickness the average burst pressure increases. For wall thicknesses of 30 µm to 45 µm the highest burst pressures were detected. Continuing the reduction of the wall thickness causes a decreasing pressure resistance. The actuator for the inordinate trend for the diameter ration of 1.15 between 25 µm and 50 µm and the resulting fluctuation of the pressure resistance is unknown at the moment.

The highest average burst pressures have been detected for a diameter ratio of 1.33. That is an effect of the inner volume of the capillaries. It can be explained with the calculation formula for cylindrical, thin-walled vessels

$$\sigma_t = p\ d / 2\ s\ , \qquad (1)$$

where σ_t – tangential stress in the wall, N/m², p – pressure, Pa, d – diameter, m, s – wall thickness, m.

With decreasing ratio between outer and inner diameter and a fixed wall thickness s, the diameter d of the capillaries is increasing. The resulting tangential stress σ_t is much higher and so the pressure resistance is decreasing by reducing the diameter ratio.

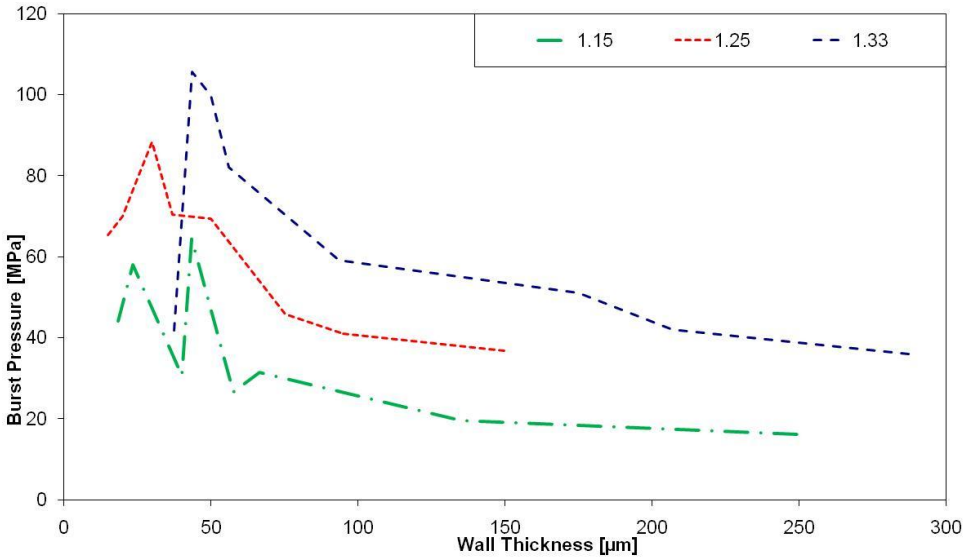

Figure 2: Average burst pressures in dependence of the wall thickness of capillaries with three different diameter ratios

The third test phase was to examine the influence of pre-treatments on the pressure resistance of the capillaries. For all tests reported so far the burst pressures were determined directly after connecting the capillaries to the experimental setup. As pre-treatments a periodic pressure load of 50 MPa as well as different residence times of 50 MPa to the capillaries and pre-treatments with different gases have been chosen.

Periodic tests were carried out with borosilicate and quartz capillaries (400 µm outer and 300 µm inner diameter). The capillaries were loaded up to 100 times with 50 MPa of clean and dry air before determining the burst pressure. In Figure 3 the burst pressures for different numbers of pressure loads determined for quartz and borosilicate capillaries of the same dimensions are shown. Each bar represents the lowest burst pressure and the highest pressure determined in the test series. The average values are plotted as symbols. For both glasses the burst pressure increases with the number of pressure loads and reaches a maximum average value after 50 applications for borosilicate and 30 applications for quartz. Another important fact is that the afterwards decrease of the burst pressure did not lead to values lower than the burst pressure without pre-treatment. This result was validated for burst pressures determined after 100 pressure applications.

In order to determine the burst pressures in dependency of the residence times a constant pressure load of 50 MPa was applied to the capillaries. Due to the influence of temperature and humidity these tests were carried out at two temperatures of 40 °C and 100 °C. Figure 4 shows the curves of the average burst pressures of the tests carried out at 40 °C. The upper curve presents the results for nitrogen. At 30 minutes of pressure load the resistance of the single capillaries decreases under the value for un-treated capillaries, at 60 minutes of pressure load, the burst pressure has the same value as like as new and untreated capillaries. The lower curve presents the results for nitrogen loaded capillaries thereby the burst pressures were determined with hydrogen. At 5 minutes of pressure load the highest burst pressure were detected. By increasing the duration of pressure load the burst pressures are decreasing. The value was never lower than for new, untreated capillaries.

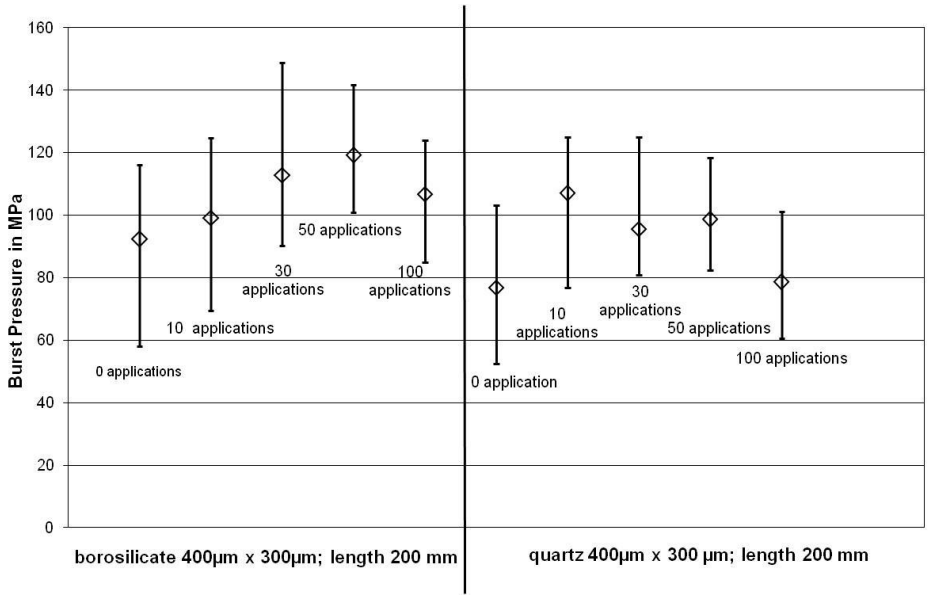

Figure 3: Burst pressures of single capillaries made from borosilicate (left) and quartz (right) determined after periodic pressure applications

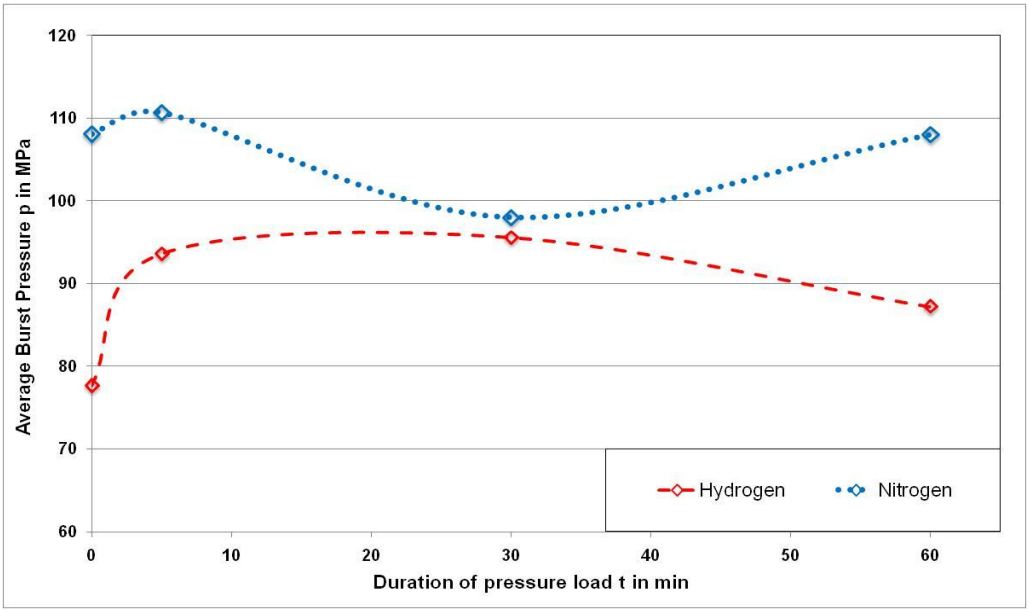

Figure 4: Burst pressures of single borosilicate capillaries in dependence of the residence time for the constant pressure loads (50 MPa, 40 °C)

The average burst pressures for the tests carried out at 100 °C are plotted in Figure 5. The lower curve presents the results for nitrogen pressure loads, whereby the burst pressures were determined nevertheless with hydrogen. The upper curve represents the results determined with nitrogen. As overall trend it turned out that the burst pressures increases with increasing the time for which the pressure is applied to the capillaries. Finally an enhancement of up to 20 MPa is possible compared to non-treated "basic" capillaries. Furthermore the burst pressures determined for nitrogen pressure loads is much higher compared to non-treated capillaries as well as to those loaded with hydrogen.

The differences between the results at 40 °C and at 100 °C are not plausible. It can be coherence between transport conditions, handling or the influence of the temperature. The correct actuator of that behavior is not known at the moment and has to be determined in prospective examinations.

The tests can be summarized that borosilicate capillaries already show a high pressure resistance when pressure is applied to the inside. Burst pressures are higher e.g. than for quartz although quartz has the larger tensile strength. Furthermore the pressure resistance of the single glass capillaries can be increased if various pre-treatments are carried out.

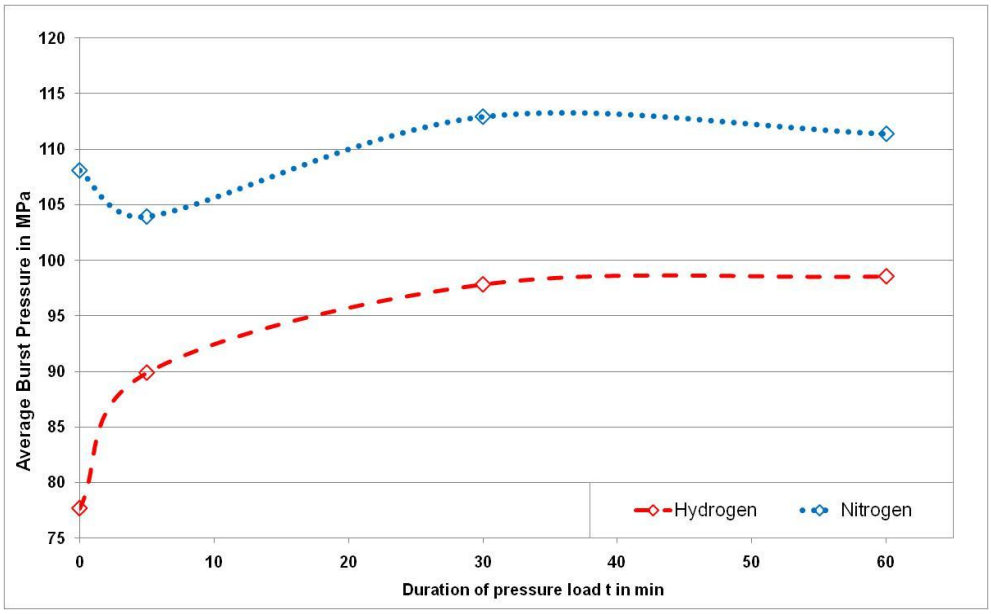

Figure 5: Burst pressures of single borosilicate capillaries in dependence of the residence time for the constant pressure loads (50 MPa, 100 °C)

First tests with the bundled capillaries or arrays have also been carried out. Thereby it turned out that there are some specific problems related to the bundling of single capillaries and if there are interspaces between them (Figure 6). The left picture is taken from an array with round capillaries with partially filled interspaces. On the right picture an array with hexagonal capillaries and without interspaces are shown. Furthermore the presence of an outer shell is of importance and can affect the pressure resistance (Figure 7).

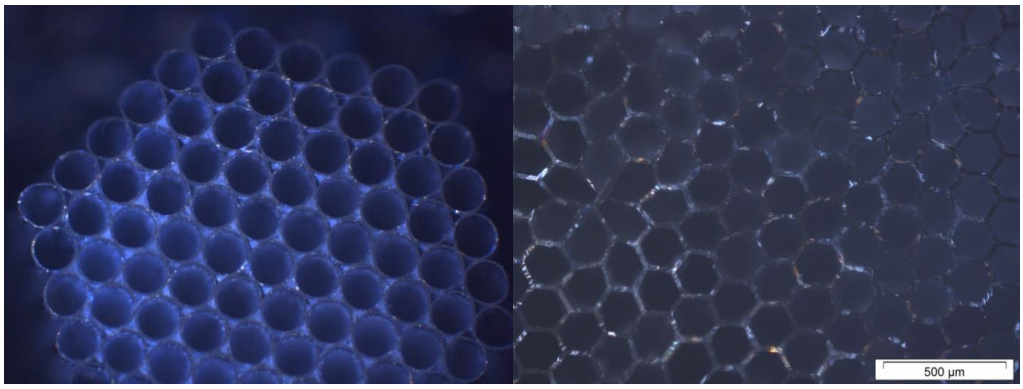

Figure 6: Bundled round capillaries with partially closed interspaces (left); bundled hexagonal capillaries without interspaces

Up to now different types of arrays were tested. The outer diameter of the outer shell was fixed to 4 mm in order to glue them most efficiently to a ¼`` stainless steel pipe. The number of capillaries varied from 70 up to 370. Determining again the burst pressures of these arrays led to a maximum value of 117.3 MPa for an array where round capillaries were bundled and the interspaces were also filled with borosilicate.

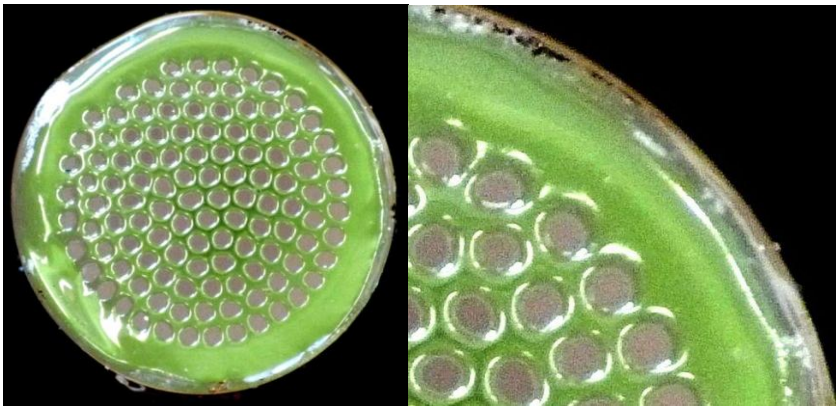

Figure 7: Bundled capillaries (array) made from borosilicate; interspaces also filled with borosilicate; maximum burst pressure 117.3 MPa

There are further open questions and the main focus for future will be in testing arrays to increase the pressure resistance and, at the same time, to optimize the structures regarding weight.

4.0 SAFETY EVALUATION

First basic and theoretical safety evaluations have been carried out on basis of a first demonstrator (Figure 8). Main focus was the determination of possible hydrogen releases and what critical situation can occur due to these releases. The demonstrator in bench-scale was designed for showing the feasibility of storing hydrogen in glass arrays and was not optimized in terms of weight or handling. It contains three arrays with an outer diameter of 4 mm, the open ends are equipped with a wire as heating supply for melting the alloy at release procedure.

In case of hydrogen releases from such a demonstrator it has to be differentiated between sudden and slow release. A slow release means in this case losses of hydrogen by permeation through the capillaries. A sudden release always occurs when the structure itself is damaged by material defects or an impact from outside. In the following the different scenarios are evaluated regarding the possible hazards arising due to the release of hydrogen.

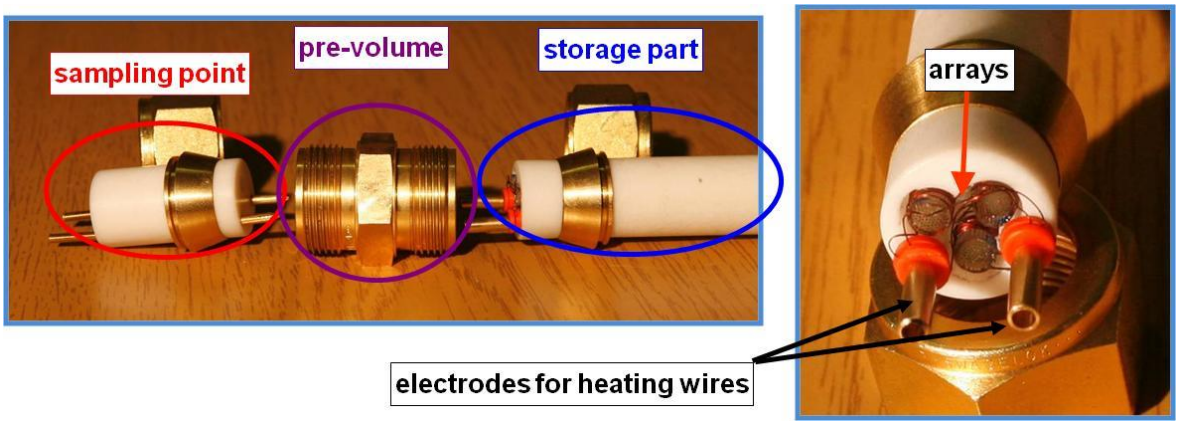

Figure 8: Demonstrator in bench-scale with three storage arrays, a special alloy is used for closing

4.1 Permeation

The permeation of hydrogen is an important fact which has to be analyzed accurately by using glass as storage material. This effect is much lower than the permeation of hydrogen e. g. through steel. Nevertheless it has to be evaluated if hydrogen can be released by permeation in amounts that will lead to an explosive atmosphere. Therefore the influence of the closing system can be neglected. The permeation process is dependent on the temperature and the pressure inside of the capillaries. In

literate it is reported that no permeation was observed through various glasses at pressures of 0.1 MPa and temperatures of 640 °C [6]. At room temperature and pressures of 10 MPa also no permeation was observed for quartz glass [7]. Due to less information in the literature first examinations with borosilicate capillaries were carried out. For this purpose single borosilicate capillaries were load with hydrogen for five days at 20 MPa and 200 °C. The amount of permeated hydrogen was determined finally by vacuum hot extraction (Figure 9). The upper curve presents the hydrogen absorbed by the surface of open capillaries. The lower curve represents the results of evacuated and closed capillaries. In this case the peak occured when the permeated hydrogen wass released during the softening of the glass. This effect was only observed for closed capillaries.

For the final storage system ambient temperatures will be in a range of -20 °C and +60 °C. At these temperatures hydrogen releases by permeation are negligible. Of course the temperature partly can be higher at the end when the release procedure is carried out and heat is applied to the alloy. Nevertheless it is assumed that hydrogen permeation at the most critical storage conditions of 100 MPa and 100 °C is very slow and can be easily prevented by coatings at the surrounding of the capillary system. Even if hydrogen is released by permeation the amount is too small to form an explosive atmosphere.

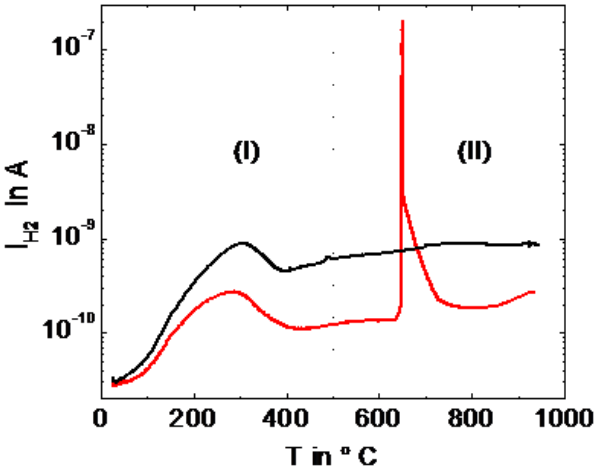

Figure 9: Permeated hydrogen at pressure load for five days at 20 MPa and 200 °C; detected with vacuum hot extraction for open (upper curve) and closed (lower curve) boroslicate capillaries

4.2 Rupture

In principle every single capillary is a pressure resistant vessel, able to withstand pressures higher than the storage pressure. Nevertheless glass is an amorphous material which can be easily damaged and break in case of an impact. The rupture of a single capillary is not that critical. By using the alloy as closing system every single capillary is isolated from the others and the released amount of hydrogen is too small to form an explosive gas mixture with the surrounding air. The installation of a micro valve as closing system implicates a network of capillaries connected to each other. The dimension of one module and the number of capillaries have a huge influence. Also the question of the number of modules, connected to one micro valve has to be examined. In this case the damage of one single capillary leads to the release of the stored amount of hydrogen. The release is limited by the sonic velocity and conditional on the small diameter of the capillary and the high fugacity of hydrogen. Therefore the probability of an explosive atmosphere is very small although a big amount of hydrogen is released. Critical might become situations in which a major number of capillaries are broken and the stored amount of hydrogen is released in a short time. That danger could be minimized by surrounding the capillary system with shock absorbing material.

Furthermore the case of fire should be evaluated and give some attention to the resistance of a glass system. Glass itself is a non flammable material. At a specific temperature glass reaches the point of softening, addicted to the type of glass. Borosilicate glass shows a softening temperature about 550 °C.

In contrast to that fact the softening temperature of quartz glass is about 1130 °C. In a normal fire quartz glass should withstand the temperature but borosilicate glass will reach the softening point and a release of hydrogen will appear. In this case not all capillaries will rupture or open at one time but one after another will collapse. The safety aspect for the closing systems in case of fire has to be examined, too. The stopper alloy will act like a safety valve because of its low melting point. The capillaries will be opened successive by melting the alloy and pushed out by inner pressure. Using the micro valve as closing system, the influence of fire is addicted to the maximum operating temperature and the cartridge seal system. That means there will be a controlled release of hydrogen, the sudden damage known from composite tanks will fail to appear.

5.0 CONCLUSIONS AND FUTURE PROSPECTS

The hydrogen storage in glass capillaries is an innovative system of trendsetting nature. In near future it might be possible to use such lightweight systems in wide fields of energy supply.

The tests carried out in the past showed, that glass is able to withstand such high pressures that are necessary to store an acceptable amount of hydrogen. The safety of such a storage system is of course very important. Basic tests and safety evaluations showed that glass structures made of a huge number of capillaries might be safer than systems with only one single vessel. If the case of a sudden release occurs of a one vessel system the whole amount of stored hydrogen will lead to a critical situation. The release out of the multi-capillary system is strongly dependent to the kind of the impact and the caused defect. The advantage of such a system is the bundling of many single capillaries each of them can be seen as single pressure vessel. If one vessel is damaged no hazardous situation is caused due to the release of only small amounts hydrogen or a decelerated release, not even the capillaries are connected to be closed by one micro valve. No overpressure appears or even spontaneous ignitions as they were observed when hydrogen was suddenly released to the atmosphere. Furthermore no explosive atmosphere is formed because the absolute amount of hydrogen was too small.

To further optimize the storage capacities over a long time, coatings for the capillaries will be developed in order to minimize hydrogen losses by permeation. Subsequently the optimized single capillaries were bundled to arrays consisting of different numbers of capillaries. These arrays were used for many safety tests. In most of them the behavior of the arrays was determined when they were mechanically damaged or heated externally by fire. In case of ruptures or damages the sudden release was noticed.

Many tests were actually carried out with single capillaries. The “numbering up” or bundling has to be examined, too. First test were carried out but there are still open questions, e.g. the strength of the capillaries in dependence of wall thickness and glass material, long term storage pressures, mechanical impact, and fire treatment of capillary arrays.

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