

Explosion Characteristics of Hydrogen-Air and Hydrogen-Oxygen Mixtures at Elevated Pressures

Schroeder, V.¹ and Holtappels, K.¹

¹Bundesanstalt für Materialforschung und –prüfung (BAM),
Unter den Eichen 87, 12205 Berlin, Germany

ABSTRACT

An essential problem for the operation of high pressure water electrolyzers and fuel cells is the permissible contamination of hydrogen and oxygen. This contamination can create malfunction and in the worst case explosions in the apparatus and gas cylinders. In order to avoid dangerous conditions the exact knowledge of the explosion characteristics of hydrogen/air and hydrogen/oxygen mixtures is necessary. The common databases, e.g. the CHEMSAFE® database published by DECHEMA, BAM and PTB, contains even a large number of evaluated safety related properties, among other things explosion limits which however are mainly measured according to standard procedures under atmospheric conditions.

Within the framework of the European research project “SAFEKINEX” and other research projects the explosion limits, explosion pressures and rates of pressure rise (K_G values) of H_2 /air and H_2/O_2 mixtures were measured at elevated conditions of initial pressures and temperatures by the Federal Institute of Materials Research and Testing (BAM). Empirical equations of the temperature influence could be deduced from the experimental values. An anomaly was found at the pressure influence on the upper explosion limits of H_2/O_2 and H_2 /air mixtures in the range of 20 bars. In addition explosion pressures and also rates of pressure rises have been measured for different hydrogen concentrations inside the explosion range. Such data are important for constructive explosion protection measures.

Furthermore the mainly used standards for the determination of explosion limits have been compared. Therefore it was interesting to have a look at the systematic differences between the new EN 1839 tube and bomb method, ASTM E 681-01 and German DIN 51649-1.

1 NOMENCLATURE

LEL	Lower explosion limit, highest concentration of a combustible substance in a fuel lean mixture with an oxidizing gas in which a flame just fails to propagate.
UEL	Upper explosion limit, lowest concentration of a combustible substance in a fuel rich mixture with an oxidizing gas in which a flame just fails to propagate.
p_{ex}	Explosion pressure, peak value of the time dependent pressure, measured in a closed vessel upon deflagration of an explosive gas mixture.
p_{max}	Maximum explosion pressure, maximum value of the explosion pressure determined by varying the fuel concentration.
$F = p_{ex}/p_0$	Pressure rising factor, explosion pressure divided by the initial pressure.
$(dp/dt)_{ex}$	Rate of pressure rise, highest value of the rate of pressure rise during a deflagration of a certain gas mixture.
$(dp/dt)_{max}$	Maximum rate of pressure rise, maximum value of $(dp/dt)_{ex}$ determined by varying the fuel concentration.
K_G	$(dp/dt)_{ex}$ related to a 1 m ³ vessel, characteristic value calculated according to the cubic law with the rate of pressure rise

2 INTRODUCTION

Hydrogen is gaining more and more significance as an alternative source of energy. Since hydrogen has a very low energy density under normal conditions (gross calorific value 3.54 kWh/m³_n compared to about 9300 kWh/m³ for liquid gasoline), it must be compressed in order to be stored as an energy

carrier. Hydrogen can be produced easily by means of electrolytic water decomposition. Conventional technologies for the electrolytic production of hydrogen are low-pressure electrolyzers up to a working pressure of 30 bars. In order to increase the energy efficiency of hydrogen production, the development of a high-pressure electrolyzer was initiated at the Research Centre Jülich [1]. In such a system there is no need for compressors and buffer tanks. Possible applications are seasonal energy storage systems, grid-connected energy buffers and decentralized fuel production. The actual operating pressure of the Jülich prototype is 120 bars. A further increase to 200 bars is planned.

An essential problem is the diffusion of gas in the diaphragm of the electrolysis cells. The product gases hydrogen and oxygen are contaminated. This contamination can create malfunction and in the worst case explosions in the apparatus and gas cylinders. For this type of electrolysis and other technical high-pressure applications as well it is necessary to have an accurate knowledge of the explosion limits. In addition to the explosion limits further explosion characteristics are important, such as explosion pressures and rates of pressure rises at certain mixture compositions. A large number of safety related properties, among them explosion limits of hydrogen, are included in the database CHEMSAFE [2] published by DECHEMA, BAM and PTB. Complete explosion diagrams of flammable gas-inert gas-oxidizer systems are given in newer data books [3]. However, these safety characteristics are mainly measured according to standard procedures under atmospheric conditions. Therefore the aim of this study was to determine the pressure influence on the explosion limits of hydrogen-air mixtures and hydrogen-oxygen mixtures up to an initial pressure of 200 bars. Furthermore explosion pressures and also rates of pressure rises should be measured for hydrogen fractions close to the explosion limits inside the explosion range. Such data are important for constructive explosion protection measures.

Another safety relevant question was the influence of the test apparatus and the test procedure on the hydrogen explosion limits at atmospheric conditions. In September 2003 a new European standard for the determination of explosion limits of gases and vapors [4] was published. Therefore it was interesting to have a look at the systematic differences between the most frequently used standard test methods, the EN 1839 tube and bomb method, ASTM E 681-01 [5] and German DIN 51649-1 [6].

3 HYDROGEN EXPLOSION LIMITS MEASURED WITH DIFFERENT STANDARD TEST METHODS

In principle explosion limits are determined by preparing gaseous test mixtures of flammable and oxidizing gases and conducting ignition tests. The amount of test substance in the test mixture is varied incrementally until the LEL or the UEL is determined. Criterion for a reaction is flame propagation through the test mixture. The standard test methods for atmospheric pressure and the experimental parameters used for the determination of the hydrogen explosion limits are summarized below:

EN 1839(T) (tube method) [4]

Ignition vessel:	vertical glass tube, inner diameter 80 mm, height 300 mm
Initial pressure:	atmospheric pressure
Ignition source:	high voltage spark, duration 0.2 s (app. 2 J)
Criterion:	flame detachment and propagation of at least 100 mm (observed visually)
Step size:	10% of sample concentration below 2 mol%, 0.2 mol% above 2 mol% sample concentration
Repetition of tests:	4
Explosion limit:	last non ignition point

EN 1839(B) (bomb method) [4]

Ignition vessel:	closed spherical steel vessel (bomb), volume 14 dm ³
Initial pressure:	atmospheric pressure
Ignition source:	fusing (exploding) wire (10 J – 20 J)
Criterion:	pressure rise of $p_{ex}/p_0 > 1.05$ (5 % of initial pressure)

Step size: 10% of sample concentration below 2 mol%,
0.2 mol% above 2 mol% sample concentration,
Repetition of tests: 4
Explosion limit: last non ignition point

ASTM E 681-01 (USA) [5]

Ignition vessel: glass flask, volume = 5 dm³
Initial pressure: 0.133 bar(a) up to atmospheric pressure
Ignition source: high voltage spark, duration 0.4 s (app. 4 J)
Criterion: flame detachment and propagation to a distance of 13 mm to the wall
(observed visually)
Step size: arbitrary (has to be stated if more than 10% of sample concentration)
Repetition of tests: 1
Explosion limit: Mean value between ignition point and non ignition point

DIN 51 649, part 1 (Germany) [6]

Ignition vessel: vertical glass tube, inner diameter 60 mm, height 300 mm
Initial pressure: atmospheric pressure
Ignition source: high voltage spark, duration 0.5 s (app. 5 J)
Criterion: flame detachment (observed visually)
Step size: 0.1 mol% below 10 mol% sample concentration,
0.2 mol% above 10 mol% sample concentration,
Repetition of tests: 5
Explosion limit: last non ignition point

The results of the ignition tests are shown in Table 1. All limits reported are given as mole fraction in % (mol%). The tests were carried out with hydrogen-air mixtures at atmospheric pressure and room temperature. Furthermore a number of explosion limits were measured with additional 40 mol% of nitrogen because the flame velocity is very slow and such mixtures are particularly sensitive to the variation of parameters.

The measuring uncertainty of the standard test methods generally is close to one step size. Therefore the reported hydrogen explosion limits have estimated measuring errors of about ± 0.2 mol%.

Table 1. Explosion limits of hydrogen in air measured at room temperature and atmospheric pressure, given in mol% H₂ [7]

	DIN 51649	EN 1839 (T)	EN 1839 (B)	ASTM E 681
LEL (H ₂ - Air)	3.8	3.6	4.2	3.75
UEL (H ₂ - Air)	75.8	76.6	77.0	75.1
LEL (H ₂ - 40%N ₂ - Air)	3.6	3.6	4.4	3.65
UEL (H ₂ - 40%N ₂ - Air)	38.2	38.4	38.2	37.3

It becomes clear that the explosion limits measured according to the 4 standard test methods show differences. The procedures according to DIN 51649 and EN 1839(T) yield comparable results. The reason is the very similar test apparatus used for both methods. The explosion range of EN 1839(T) is a little bit wider because the diameter of the explosion tube is larger so that flame quenching effects are better eliminated. The ASTM method shows a similar LEL but a lower UEL. DIN 51649, ASTM E 681 and EN 1839(T) are so called open vessel methods. The pressure inside the test vessel during the reaction is nearly constant at atmospheric pressure and burned gases can escape through a gas outlet.

The closed vessel method according to EN 1839(B) shows the largest deviations. The LEL is higher compared to the other methods. The reason might be the pressure threshold criterion for reaction indication. It is obviously less sensitive than the visual criterion. Nevertheless, the bomb method

supplies the highest UEL in case of hydrogen-air mixtures. Possibly the large vessel size of 14 dm³ compared to the smaller volumes of the open vessel methods plays a role.

For the proper use of safety characteristics such as explosion limits it is necessary to know their transferability to practical conditions. In the field of explosion prevention both types of explosion limits (flame propagation in a tube and pressure rise in a closed vessel) are useful. In some cases it is not necessary to apply the more conservative flame propagation limits, e.g. for a gas mixture in a closed chemical reactor. On the other hand it can be important to prevent flame propagation in a flowing gas mixture and the flame propagation criterion is most meaningful.

Consequently the new European standard EN 1839 recommends two determination methods and the corresponding explosion limits have to be indicated clearly.

4 TEMPERATURE INFLUENCE ON THE EXPLOSION LIMITS

The temperature influence on the explosion limits of hydrogen-air mixtures was investigated by GASSE [8]. GASSE used an apparatus according to DIN 51649-1, which was mounted into a laboratory oven. The results are given in Table 2 and Figure 1.

Table 2. Influence of the temperature on the explosion limits of hydrogen-air mixtures, measured at atmospheric pressure according to DIN 51649-1 [8]

Temperature in °C	Lower explosion limit in mol% H ₂	Upper explosion limit in mol% H ₂
20	3.9	75.2
100	3.4	77.6
200	2.9	81.3
300	2.1	83.9
400	1.5	87.6

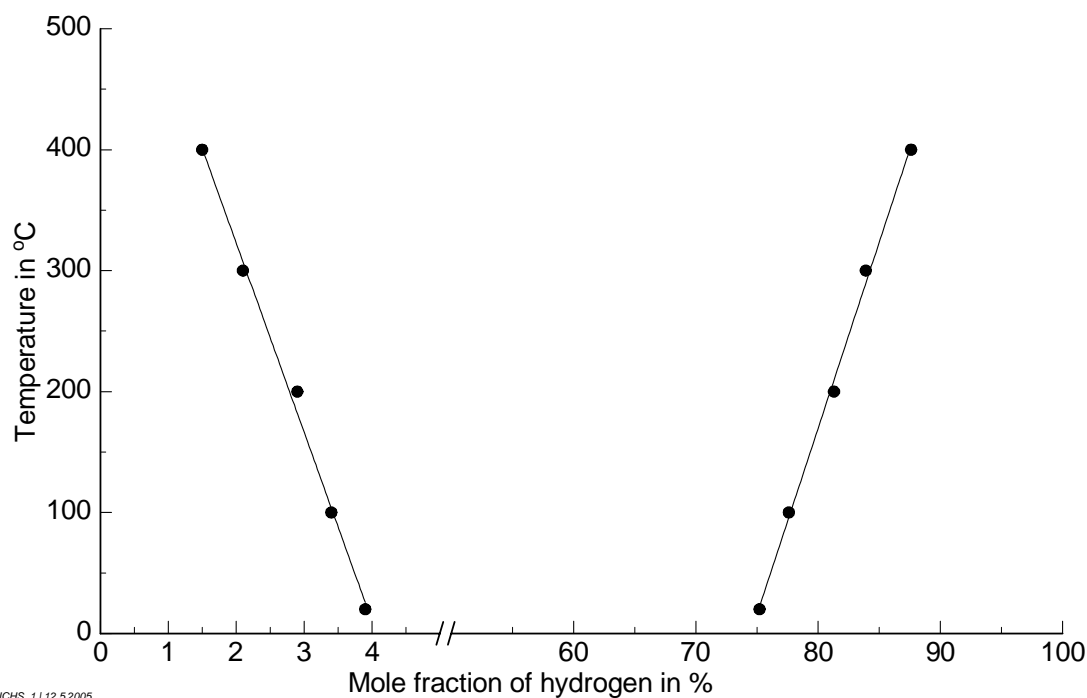


Figure 1. Influence of the temperature on the explosion limits of hydrogen-air mixtures, measured at atmospheric pressure according to DIN 51649 [8]

The experiments show that the explosion range becomes wider with increasing temperature. As a good approximation the quantitative influence can be described by a linear function in the temperature range of 20 °C to 400 °C.

$$LEL(T) = LEL(T_0) \cdot [1 - K_L \cdot (T - T_0)] \quad (1)$$

where $LEL(T_0) = 4.1$ mol% and $K_L = 0.00157 \text{ K}^{-1}$ or

$$UEL(T) = UEL(T_0) \cdot [1 + K_U \cdot (T - T_0)] \quad (2)$$

where $UEL(T_0) = 74.5$ mol% and $K_U = 0.00044 \text{ K}^{-1}$

$LEL(T)$, $UEL(T)$ are the explosion limits at the designated temperature T and $LEL(T_0)$, $UEL(T_0)$ are the explosion limits at the reference temperature $T_0 = 273.15 \text{ K}$ (0 °C). The factors K_L and K_U characterize the dependence of the explosion limits on the temperature increase.

5 PRESSURE INFLUENCE ON THE EXPLOSION LIMITS OF HYDROGEN-AIR MIXTURES

The pressure influence on the explosion limits of hydrogen-air mixtures at room temperature was investigated by BAM some years ago [9] (see Tab. 3 and Fig. 2). The tests were carried out in a cylindrical 6 dm³ steel autoclave with a pressure resistance of 700 bars. A fusing (exploding) wire igniter was used for the tests. The ignition energy of this type of igniter is about 70 J. Criterion for a reaction was a pressure rise of more than 10% after ignition.

Table 3. Influence of the initial pressure on the explosion limits of hydrogen-air mixtures, measured at room temperature [9]

Initial pressure in bar	Lower explosion limit in mol% H ₂	Upper explosion limit in mol% H ₂
1	4.3	76.5
5	4.4	73.1
10	4.7	72.1
20	4.9	71.1
30	5.1	71.7
40	5.3	73.3
50	5.6	73.8
100	5.6	73.4
150	5.6	72.9

The LEL increases with increasing initial pressure. This behavior of hydrogen is contrary to that of most other flammable gases of the hydrocarbon type. The pressure dependence of the UEL shows a remarkable anomaly. After decreasing up to an initial pressure of about 20 bars, the UEL increases again. This anomalous behavior of hydrogen can be observed with air as oxidizer and with pure oxygen as well.

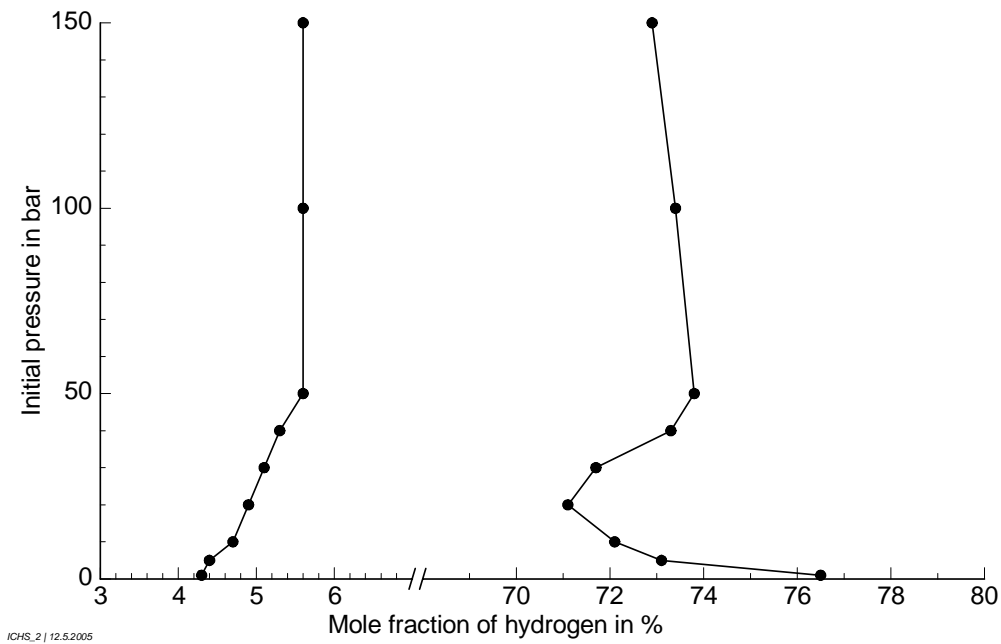


Figure 2. Influence of the initial pressure on the explosion limits of hydrogen-air mixtures, measured at room temperature [9]

6 PRESSURE INFLUENCE ON THE EXPLOSION LIMITS OF HYDROGEN-OXYGEN MIXTURES

The explosion limits of hydrogen-oxygen mixtures were determined by BAM following closely the European standard EN 1839(B). The ignition source, the criterion for a reaction and the step size were in accordance with the requirements of the standard. Up to 20 bars a cylindrical stainless steel autoclave, $H/D = 1$, with a volume of 6 dm^3 was used in accordance with EN 1939. In deviation to the standard at pressures of more than 20 bars a smaller 2.8 dm^3 vessel was used. The gas mixtures were prepared based on the partial pressures of each component in a separate mixing vessel. The components were filled at lower pre-pressures and then compressed for the ignition tests. Each mixture was analyzed by a paramagnetic oxygen analyzer with a resolution of 0.1 mol\% O_2 in order to check the composition. The pressure-time curves were recorded by piezoresistive pressure transducers after ignition.

Table 4. Influence of the initial pressure on the explosion limits of hydrogen-oxygen mixtures, measured at room temperature [10]

Initial pressure in bar	Lower explosion limit in mol% H_2	Upper explosion limit in mol% H_2
1.0	4.0	95.2
5.0	4.6	94.6
10.0	5.0	94.2
20.0	5.4	94.2
50.0	5.5	94.6
100.0	5.7	94.9
150.0	5.7	95.1
200.0	5.9	95.1

Table 5. Influence of the initial pressure on the explosion limits of hydrogen-oxygen mixtures, measured at 80 °C [10]

Initial pressure in bar	Lower explosion limit in mol% H ₂	Upper explosion limit in mol% H ₂
1.0	3.8	95.4
5.0	4.4	95.0
10.0	4.8	94.6
20.0	5.2	94.6
50.0	5.3	95.0
100.0	5.7	95.3
150.0	5.3	95.5
200.0	5.7	95.5

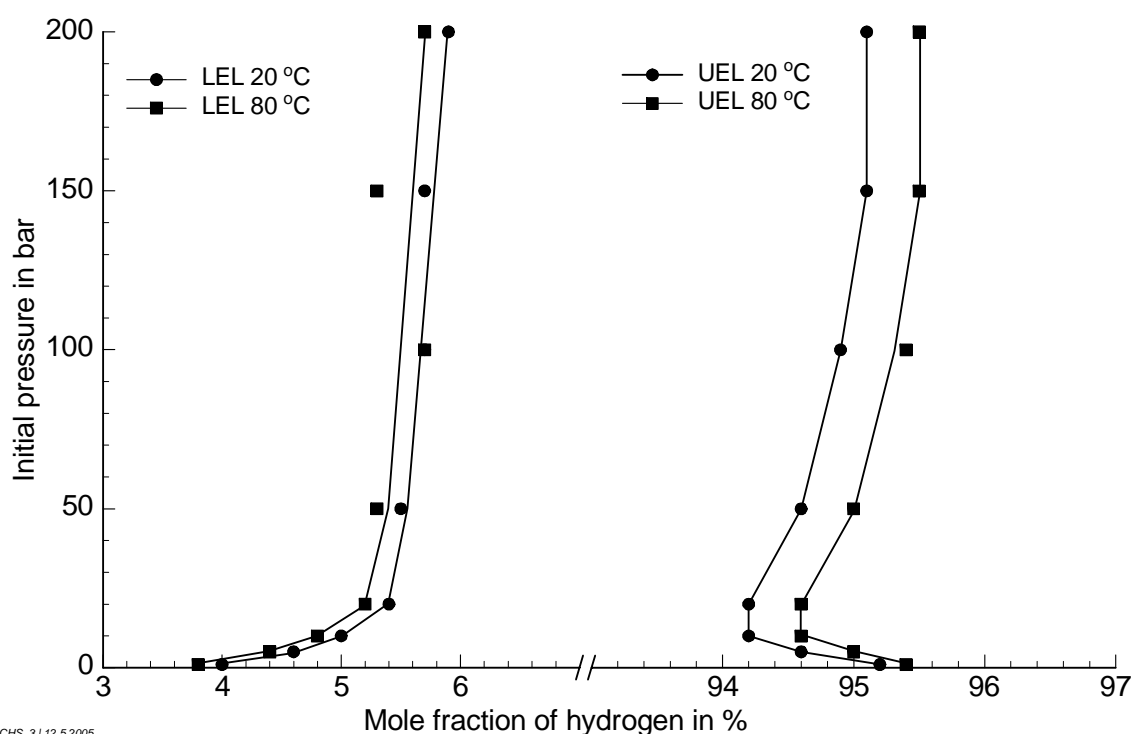


Figure 3. Influence of the initial pressure on the explosion limits of hydrogen-oxygen mixtures, measured at room temperature and 80 °C [10]

7 EXPLOSION PRESSURE AND RATE OF PRESSURE RISE

In addition to the explosion limits (concentration limits of H₂) the effects of hydrogen explosions inside the apparatus are interesting. Therefore mixtures within the explosion range were prepared and the explosion pressures (p_{ex}) and the highest rates of pressure rise $(dp/dt)_{ex}$ after the ignition were determined. The rate of pressure rise $(dp/dt)_{ex}$ depends strongly on the vessel volume. For a vessel volume of 1 m³ $(dp/dt)_{ex}$ is equal to the so called K_G -value according to the cubic law (see equation (3)). This value should be largely volume independent and describes the violence of a gas explosion in a closed vessel. In fact the K_G value depends in many cases on the vessel volume, because the flame propagation is often disturbed and not laminar in large vessels.

$$K_G = (dp/dt)_{ex} * V^{1/3} \quad (3)$$

where K_G – explosion index, bar m s⁻¹; $(dp/dt)_{ex}$ – rate of pressure rise, bar s⁻¹; V – vessel volume, m³.

One task of the European SAFEKINEX project [11] was the determination of explosion pressures and rates of pressure rise of hydrogen-air mixtures at temperatures of up to 250 °C and pressures of up to 30 bars. An overview of the results is given in Figures 4 to 6. The experiments were carried out in the 6 dm³ vessel at pressures of up to 5 bars and in a 2.8 dm³ vessel at pressures of more than 5 bars using the exploding wire igniter recommended by EN 1839(B). The explosion pressures are shown as the so called pressure rising factors p_{ex}/p_0 .

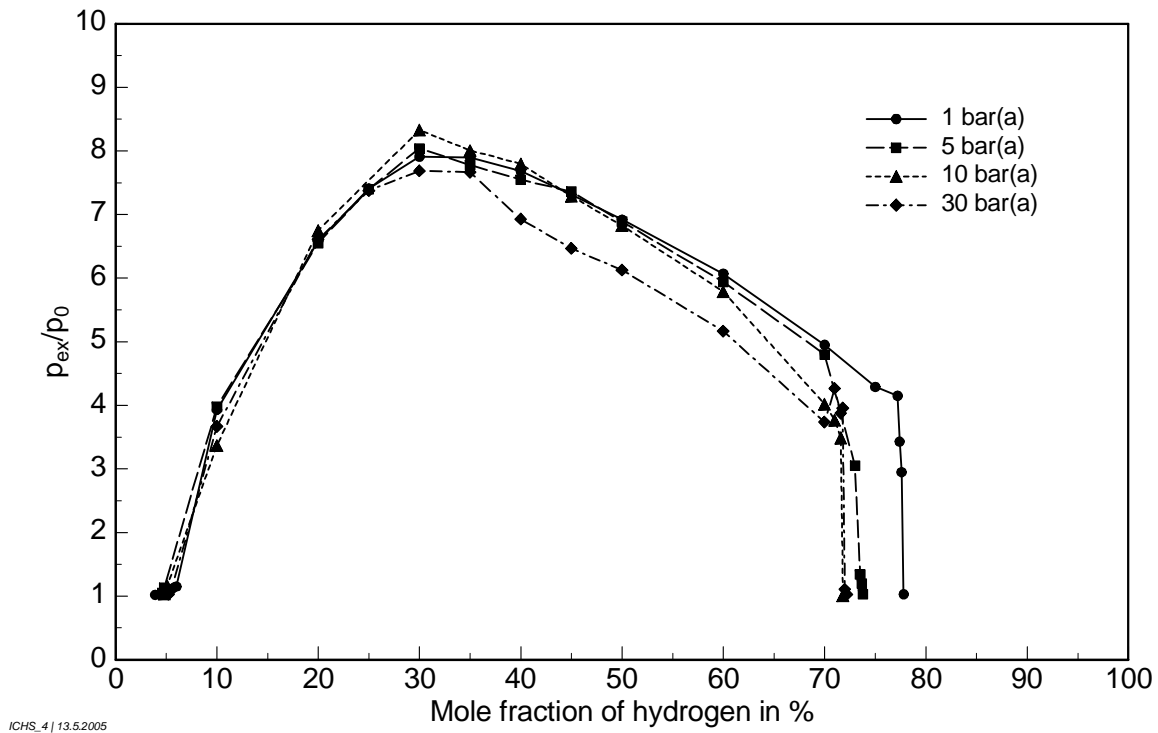


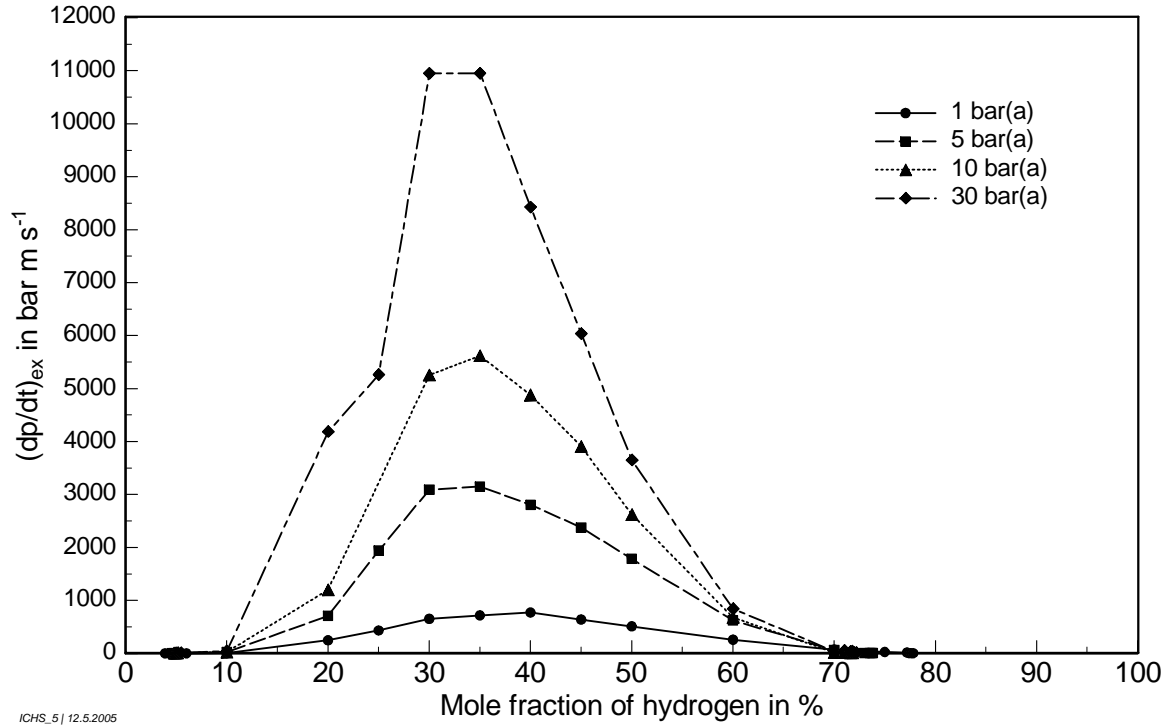
Figure 4. Explosion pressures of hydrogen-air mixtures at 20 °C and different initial pressures [11]

It is clear to see that the ratio of pressure rise does not depend significantly on the initial pressure. Particularly in the stoichiometric range, close to the maximum explosion pressure, there is only a slight influence of the initial pressure.

At the UEL the anomalous pressure dependence of hydrogen can also be observed (see Figures 2 and 4). The widest explosion range is reached with the lowest initial pressure.

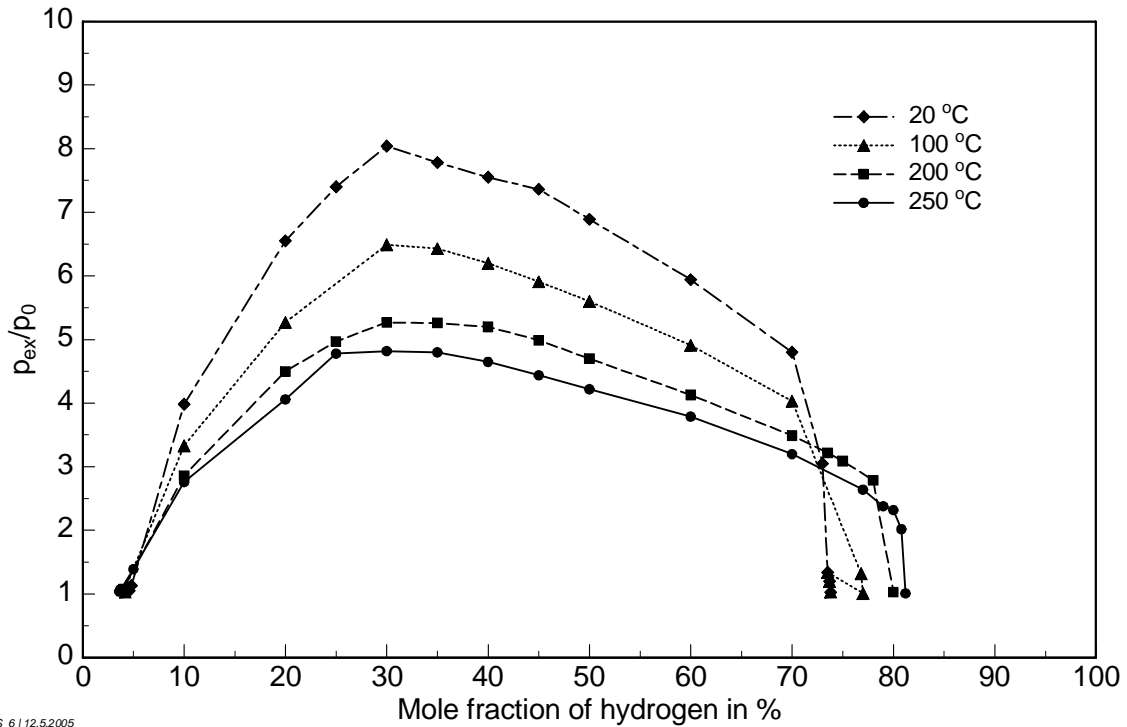
In the range of lower hydrogen concentrations the explosion pressures and particularly the rates of pressure rise are relatively low (see Figure 5). At 30 bars initial pressure the $(dp/dt)_{ex}$ -values become very high, so that the measured raw data show strong oscillations. Therefore special smoothing software was developed and applied.

The maximum explosion pressure decreases with higher initial temperatures (see Figure 6). The reason is the almost constant flame temperature of the hydrogen-air flame. According to the ideal gas law the pressure rise corresponds to the temperature increase which is smaller at higher initial temperatures.



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Figure 5. Rates of explosion pressure rises (K_G values) of hydrogen-air mixtures at 20 °C and different initial pressures [11]



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Figure 6. Explosion pressures of hydrogen-air mixtures at 10 bars and initial temperatures of up to 250 °C [11]

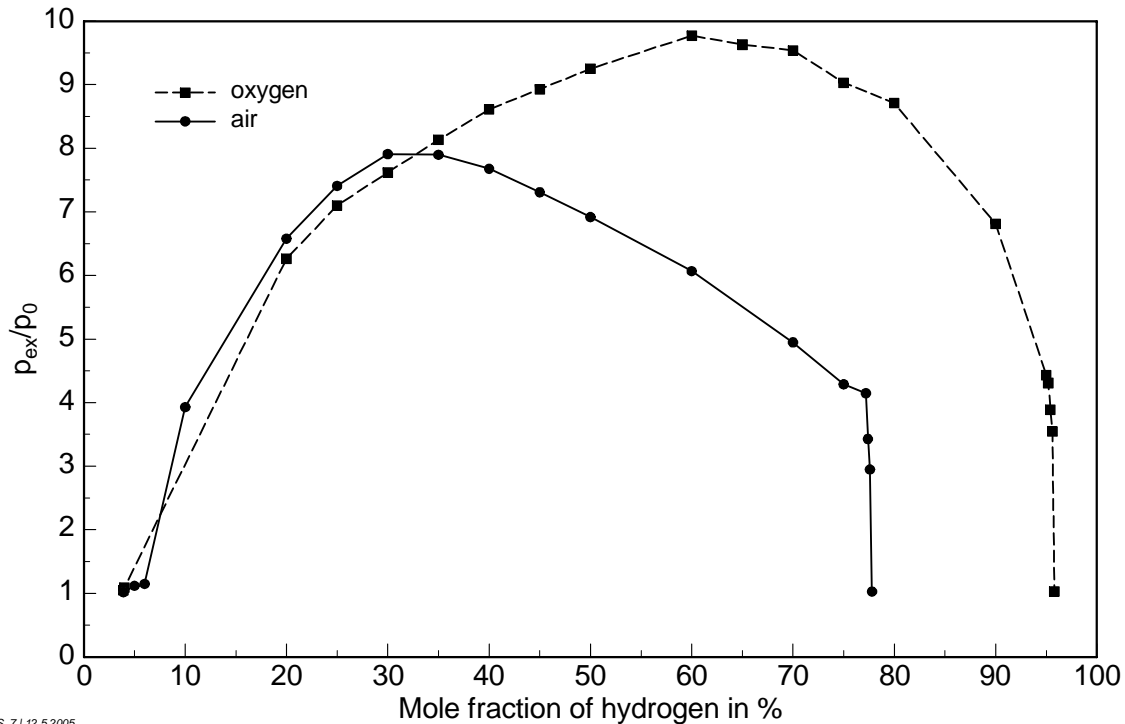


Figure 7. Explosion pressures of hydrogen-air and hydrogen-oxygen mixtures at 1 bar(a) and room temperature [11]

In Fig. 7 the explosion pressures of hydrogen-air and hydrogen-oxygen mixtures at 1 bar and 20 °C are illustrated. The experiments were carried out in the 6 dm³ autoclave. For hydrogen-oxygen mixtures higher explosion (deflagration) pressures were observed. Nevertheless, these higher p_{ex} do not correspond to the expected values when considering the system energy only.

In the Tables 5 and 6 explosion characteristics of hydrogen-oxygen mixtures close by the explosion limits at initial pressures of 5 bars and 50 bars are listed. Since hydrogen has a very high diffusion coefficient, especially hydrogen impurities in the oxygen (range of the lower explosion limit) are to be expected during the technical operation of electrolyzers. One can see in the tables that the pressure rising factors and K_G values increase only very slowly when the lower explosion limit is exceeded by a few mol%. There are slow deflagrations in fuel lean regions. Therefore pressure relief devices (rupture disks, safety valves) can be effectively used for such mixtures.

On the other hand in the range just below of the upper explosion limits of hydrogen-oxygen mixtures fast reactions with high explosion pressures take place. At about 1 mol% below the UEL much higher K_G values and pressure rising factors were observed.

Here it has to be mentioned that in Table 5 and 6 only the results of single tests are shown. They are done to present the different reaction courses at the upper and lower explosion limit and they are not suitable for the construction of safety devices. Due to the fact that the results of ignition tests do strongly scatter, the explosion indices which are to be used for constructive protection measures have to be confirmed by a greater number of tests.

Table 5. Explosion indices for H₂/O₂ gas mixtures at 20 °C and an initial pressure of 5 bar (6-dm³-vessel) [12]

Test No.	amount of H ₂ in mol%	F (p _{ex} /p ₀)	K _G in bar m s ⁻¹
LEL = 4.6 mol% H ₂			
H00052a	10.0	3.53	9.3
H900052a	9.0	2.69	4.1
H800052a	8.0	2.51	3.3
H700052a	7.0	1.76	1.7
H600052a	6.0	1.40	0.8
H550052a	5.5	1.34	0.5
H500052a	5.0	1.11	0.2
H480052a	4.8	1.05	0.1
H460052a	4.6	1.01	0.1
UEL = 94.6 mol% H ₂			
O650052a	93.5	4.92	103.1
O600052a	94.0	4.41	30.1
O580052a	94.2	3.85	8.2
O560052c	94.4	3.34	3.4
O540052a	94.6	1.01	0.1

Table 6. Explosion indices for H₂/O₂-gas mixtures at 20 °C and an initial pressure of 50 bar (2.8-dm³-vessel) [12]

Test No.	amount of H ₂ in mol%	F (p _{ex} /p ₀)	K _G in bar m s ⁻¹
LEL = 5.5 mol-% H ₂			
H000502a	9.9	3.16	18.8
H900502a	8.9	2.84	29.0
H800502a	7.9	1.93	10.6
H700502a	6.9	1.33	4.3
H620502a	6.1	1.08	1.2
H600502a	5.9	1.05	0.8
H580502c	5.7	1.06	0.8
H560502a	5.5	1.01	0.6
UEL = 94.6 mol-% H ₂			
O600502a	94.0	4.43	97.4
O580502a	94.2	4.18	74.8
O560502a	94.4	4.16	65.9
O540502a	94.6	1.01	0.5

8 CONCLUSIONS

Explosion limits are not the type of independent physicochemical material characteristics such as melting temperature or density. As with most other safety characteristics they are influenced by the test apparatus and determination procedure. Also the explosion limits of hydrogen-air mixtures measured according to different standard test methods at atmospheric pressure show such influences. For the proper use it is necessary to know their transferability to practical conditions. In the field of explosion prevention both types of explosion limits (flame propagation in a tube and pressure rise in a

closed vessel) can be useful. Consequently the new European standard EN 1839 recommends two determination methods and the corresponding explosion limits have to be indicated clearly.

The experiments at higher initial temperatures using the DIN apparatus show that the explosion range becomes wider with increasing temperature. As a good approximation the quantitative influence could be described by a linear function in the temperature range of 20 °C to 400 °C.

In many practical cases it is necessary to determine the explosion limits and explosion pressures at elevated pressures. Therefore the bomb method according to EN 1839 is suitable. Contrary to most of the other flammable gases the LEL of hydrogen increases with increasing initial pressure. The pressure dependence of the UEL shows a remarkable anomaly. After decreasing up to an initial pressure of about 20 bars, the UEL increases again. This anomalous behavior of hydrogen can be observed with air as oxidizer and with pure oxygen as well.

Since hydrogen has a very high diffusion coefficient, especially hydrogen impurities in the oxygen gas are to be expected during the technical operation of electrolyzers. The pressure rising factors and K_G values of such mixtures increase very slowly when the lower explosion limit is exceeded at only a few mol%. For these mixtures pressure relief devices (rupture disks, safety valves) can be effectively used.

ACKNOWLEDGEMENTS

The authors wish to thank for the financial support by the Research Center Jülich, Germany, and the European Union within the Fifth Framework Programme on Energy, Environment and Sustainable Development, project SAFEKINEX, contract EVG1-CT-2002-00072.

REFERENCES

1. Janssen, H., Bringmann, J.C., Emonts, B. and Schroeder, V., Safety related studies on hydrogen production in high-pressure electrolyzers, *International Journal of Hydrogen Energy*, **29**, 2004, pp. 759–770
2. *CHEMSAFE – A database of evaluated safety characteristics*, Edited by DECHEMA, BAM and PTB, Frankfurt/M., Germany, Update 2004
3. Molnarne, M., Schendler, Th. and Schroeder, V., Sicherheitstechnische Kenngrößen, Teil 2: Explosionsbereiche von Gasgemischen, 2003, NW-Verlag, Bremerhaven.
4. EN 1839, Determination of explosion limits of gases and vapors, 2003, (European standard).
5. ASTM E 681-01, Standard test method for concentration limits of flammability of chemicals (vapors and gases), 2001 (US standard).
6. DIN 51649-1, Bestimmung der Explosionsgrenzen von Gasen und Gasgemischen (German standard)
7. Daubitz, R., Bestimmung der Explosionsgrenzen von Wasserstoff/Sauerstoff-Gemischen bei erhöhten Anfangsdrücken, Research Report, BAM and TU Berlin, 2001.
8. Gasse, A., Experimentelle Bestimmung und Simulation von Explosionsgrenzen, untersucht an wasserstoffhaltigen Brenngasgemischen, Dissertation, Uni-GH Paderborn, Germany, 1992.
9. Schroeder, V.: Explosionsgrenzen von Wasserstoff und Wasserstoff/Methan-Gemischen, BAM Research Report No. 253, NW-Verlag, Bremerhaven, 2003.
10. Schroeder, V., Sicherheitstechnische Untersuchungen für die Hochdruck-Wasserelektrolyse zur Speicherung regenerativer Energie, Report No. VH2226, BAM Berlin, 2002.
11. EU-Project SAFEKINEX, SAFE and Efficient hydrocarbon oxidation processes by KINetics and Explosion eXpertise, Programme “Energy, Environment and Sustainable Development”, Contract No. EVG1-CT-2002-00072, 2003 - 2006
12. Schroeder, V., Emonts, B., Janssen, H. and Schulze, H.-P., Explosionsgrenzen von Wasserstoff/Sauerstoff-Gemischen bei Drücken bis 200 bar, *Chemie-Ingenieur-Technik*, **75**, No. 7, 2003, pp. 914-918.