HYDROGEN COMBUSTION EXPERIMENTS IN A VERTICAL SEMI-CONFINED CHANNEL

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ABSTRACT

Experiments in an obstructed semi-confined vertical combustion channel with a height of 6 m (cross-section 0.4 x 0.4 m) inside a safety vessel of the hydrogen test center HYKA at KIT are reported. In the work, homogeneous hydrogen-air-mixtures as well as mixtures with different well-defined H_2-concentration gradients were ignited either at the top or at the bottom end of the channel. The combustion characteristics were recorded using pressure sensors and sensors for the detection of the flame front that were distributed along the complete channel length. In the tests slow subsonic and fast sonic deflagrations as well as detonations were observed and the conditions for the flame acceleration (FA) to speed of sound and deflagration-to-detonation transition (DDT) are compared with the results of similar experiments performed earlier in a larger semi-confined horizontal channel.

1.0 INTRODUCTION

In hydrogen safety considerations the phenomena of effective flame acceleration (FA) and subsequent deflagration-to-detonation transition (DDT) are very important, especially when large semi-confined spaces, such as rooms or tunnels, are studied. These scenarios must also be understood for nuclear reactor safety, where hydrogen, released due to a LOCA MCCI accident, might accumulate below the ceiling of a reactor building under formation of a partially confined stratified layer of flammable hydrogen-air mixture [1]. When ignited, such mixtures can lead to high pressure loads during the combustion and might cause strong structural damage to the facility. In contrast to homogeneous H_2-air mixtures in closed geometries, only few experimental data on the combustion behaviour of stratified H_2-air-mixtures in semi-confined geometries is currently available.

The expansion ratio (ratio of specific volume of combustion products over reactants) was identified as a potential for effective flame acceleration (FA) to sonic speed [2]. This is of special importance since fast flames, with velocities in the order of the speed of sound, are a pre-requisite for the transition into the fastest combustion regime as a detonation [3]. In earlier experimental investigations on unconfined combustions or lateral venting a large influence of vents on the flame dynamics was shown [1, 4-6]. The critical conditions for a significant flame acceleration to sound speed in tubes with lateral venting were expressed using a critical expansion ratio σ^*. A linear dependency between this critical expansion ratio and the vent ratio was formulated:

$$\sigma^* = \sigma_0^* \cdot (1+2\cdot\alpha), \qquad (1)$$

where σ_0^* - critical expansion ratio for FA in closed tubes; α - vent ratio (vent area/total side walls area).

The critical conditions for detonation onset in a tube with lateral venting were found to remain the same as for a closed tube, since the flame velocity reaches sonic speed [7].

In a previous experimental series in a large-scale (9 x 3 x 0.6 m³) horizontal combustion channel with an open ground face an extended criterion for the onset of FA in semi-confined geometries was formulated [1, 6-10]. This criterion was derived by analysing numerous experiments with various layer thicknesses, obstacle configurations and mixture properties. In the resulting graph the expansion ratio of the mixture, representing its thermodynamic properties, was plotted over a dimensionless distance, representing the main geometric properties of the combustion channel. This graph, in which open symbols indicate experiments where FA was observed and solid symbols stand for experiments without FA, is depicted in the left part of Fig. 1.

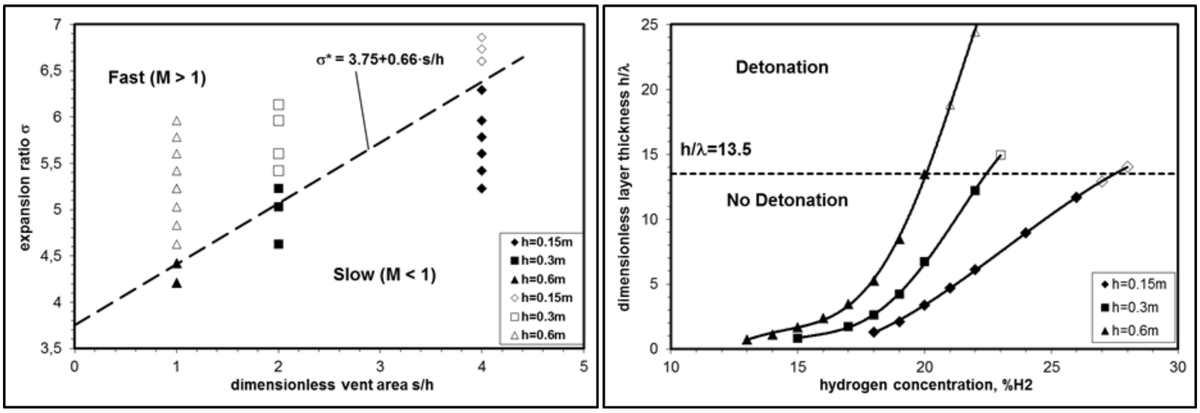

Figure 1. Critical conditions for an effective flame acceleration in a semi-confined horizontal channel as function of the expansion ratio [7] (left) and critical conditions for DDT-onset in the same facility as function of the detonation cell size [7] (right).

The dashed straight line in the diagram represents the critical expansion ratio σ*, which separates experiments with significant flame acceleration from the experiments without FA. This straight line can be formulated as equation (2):

$$\sigma^* = \sigma_0^* \, (1 + K \cdot s/h), \qquad (2)$$

where σ_0^* – critical expansion ratio for FA in closed tubes; K – channel-specific constant as a function of integral scale and blockage ratio (BR); s – obstacle spacing, m; h –layer height, m. The ratio s/h can be considered as an effective vent ratio for a layer geometry similar to α in Eq. (1).

In the frame of the work with the horizontal channel also a criterion for the onset of DDT in semi-confined geometries was proposed using the right graph of Fig. 1. In this graph a dimensionless distance is plotted over the hydrogen content of the mixture. Again a dashed line was used to separate experiments with DDT (open symbols in right part of Fig. 1) from experiments without DDT (solid symbols in right part of Fig. 1). The equation for the horizontal dashed line can be formulated as follows:

$$L \approx 13.5\,\lambda, \qquad (3)$$

where L – characteristic length (layer thickness) of the geometry, m; λ – detonation cell size, m, as a measure of mixture detonability depending on mixture reactivity and gas dynamics of the system. Smaller detonation cell size means higher detonability of the system.

In this formula, the detonation cell size includes the properties of the mixture, while the properties of the geometry are represented by the characteristic length L of the facility (the layer thickness h in the previous work). Therefore, in the reported experiments with the horizontal channel a DDT event could occur in experiments where the detonation cell size of the test mixture was at least 13.5 times smaller than the layer thickness of the test mixture.

A further outcome of the previous work was the so-called *Concept of Maximum Concentration*, according to which stratified H_2-containing layers with a given maximum H_2-concentration in a semi-confined geometry behave similar to homogeneous layers of the same H_2-concentration concerning flame velocities and combustion pressures [9].

The main objective of this work was to evaluate the critical conditions for FA and DDT in a semi-confined obstructed **vertical** layer and to compare these conditions with results of the previous campaign in the semi-confined **horizontal** channel.

2.0 EXPERIMENTAL DETAILS

2.1 Test Facility and Instrumentation

All experiments were performed in a vertical channel with a height of 6 m and a square cross-section of 0.4 x 0.4 m (Fig. 2 left) that is installed to the safety vessel A3 (h = 8 m, di = 2.5 m, V = 33 m^3, p_{Stat} = 60 bar) at the Hydrogen Test Site HYKA of the Institute for Nuclear and Energy Technology (IKET) at the Karlsruhe Institute of Technology (KIT). The channel with one open side face consists of a framework structure of aluminium profile rails that is covered by wooden plates (Fig. 2 center). The wooden inner surface of the channel is sealed by a welded steel shell that also protects the structure against flames. Due to the steel plates the 16 grid obstacles (BR 50%) that were used in all experiments can be easily positioned via magnets in a distance of 25 cm to each other.

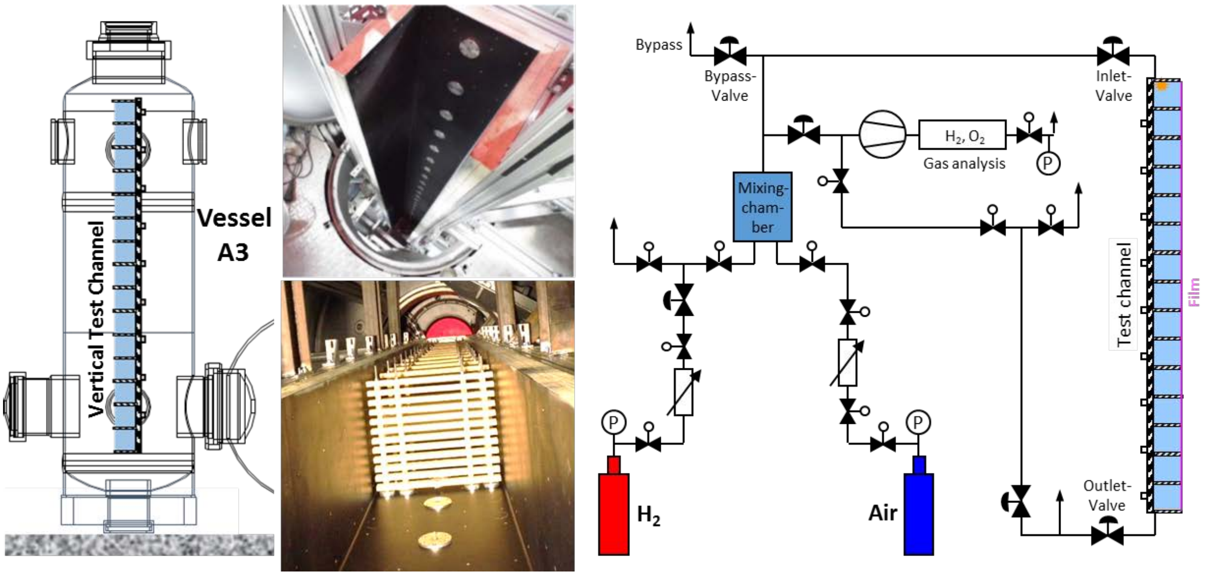

Figure 2. Sketch and photos of the test channel inside vessel A3 (left)
and flow chart of the complete facility (right).

In total 35 sensors (8 pressure transducers, 18 ionisation probes and 9 modified thermocouples for flame front detection) were installed to the facility. All sensors were installed along the centerline of the channel along its rear face (face opposite to open face), except for two pressure sensors that were positioned outside the channel inside the safety vessel A3. The positions of the sensors are sketched in Fig. 3 as well as the shape of the obstacles used in the experiments. Depending on the ignition position (top or bottom of the channel), the obstacles were arranged in a way that the flame always had to pass through the obstructed region (length: 4 m) before reaching the unobstructed part of the channel (length: 2 m). The mixtures were ignited using a glow wire, which was installed in a perforated tube with a length of 280 mm and an internal diameter of 50 mm. This tube was positioned horizontally at the ignition end of the channel and through its openings it was filled together with the channel with test mixture during the filling procedure. After ignition, the flame leaves the tube through the perforation and the open ends, producing an almost planar flame front that propagates through the channel.

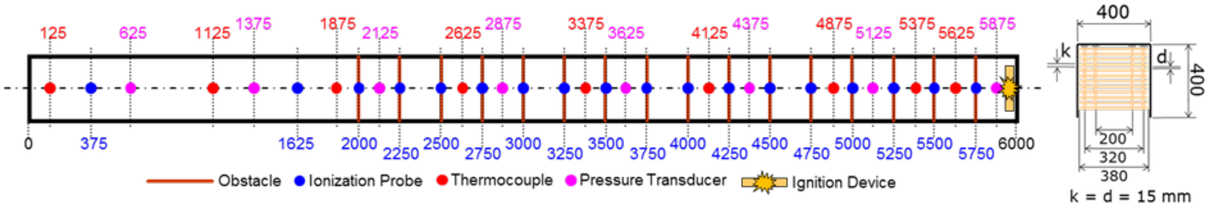

Figure 3. Instrumentation of the channel (left) and sketch of the obstacle geometry (right). All dimensions are in mm.

2.2 Test Procedure

Prior to all experiments, the open side face of the channel was sealed with a thin plastic film to close the channel for the filling procedure (Fig. 2, right). Then the test mixture was generated using mass flow controllers for hydrogen and synthetic air. The two gas flows were conducted into a mixing chamber, from where the mixture was initially directed through a bypass to the ambience. When a stable flow with the preset H_2-concentration was measured by the gas analyzer in the feed line, the flow was directed through the inlet valve into the test channel. The initial channel atmosphere was then replaced with test mixture and pushed out of the channel through the outlet valve at its opposite lower end. When the desired H_2-concentration or H_2-concentration gradient was reached inside the channel (see below) inlet and outlet valves were closed and the lines were purged with N2 to avoid flames traveling through the pipes when a valve was damaged during an experiment. To avoid any influence of the film that sealed the open side face of the channel it was destroyed over its complete height by a falling knife prior to the ignition of the mixture. This cut was observed by four video cameras that were distributed in the safety vessel. An experiment was not further evaluated if the cut failed or was incomplete.

In the experiments different gas layers were investigated that were generated using the following procedures:

a) Homogeneous mixture inside the channel: mixture with a constant H_2-concentration was injected from the top of the channel until the gas analysis measured an equal H_2-concentration in the exhaust line, which leaves the channel at its opposite lower end.

b) Positive concentration gradients (higher H_2-concentrations in the upper part of the channel): Such mixtures were generated by increasing the H_2-content in the inlet flow steadily during the filling procedure after the complete channel was initially filled homogeneously with the lowest concentration of the gradient. The exact settings needed for the automated mass flow controllers to gain almost linear concentration gradients over the complete channel height were identified in pre-experiments without ignition, where gas samples were taken in many different positions along the channel height and analyzed offline.

c) Negative concentration gradients (against gravity with higher H_2-concentrations in the lower part of the channel): To generate such gradient mixtures pure air was injected from the channel top after the complete channel was initially filled with the highest concentration of the gradient. Again, the exact settings needed for the mass flow controllers to gain almost linear concentration gradients over the complete channel height were identified in pre-experiments without ignition but thorough analysis of the gas distribution inside the channel via gas samples and offline analysis.

Figure 4 shows examples of concentration gradients that were generated in the channel using the methods described above. The figure also shows that it was possible to generate almost linear positive gradients with different slopes, while only one gradient slope was possible for the negative gradients. Positive gradients were quite stable concerning time, while negative gradients were very unstable and started to change their shape immediately. The concentrations plotted in Fig. 4 were determined by analyzing gas samples that were taken at the point in time of the ignition during distribution pre-experiments without ignition with the same filling procedure.

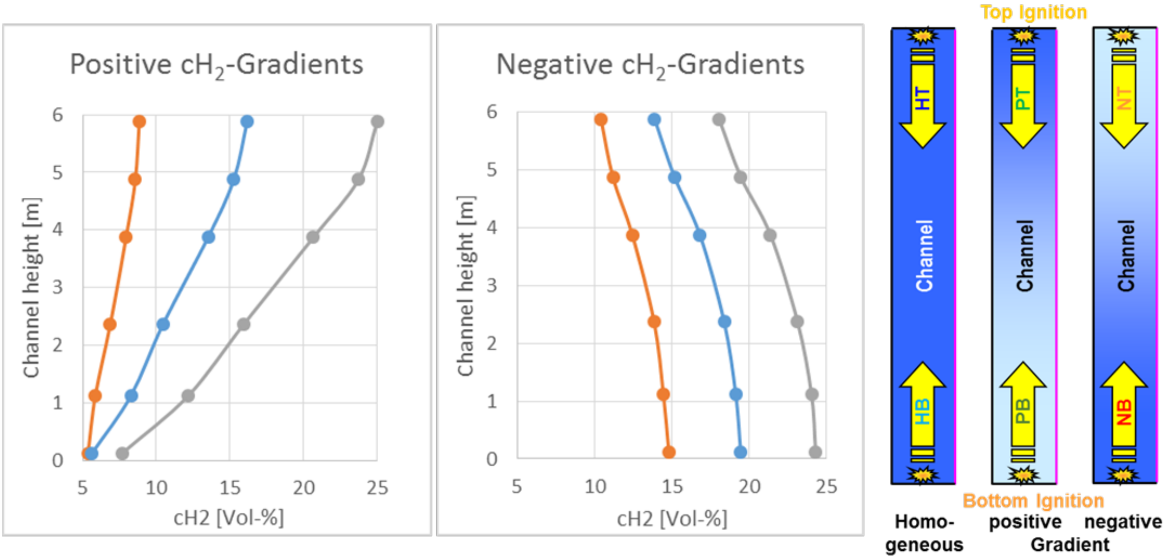

Figure 4. Examples for positive (left) and negative (center) H_2-concentration gradients generated in the test channel and different configurations used in the experiments with their abbreviations (right).

In the following discussion, the concentration gradients will be treated as linear gradients with a mean slope that is defined by the concentration increase over the complete channel height in upward direction (unit Vol%H_2/m).

In the experiments the test mixtures were ignited either at the bottom of the channel or at its top, and so the following abbreviations will be used to distinguish the different experimental configurations that are illustrated in the right part of Fig. 4. HB indicates that a homogeneous mixture is ignited at the bottom of the channel, while HT stands for top ignition of a homogeneous mixture. Similarly PB and PT as well as NB and NT stand for experiments were a mixture with a positive (PB and PT) or negative (NB and NT) gradient is ignited either at the bottom (PB and NB) or the top (PT and NT) of the channel.

3.0 EXPERIMENTAL RESULTS AND DISCUSSION

In total 25 experiments were performed with homogeneous mixtures in the vertical channel. In 13 experiments the mixture was ignited at the channel top, while it was ignited at the channel bottom in the remaining 12 experiments. Concentration ranges were 9 to 21 Vol-% H2 for top ignition and 6 to 16 Vol-% H2 for bottom ignition. Table 1 summarizes the main properties of all experiments that were evaluated. The detonation cell sizes were calculated according to paper [11] (values for hydrogen concentrations below 11%H_2 are not meaningful).

Table 1. Main properties (at 1 bar and 293 K) of tested homogeneous mixtures.

cH_2 [Vol%]	Igni-tion	Expansion ratio σ [-]	Detonation cell size λ [mm]
6	B	2.58	
8	B	3.08	
9	T / B	3.31	
9.5	T	3.43	
10	T / B	3.54	
11	T / B	3.77	2319
12	T / B	3.99	1289
13	T	4.21	798
14	T / B	4.42	530
15	T / B	4.63	361
16	B	4.83	252
18	T	5.23	114
20	T	5.60	44.6
21	T	5.79	31.9

43 experiments with vertical gradients were performed, of which 25 were with positive gradients and 18 with negative gradients. In 21 experiments the mixture was ignited at the channel top and in 22 it was ignited at the bottom. Tables 2 and 3 summarize the main properties of all experiments that were evaluated.

Table 2. Main properties (at 1 bar and 293 K) of tested mixtures with positive vertical H_2-concentration gradients.

cH_2max [Vol%]	cH_2min [Vol%]	cH_2av# [Vol%]	Igni-tion	Expansion ratio σ for		Det. cell size λ [mm] for	
				cH_2max	cH_2av#	cH_2max	cH_2av#
25.0	18.6	22.9	T	6.45	6.11	14.5	20.6
24.5	18.5	20.5	B	6.38	5.70	15.5	37.3
23.2	17.1	21.2	T	6.17	5.82	19.3	30.3
21.9	15.5	19.8	T	5.94	5.56	25.3	48.8
21.4	15.4	17.5	B	5.86	5.12	28.2	145
20.6	14.3	18.5	T	5.72	5.33	35.6	89.5
16.3	10.3	14.3	T	4.90	4.48	158	593
		12.3	B	4.89	4.05	227	1121
15.3	9.2	13.2	T	4.68	4.26	310	1045
14.0	8.0	12.1	T	4.43	4.00	521	1257
12.3	6.1	10.2	T	4.05	3.60	1123	(4164)
12.1		8.1	B	4.02	3.11	1206	(170151)
13.8	6.2	11.2	T	4.37	3.82	586	1949
15.4	6.4	12.4	T	4.72	4.08	330	724
		9.4	B	4.71	3.41	312	(9833)
17.2	6.7	13.7	T	5.08	4.36	224	593
18.2	12.2	14.2	B	5.27	4.46	105	493
19.7	7.2	15.5	T	5.55	4.73	50.3	301
19.1	7.1	11.1	B	3.79	5.44	67.1	2137
19.2	13.2	15.2	B	5.46	4.67	63.4	335
22.9	7.9	12.9	B	6.11	4.18	20.5	846
24.9	8.4	13.9	B	6.44	4.40	14.7	552
27.3	9.1	15.2	B	6.77	4.66	11.3	342
31.8	10.7	17.7	B	7.03	5.17	15.9	130
37.2	12.9	21.0	B	6.77	5.79	19.9	31.5

Table 3. Main properties (at 1 bar and 293 K) of tested mixtures with negative vertical H_2-concentration gradients.

cH_2max [Vol%]	cH_2min [Vol%]	cH_2av# [Vol%]	Ignition	Expansion ratio σ for		Det. cell size λ [mm] for	
				cH_2max	cH_2av#	cH_2max	cH_2av#
11.1	7.9	10.4	B	3.80	3.63	2074	3727
12.1	8.6	11.2	B	4.01	3.82	1243	1965
13.0	9.2	12.1	B	4.21	4.01	798	1230
13.9	9.9	11.6	T	4.41	3.90	545	1631
		13.0	B		4.20		814
14.9	10.5	12.4	T	4.60	4.07	379	1065
	10.6	13.8	B		4.38		569
15.8	11.2	13.2	T	4.79	4.24	272	746
		14.7	B		4.56		405
16.7	11.9	13.9	T	4.98	4.41	193	545
		15.5	B		4.74		297
17.6	12.5	14.7	T	5.16	4.57	133	402
18.1	12.9	15.1	T	5.25	4.65	109	349
18.6	13.2	15.5	T	5.34	4.73	87.4	304
21.4	15.2	17.8	T	5.85	5.19	28.8	125
		19.9	B		5.58		46.6
22.3	15.8	18.6	T	6.01	5.34	23.1	87.4
		20.7	B		5.74		34.6

3.1 Flame Acceleration in the Obstructed Semi-Confined Vertical Channel

In the previous work with a semi-confined horizontal channel it was found that a H_2-air mixture might be able to accelerate to sonic burning velocity when its expansion ratio σ is larger than the critical expansion ratio σ*, which can be determined using equation (2). In this equation, the properties of the geometry are summarized by the ratio of obstacle spacing and layer height (s/h) and a channel-specific constant K. To compare these findings with the results of the current experimental series in a vertical channel a similar representation as in Fig. 1 was chosen to summarize the results. But since in the current series the channel parameters s and h remained unchanged, all data points of the current series would collapse on one straight line at a s/h-value of 0.625. Therefore, to gain more clarity, the representation was changed in the graphs of Fig. 5, where the expansion ratio σ of the tested mixtures is plotted over the experimental configuration. In the left graph σ was calculated using the maximum concentration cH_2max in the gradient, while in the right graph the mean concentration cH_2av# in the obstructed region (first 4 m after ignition) was used. As in Fig. 1 open symbols stand for experiments where FA was observed, while solid symbols represent experiments without FA.

As in Fig. 1 a straight line can be used to separate the experiments with FA from experiments without FA. To be conservative this line has to be drawn below the symbol representing the experiment with the lowest expansion ratio where still a significant FA was observed. The critical expansion ratio σ* for flame acceleration, determined in this way for the vertical channel has a value of approx. 4.5, which is slightly higher than the value $\sigma^*_{HC} = 4.16$, which is calculated using equation (2) with the constant K_{HC} of the horizontal channel and the s/h ratio of 0.625 of the vertical channel. On the other hand, due to the differences between the two facilities, it seems more practical to define a new K factor for the vertical channel, which is calculated to a value of $K_{VC} = 0.32$ using equation (2).

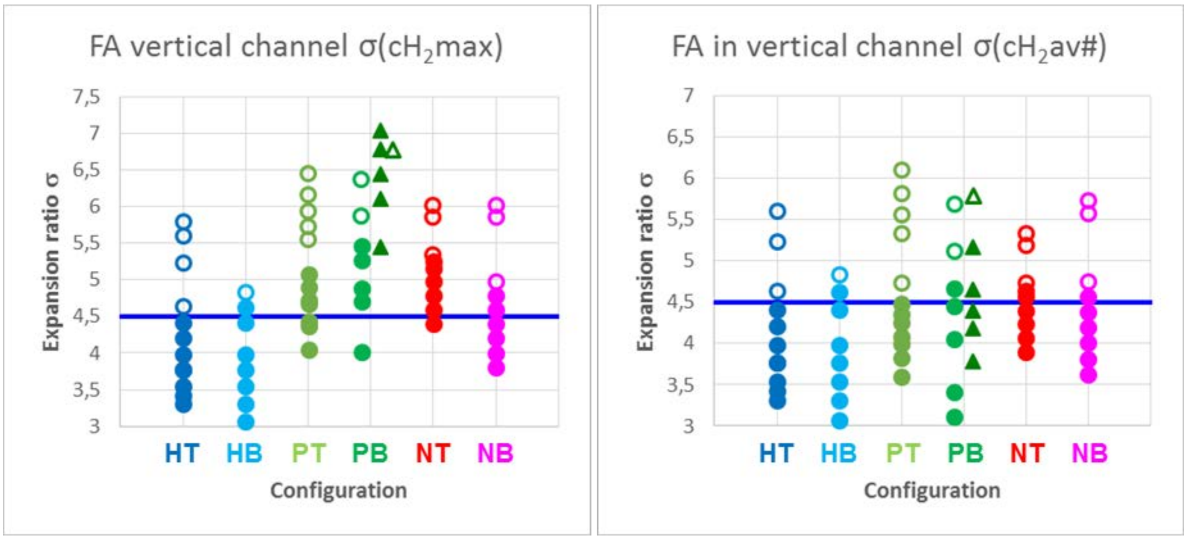

Figure 5. Dimensionless summary of the current experimental series in the semi-confined vertical channel with respect to FA. Left: expansion ratio σ calculated for maximum H_2-concentration cH_2max, right: σ for mean H_2-concentration $cH_2av\#$ in concentration gradient.

The graphs in Fig. 5 demonstrate that when the maximum H_2-concentration in the gradient is used for the calculation of the expansion ratio σ, large deviations from the blue line that indicates the criterion are observed for the onset of FA in the different experimental setups. In contrast to this, the use of the mean concentration for the calculation of σ shows much better consistency in the application of the extended σ*-criterion for semi-confined geometries. In this representation, the onset of FA occurs at roughly the same expansion ratio in all cases investigated.

This behavior indicates that the *Concept of Maximum Concentration* (stratified horizontal H_2-containing layers with a given maximum H_2-concentration in a semi-confined geometry behave similar to homogeneous layers of the same H_2-concentration [9]) is very conservative when applied to the experiments in the vertical channel, and that better agreement is achieved when the mean concentration in the gradient is used. However, in this comparison directions of flame propagation and gradient orientation are different: In all experiments in the horizontal channel the flame had propagated along layers of equal concentrations with a preferential propagation through the hydrogen enriched mixture due to buoyancy effect, while in the vertical channel the flame propagated along the concentration gradient. Thus, in the vertical channel the maximum concentration cannot influence the burning behaviour over the complete channel length and thus the *Concept of Maximum Concentration* is very conservative this case.

The triangular green symbols in Fig. 5 represent a series of experiments with very steep positive concentration gradients (slope > 2 $Vol\%H_2/m$) and bottom ignition. The symbols are plotted separately to avoid overlapping with the other experiments in this configuration (slope < 2 $Vol\%H_2/m$). In the experiments with steep concentration gradients FA occurs at much higher expansion ratios σ compared to the rest of the experiments. It is assumed that the very low H_2-concentrations close to the ignition, which have to be applied to avoid too high H_2-concentrations at the channel top, are the reason for this behavior.

Despite the differences between the two facilities (horizontal and vertical channel) the successful application of a σ-criterion for the onset of FA in semi-confined geometries is a proof for the capacity of the method used.

3.2 DDT and Detonations in the Obstructed Semi-Confined Vertical Channel

In earlier works it was found, that the critical obstacle opening d for a detonation propagation through an obstructed channel with blockage ratios from 0.3 to 0.43 has to be larger than the detonation cell size λ of the mixture ($d/\lambda > 1$) [12-13]. With increasing blockage ratio also the critical dimensionless obstacle diameter increases to $d/\lambda > 3$ for BR = 0.6 and $d/\lambda > 10$ for BR = 0.9 [13-14]. The blockage ratio of the obstacles used in the vertical channel is BR = 0.5, which is the same value as in most of the experiments of the earlier campaign in the horizontal channel, where a value of $d/\lambda \approx 2.5$ was found for the detonation propagation criterion [15]. So the small gap size in the obstacles of the vertical channel (d = 1.5 cm) is definitely too small to allow a detonation to pass through, since λ has its smallest value of approx. 0.95 cm close to the stoichiometric composition of H_2-air-mixtures. This is a specific feature of the vertical channel with respect to detonations, since, when a detonation occurs in the obstructed region of the vertical channel it will be quenched in the next obstacle and has to be re-initiated after it. This periodic quenching and re-initiation surely has a significant influence on the macroscopic flame velocity measured in the experiments, where often mean detonation velocities of 800 m/s to 1500 m/s were observed. To assure the identification of a DDT-event in an experiment additionally sooted steel plates were mounted to the channel walls to record detonation cells, which are a reliable indicator for a detonation event in an experiment.

To check the applicability of criterion (3), which was derived for the horizontal channel, a similar representation for a summary of the results of the experiments in the vertical channel is depicted in Fig. 6. In the graphs the h/λ-values are plotted over the different experimental configurations and again there are two possibilities for plotting the experiments with concentration gradients. They can be either plotted using the detonation cell size corresponding to the maximum H_2-concentration in the gradient, or the detonation cell size for the mean H_2-concentration in the concentration gradient can be used. Fig. 6 compares both representations in which open symbols represent experiments where DDT was observed, while solid symbols stand for experiments without DDT. The extended DDT-criterion (3) for the semi-confined horizontal channel for is added as yellow line at a h/λ-value of 13.5 in both graphs.

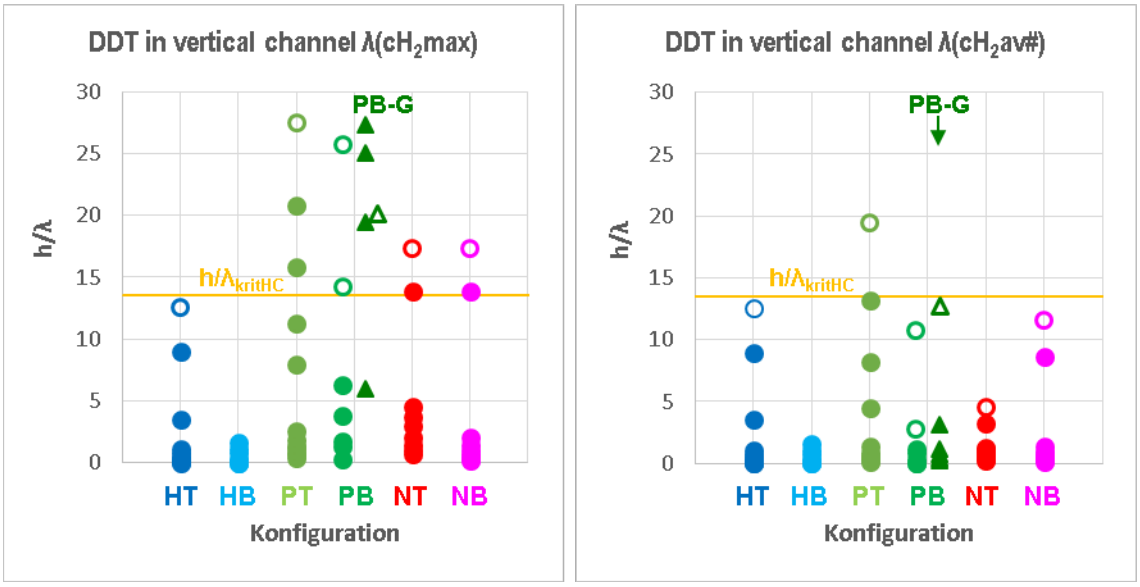

Figure 6. Dimensionless summary of the current experiments in the vertical channel with respect to DDT. Left: h/λ with λ for cH_2max, right: h/λ with λ for $cH_2av\#$ (mean cH_2 in obstructed region).

Fig. 6 shows that for the experiments with homogeneous mixtures in the vertical channel, a good agreement with the DDT-criterion for the horizontal channel of Eq. (3) can be found. All symbols for experiments without DDT lie below the yellow line representing the DDT-criterion derived for the horizontal channel (h/λ_{critHC}). The only data point for an experiment where DDT was observed in this series' is also below this line, but with a value of $\lambda = 12.5$ it lies very close to it. The experiments with mixtures with concentration gradients show better agreement with the DDT-criterion of Eq. (3) when the maximum concentrations cH_2max in the gradient mixtures is used for the determination of λ, compared to the use of the average concentration $cH_2av\#$. It looks reasonable because the supersonic detonation front will preferentially propagate through the mixture with higher detonability corresponding to maximum concentration. Solely for the experiments in configuration PT and the very steep gradients of configuration PB-G the use of $cH_2av\#$ gives a more accurate agreement with Eq. (3), but for the majority of configurations (PB, NT and NB) the possibility of detonations is strongly underestimated. So when the detonation cell sizes are determined using the maximum H_2-concentration in the gradients the extended DDT criterion of Eq. (3) can be used to evaluate the possibility for a DDT event in a stratified mixture in a vertical channel.

4.0 SUMMARY AND CONCLUSION

To evaluate the critical conditions for an effective flame acceleration (FA) to speed of sound and the deflagration-to-detonation transition (DDT) in semi-confined obstructed **vertical layers** of hydrogen-air mixtures numerous combustion experiments were performed in a vertical channel (6 x 0.4 x 0.4 m^3) at KIT. In the tests, slow subsonic and fast sonic deflagrations as well as detonations were observed and the conditions for an FA and DDT were determined and compared with the results of a previous campaign with semi-confined **horizontal layers**.

The criterion for FA in semi-confined horizontal layers of Eq. (2), which uses the expansion ratio σ as measure for the mixture reactivity, was successfully adapted to vertical layers with homogeneous H_2-concentrations. Applied to layers with vertical H_2-concentration gradients it proved to be rather conservative, when, according to the *Concept of Maximum Concentration* (stratified horizontal H_2-containing layers with a given maximum H_2-concentration in a semi-confined geometry behave similar to homogeneous layers of the same H_2-concentration), the maximum concentration in the gradient was used for the calculation of σ. Higher accuracy was achieved when the mean concentration in the gradient was used for the evaluation, which might be due to the different orientations of flame propagation and gradient orientation in the different experimental series'.

The criterion for DDT in semi-confined horizontal layers of Eq. (3), in which the detonation cell size λ represents the mixture reactivity, was also successfully applied to all tested vertical layers with homogeneous and gradient H_2-air mixtures. In some special cases it proved to be rather conservative when, according to the *Concept of Maximum Concentration*, the maximum H_2-concentration in the gradient is used for the evaluation of the mixture reactivity. Using the mean H_2-concentration instead brought better agreement in these cases, but resulted in an underestimation of the DDT-potential of the mixture in the majority of the other cases investigated.

The previously formulated criteria for FA and DDT in semi-confined horizontal H_2-air layers were applied successfully to vertical H_2-air layers with and without concentration gradients, which is a proof for the capacity of the methods used.

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