EXPERIMENTAL STUDY OF HYDROGEN-AIR DEFLAGRATIONS IN FLAT LAYER

A. Friedrich[1], J. Grune[1], T. Jordan[2], A. Kotchourko[2†], N. Kotchourko[1], M. Kuznetsov[2], K. Sempert[1], G. Stern[1]
[1] ProScience GmbH, Parkstr. 9, 76275 Ettlingen, Germany
[2] Research Center Karlsruhe, P.O. Box 3640, 76021 Karlsruhe, Germany

ABSTRACT

In the present paper the results of experiments on study of high-speed deflagrations in flat layer of hydrogen-air mixtures unconfined from below are presented. The experiments were performed in two different rectangular channels: small-scale with mixture volume up to 0.4 m^3 and large-scale with volume up to 5.5 m^3. The main goal of the experiments was to examine the possibility of the layer geometries to maintain high-speed deflagration and detonation. With the aim to study a range of combustion regimes the experiments were performed varying degree of channel obstruction, hydrogen concentration and thickness of the layer. Depending on the experimental conditions all major combustion regimes were observed: slow flame, fast – 'choked' flame and steady-state detonation. It was found that minimum layer thickness in the range of 8 to 15 detonation cell widths is required for sustainable detonations.

1.0 INTRODUCTION

With the increased role of hydrogen as contemporary and future energy carrier the growing demand in understanding of different aspects of industrial safety is coming into light. Since the major hazards are connected with destroying potential of blast waves resulted from combustion and explosion of combustible gases, in particular hydrogen-air mixtures, understanding of conditions providing high-speed deflagrations is of major importance. Intensive studies performed by different authors during last two decades permitted to determine conditions necessary for flame acceleration and detonation onset in confined volumes [1-7] and to derive corresponding criteria [2,4,5]. To approach more realistic geometrical conditions, which are mostly expected in industrial environment, the systems with transverse venting were studied [7-10]. These studies formulated extensions of criteria [10] valid for confined systems with ventings; however the potential of partially confined and unconfined configurations to support flame acceleration, onset of detonation and detonation propagation is still poorly understood. The aim of the presented work is to study hydrogen-air mixture deflagration in one of such configurations and obtain critical conditions defining the possibility of the self-sustained detonation in flat mixture layer.

In the presented work two series of experiments with high-speed deflagrations in flat hydrogen-air mixture layers are described. Preliminary experiments were performed in a small scale facility with the dimensions 1.5 x 0.5 x 0.4 m while the main set of experiments was conducted in a wide rectangular channel with the dimensions 5.7 x 1.6 x 0.6 m. Both channels were opened from below and in both cases two sets of tests were performed. The first preliminary experiments were conducted without any channel obstructions while in later experiments an acceleration section, consisting of a large number of thin metal grids piled up in longitudinal direction, was installed close to the ignition end of the channel. The main set of experiments was performed either in the unobstructed channel or in the channel with obstacles located downstream after the acceleration section. Both presented series included variations of the hydrogen concentration in H_2-air mixtures, whereas only in the main experiments additionally the layer thickness was altered. Hydrogen concentration was maintained uniform throughout the whole channel at the level of non-uniformity not more than 1% vol. of H_2. The

† Corresponding author: alexei.kotchourko@iket.fzk.de

experiments were equipped with pressure transducers (only main experiments), ion probes, light sensors, and high-speed photography. The sequence of frames obtained from high-speed photography was processed using 'background-oriented schlieren' method with the aim to provide visualization assistance of the flame propagation process. Depending on the conditions of the test, various regimes of flame propagation were observed: slow flame, fast deflagration up to one identified as 'choked' regime and steady-state detonation. In one experiment the propagation of a self-sustained detonation was proved by registration of detonation cells on sooted foils.

2.0 EXPERIMENTAL DETAILS

Preliminary experiments. The preliminary experiments were carried out with the aim to obtain pilot information permitting to design the large-scale facility and to plan the details of the main set of experiments. These preliminary experiments were performed in a small scale facility sketched in Figure 1.

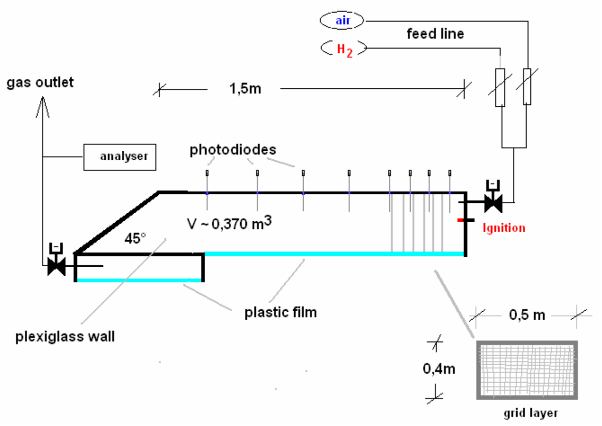

Figure 1. Sketch of the small scale facility for the preliminary experiments.

The small scale facility consisted of a rectangular channel with a length of 1.5 m, a width of 0.5 m and a height of 0.4 m that ended at a tilted (45°) wall, enclosing a volume of 0.37 m^3. Its frame was built of metal bars, while the side and top faces of it were made of p*lexiglas* to allow optical observation of the experiments.

Figure 2. Photographs of the unobstructed channel (left) and the flame distributor and the grid layers installed in later experiments (right).

The channel had one open face at its bottom that was sealed by a thin plastic film before the filling. This film was not intentionally removed or destroyed before the ignition. The ignition source (spark plug) was mounted in the centre of the vertical end wall of the channel which was fabricated of metal sheet. In all experiments a flame distributor, made of perforated metal sheet was used, consisting of a cylindrical body covering the ignition source and a plate that covered the whole cross-section of the channel. It was employed to obtain an almost planar flame front traveling through the channel. The facility was equipped with a row of photodiodes and ionization probes, located in the middle of the top wall of the channel. In later experiments, to obtain higher flame propagation velocities, additional obstacles, consisting of 64 metal grid layers, were introduced between flame distributor and position 400 mm from the ignition end of the channel. Figure 2 shows photographs of the facility.

Main experiments. All main experiments were performed in a channel with the dimensions 5.7 m x 1.6 m x 0.6 m (L x W x H) designed and assembled by Pro-Science GmbH in the safety vessel A1 (Research Center Karlsruhe).

The channel, opened from the bottom and on one end, was constructed of wooden walls, covered by thin metal sheets and fastened to metal bars (Bosch-Profile 90 x 90 mm), connected to holders inside the safety vessel. In its interior the channel was stabilized by vertical (only edges and ignition wall) and horizontal beams (Bosch-Profile 45 x 45 mm) to realize different channel heights. The channel heights used in the experiments were 0.6 m, 0.3 m and 0.15 m, producing internal volumes of 5.47 m^3, 2.74 m^3 and 1.37 m^3 respectively.

Figure 3. Photograph and schematic (with obstacles) of the main experimental facility.

The channel was filled with the H_2-air mixture of given composition and after the completion of the filling procedure the mixture was ignited. In all experiments specially designed flame distributor was used to spread the flame at the ignition end over the whole width of the channel. It consisted of an open-ended tube that was fixed in horizontal direction parallel to the ignition end wall of the channel and was equipped with a row of holes pointing backwards in the direction of the wall. In the middle of the tube the ignition source (electrodes) was located. Additionally, to achieve higher flame velocities, a booster section and obstacles were placed into the channel in some experiments. In the booster section the layers of a thin metal grid were piled in longitudinal direction over a length of 70 cm. At the end of this section the first obstacle was installed. Other obstacles, all with a blockage ratio of 60%, were mounted at a distance of 50 cm from each other along the channel.

Test matrix. In total nine experiments were conducted in the small scale facility. Two experiments without hydrogen were performed to check the experimental procedure and the triggering of the data acquisition system, and seven experiments with hydrogen concentrations of 15, 20 and 25% vol. were conducted. Table 1 summarizes the initial conditions for all preliminary experiments.

Table 1. Test matrix for the preliminary experiments.

Experiment #	C(H_2), [% vol.]	Acceleration section
HT01, HT02	0	-
HT03, HT04	15	-
HT05	20	-
HT06	25	-
HT07	15	+
HT08	20	+
HT09	25	+

Ten tests in the main series were performed. In these tests the layer heights and hydrogen concentrations were varied. One additional experiment was conducted in advance to check the experimental procedure with the destruction of the film and the subsequent ignition, as well as the triggering of the data acquisition system. The test matrix for the main set is shown in Table 2.

Table 2. Test matrix for the main experiments.

Experiment #	Thikness of layer δ, [m]	C(H_2), [% vol.]	Obstruction BR, [%]
HLT00		0	-
HLT01	0.30	15	-
HLT02	0.30	17.5	-
HLT03	0.30	25	-
HLT04	0.30	15	60
HLT05	0.30	20	60
HLT06	0.60	15	60
HLT07	0.15	15	60
HLT08	0.15	20	60
HLT09	0.15	25	60
HLT10	0.30	25	60

Filling procedure. In all experiments the open faces of the channels were closed with a thin plastic film to assure that the volume was sealed during the filling procedure. The volumes were filled with hydrogen-air mixture of a given concentration that was prepared in mixing chamber.

Hydrogen was supplied by gas cylinders, while the air required for the mixtures was taken from the compressed air system. To control the mixture composition the gas samples were taken from the mixing chamber and were examined by a gas analysis system. Until a stable mixture composition was reached, the mixture was piped from the mixing chamber through a bypass leading to the outside from safety vessel A1. Finally, the valves of bypass and gas injection were switched and the mixture was piped into the channel. In the main experiments an injection pipe, located at the top of the channel close to the ignition end inside the channel, was used to provide an injection of the mixture over almost the whole width of the channel. During the filling procedure, which lasted up to 1 hour, the composition of the injected gas was checked several times.

In the preliminary experiments the mixture was ignited after the completion of the filling procedure, while in the main experiments the plastic film, covering the bottom face of the channel, was destroyed by three sets of heating wires to avoid an influence of the film on the combustion propagation conditions. Then, immediately after the destruction of the film, the mixture was ignited. To control the mixture quality and to analyze the exhaust gas taken away from the channel, a gas analysis system (*Fisher-Rosemount* series *MLT*) with a measuring range from 0 to 100 % vol. of H_2 and 0 to 100 % of O_2 was used.

Ignition source and registration. In the experiments in small scale a standard commercial spark plug was used for ignition. A high frequency spark generator was used in the large scale facility. The spark was generated between two electrodes in a distance of 3 mm to each other. A stable current and high voltage discharge at 60 kV with a frequency of 20 kHz produces a stable electric arc between the electrodes of the ignition device. Using the control unit the discharge power was maintained at the level of 10 to 20 W.

In the main set of experiments at the ceiling of the channel three rows of sensors were installed: in total 13 photodiodes, 16 ion-probes and 5 pressure gauges; up to 6 supplementary pressure gauges were installed on the floor (2 transducers) and the walls (5 transducers) of the safety vessel A1. For registration of the pressure records *PCB* type transducers were used (*PCB*, models 112A22, 113A24 and 113A31). Additionally, an optical observation of the combustion process was made possible due to two sets of windows at positions close to the ignition and the open end of the channel. The high speed movies of the experiments were recorded through the *plexiglas* side walls of the small scale facility or the windows of the large channel using *Weinberger* camera (model *SpeedCam Visario 1500*) with a maximum resolution of 1536 x 1024 pixel and a maximum framing rate of up to 10000 fps at a reduced resolution of 512 x 192 pixel. To observe the whole window width with the high-speed camera maximum framing rates of 4000 fps (resolution 768 x 512 pixel) were used in the main experiments. In both experimental series an irregular pattern was located behind the opposite end of the channel/window to allow processing of the movies using background-oriented-schlieren (BOS) technique.

3.0 RESULTS

Preliminary experiments. Four experiments in the unobstructed small scale facility were conducted with hydrogen concentration of 15, 20 and 25 % vol. H_2.

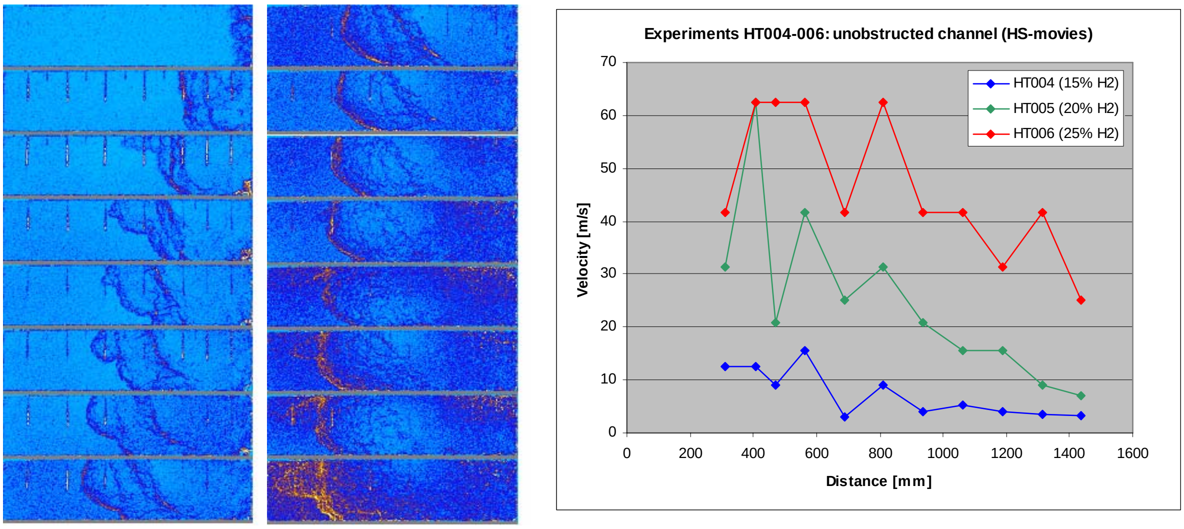

Figure 4. Photographs taken from the processed BOS-high-speed-movie of experiment HT004 and the corresponding v-x diagram of all experiments in the unobstructed channel. Visible vertical stripes on the photographs are the ion probes.

Two tests were performed with 15% vol. H_2 (HT003 and HT004) at the beginning of the series since the “prototype” flame distributor, made of *plexiglas*, was destroyed in the first experiment and had to be replaced by the more solid one described above. In these experiments the observed flame speed was in the range from 5 to 50 m/s (maximum in test HT006, $C(H_2)$ = 25% vol.). With increasing hydrogen fraction a growth of the flame velocity was registered; though there was no strong flame acceleration over the whole length of the channel.

The visible flame speed was additionally evaluated using the processed BOS-high-speed-photographs. The frames taken from the movie of experiment HT004 and the corresponding v-x diagram of all experiments in the unobstructed channel are shown in Figure 4. Both methods produce similar flame propagation velocities for the three experiments performed in this configuration.

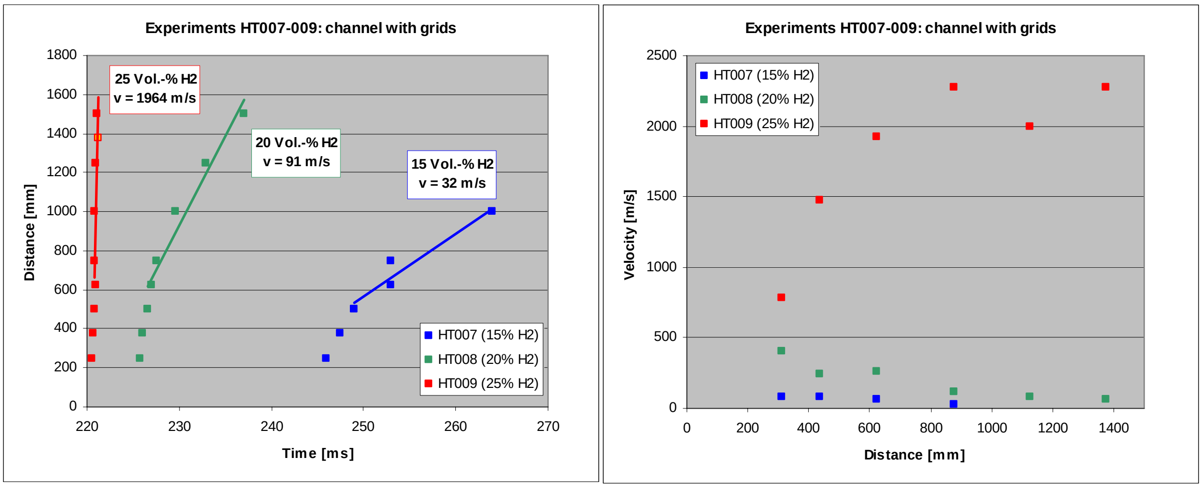

Figure 5. x-t - and v-x - diagrams of preliminary experiments HT007-009 in the obstructed channel.

Three experiments with 64 grid layers between the flame distributor and position 400 mm were carried out with hydrogen concentrations of 15, 20 and 25 % vol. The results are summarized in Figure 5. In the x-t diagram (Figure 5, left) the slope of a linear fit through the measured data points at positions farther than 400 mm from the ignition source (end of acceleration section) was used to determine the mean flame propagation velocity in the experiments. The v-x diagram of the experiments (Figure 5, right) shows that in experiment HT007 ($C(H_2)$ = 15%) slow flame propagation velocities were determined inside and outside the acceleration section of the channel, while in HT008 ($C(H_2)$ = 20%) fast flame velocities were calculated from the signals of the sensors in the obstructed region. In both experiments the flame velocity decreased after the flame had left the acceleration section of the channel. In contrast to this, in experiment HT009 ($C(H_2)$ = 25%) the flame further accelerated after having left the obstructed region of the channel, reaching detonation velocity at position ca. 500 mm from the ignition source. This velocity then remained almost stable over the whole length of the channel. HT009 was the last experiment conducted in the small scale facility. Due to the large loads of a detonation inside the channel it was completely destroyed.

Main experiments. Experiments in the unobstructed channel. Three experiments without booster section and obstacles were performed in the large scale facility with a layer height of 0.3 m and hydrogen concentrations of 15, 17.5 and 25 % vol. H_2.

Figure 6 (left) shows the x-t-diagram of the three experiments HLT01-03, generated with the values of the arrival time of the flame front at the ion-probes. The velocity of the flame front was estimated by the slope of a linear fit through the measured data points. The right part of Figure 6 shows photographs taken from the high-speed movie recorded during experiment HLT03. This movie was recorded with a framing rate of 4000 fps but only every 8th image is depicted in Figure 6, leading to time step of 2 ms between two photographs.

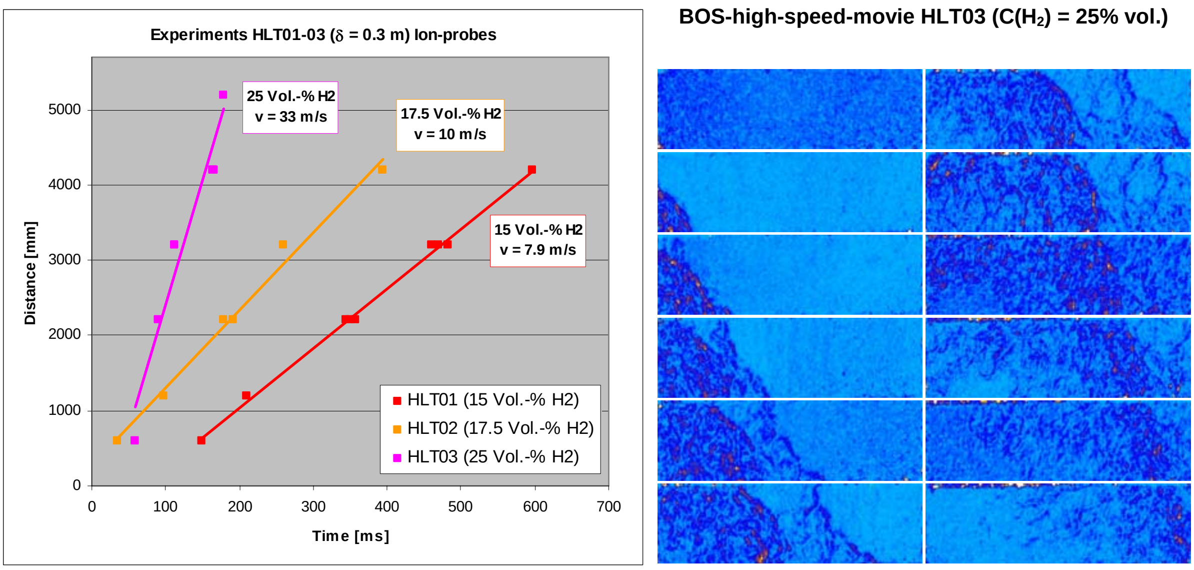

Figure 6. x-t-diagram of experiments HLT01 - HLT03 (δ = 0.3 m) in the unobstructed channel and sequence of photographs taken from the high-speed movie of experiment HLT03.

The diagram shows that in all three experiments slow flame propagation velocities with a maximum mean value of approx. 33 m/s for HLT03 ($C(H_2)$ = 25%) were determined using the linear fits. With approx. 9 m/s the velocity derived from the analysis of the high-speed-movie of experiment HLT01 (15%) lies very close to the one calculated using the sensor signals. For experiment HLT03 (25%), possibly due to a non-planarity of the flame front, two fronts travel through the visible part of the channel with velocities of approx. 33 and 60 m/s. The lower flame velocity is almost the same as the mean velocity calculated using the linear fit through all data points, while the higher one correlates well with the calculated velocity using the sensor signals for the region observed by the high-speed camera (v = 52 m/s in between positions 600 and 2200 mm from the ignition).

Experiments in the channel with booster section and obstacles. In total seven experiments with the obstructed channel were performed. For the layer heights of 0.15 m and 0.3 m the experiments with three hydrogen concentrations (15, 20 and 25%) were conducted, whereas only one experiment with a layer height of 0.6 m was performed (15%).

Two experiments, with the layer thickness of 0.15 m and H_2 concentration equal to 15 and 20%, show slow flame propagation with the flame velocities of 10 and 33 m/s. These data are obtained on the basis of ion probe recordings at the distance more than 2 m from ignition source. The analysis of the high-speed-movies of these experiments gave the higher velocities of 16 and 188 m/s, which were achieved in the region where the transparent windows were positioned. These windows were located between 1.050 and 1.850 m from the ignition wall and therefore the propagation velocity is still affected by the acceleration section. The velocities calculated from the sensor signals in this region lay in the range of 8 to 13 m/s for HLT07 and 57 to 270 m/s for HLT08. The experiment with 25% vol. and a layer height of 0.15 m (HLT09) shows a different behavior: observed velocity was almost constant over the whole channel and achieved the value of approx. 820 m/s.

In the experiment HLT09 the flame further accelerates after it has left the acceleration section of the channel. The calculated maximum velocity is close to 1600 m/s. After this maximum, with increasing distance from the ignition source, the velocity slowly decreases to a value of approx. 600 m/s near to the end of the channel. The pressures measured along the top of the channel vary from 9 to 13 bar.

This behavior indicates that a detonation or quasi-detonation occurred in the region of 2 m from the ignition, but the detonation then decayed to a deflagration with increasing distance.

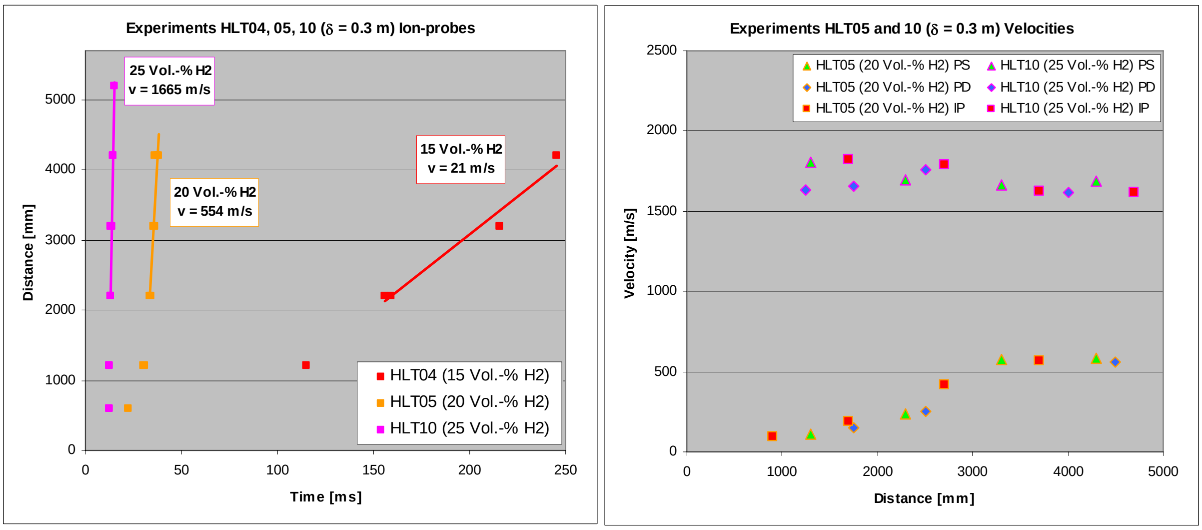

Figure 7. x-t- and v-x-diagram of experiments in the obstructed channel with a layer height of δ = 0.30 m and hydrogen concentrations of 15, 20 and 25% vol.

Three experiments with the layer height of 0.3 m and hydrogen concentrations of 15, 20 and 25% vol. were conducted in the obstructed channel. The left part of Figure 7 shows the x-t-diagram derived from the signals of the ion probes in these experiments. Again, with respect to the acceleration section, a linear fit through the data points recorded in a distance of more than 2 m from the ignition was used to estimate the flame propagation velocities.

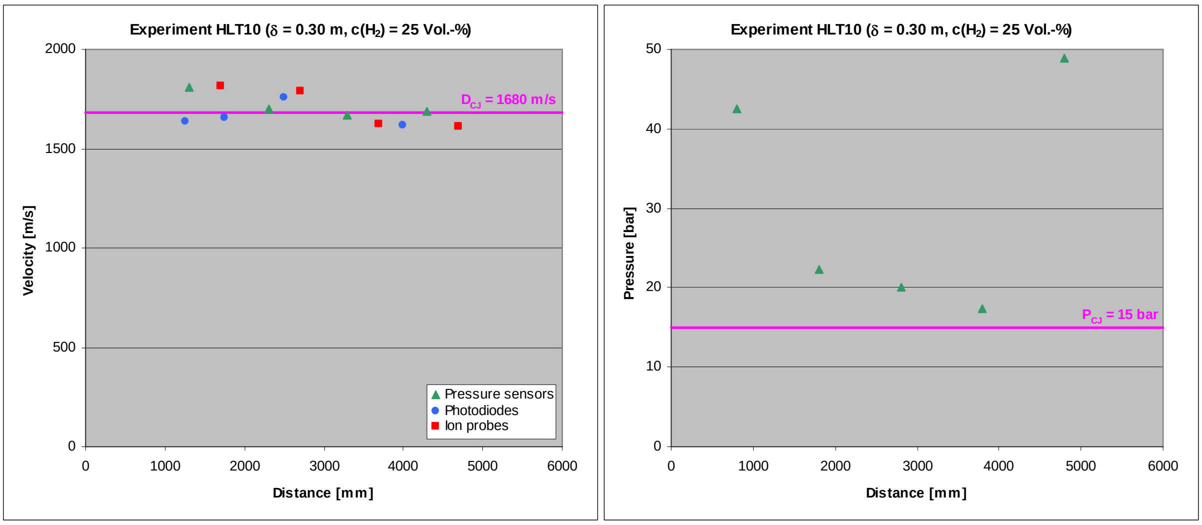

Figure 8. Comparison of the experimental and theoretical predictions (Chapman-Jouguet values) for the pressure (right) and flame speed (left) in the experiment HLT10 (δ = 0.30 m, $C(H_2)$ = 25% vol.).

In this set of tests strong dependence on hydrogen concentration was found. In the experiment HLT04 (15%) mean velocity was equal to 21 m/s, in the experiment with 20% (HLT05) the mean velocity grows to 554 m/s, and in the experiment HLT10 (25%) the flame velocity achieved the value of 1665 m/s. The right part of Figure 8 shows the v-x-diagram of the experiments HLT05 and HLT10 in which the velocities, calculated for all centric sensors are plotted. As it can be seen, in the experiment HLT05

(20%) the flame further accelerated after it has left the acceleration section, but the velocity remains stable at a value of approx. 550 m/s for the region from about 3 to 4.5 m.

In experiment HLT10 (25%) a stable flame propagation velocity of approx. 1700 m/s had established soon after the flame had left the acceleration section of the channel. This velocity is very close to the calculated Chapman-Jouguet detonation velocity of D_{CJ} = 1680 m/s for this mixture. At the beginning and at the end of the channel the pressure values are significantly higher than the calculated Chapman-Jouguet detonation pressures, though from 1.8 m to 3.8 m they are close to the theoretical values. As an additional confirmation of the existence of self-sustained detonation propagating through out the entire facility the fact of the flame front and pressure wave coupling along the whole facility length can be brought to play (Figure 9).

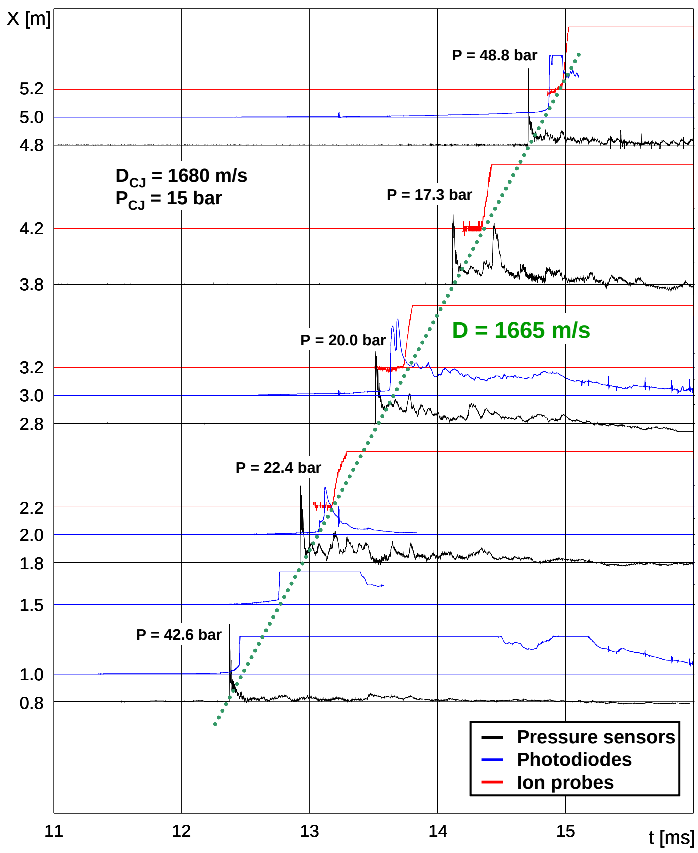

Figure 9. x-t -diagram of experiment HLT10 (δ = 0.30 m, C(H_2) = 25% vol.).

Aadditionally with the aim to register possible detonation sooted steel plates were placed into the channel in test HLT10. They were installed at the top and at the side walls of the channel. Figure 10 shows two examples of the typical diamond patterns obtained in the experiment. Average cell width of 15 - 17 mm obtained from many places inside the channel correspond very well to the literature data for hydrogen-air mixture of 25% vol. H_2.

Only one experiment was performed with a layer thickness of 0.6 m (HLT06: C(H_2) = 15%). In this experiment the flame front reaches its maximum velocity in the region of approx. 4 m from the ignition with the corresponding velocities reaching in the maximum 300 – 450 m/s, demonstrating noticeable flame acceleration. In the diagrams depicted so far only the influence of the hydrogen fraction in the mixtures on the combustion behavior was discussed. To show the influence of the other parameter, namely, the layer thickness, in Figure 11 the mean velocities, represented by the slope of a linear fit through the measured arrival times of the flame front at the ion-probes, for all experiments with a hydrogen concentration of 15% vol. (left) and 20% vol. (right) are compared. The black curves in the diagrams represent experiments in the unobstructed channel, while the other curves stand for experiments with booster section and obstacles.

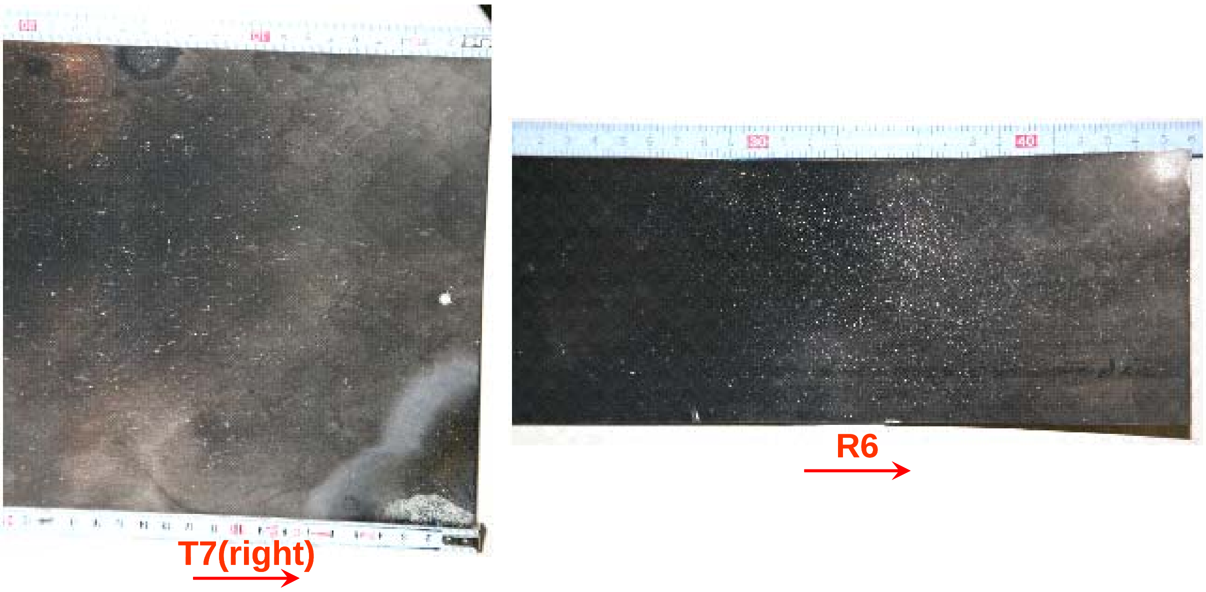

Figure 10. Photographs of the sooted plates with the characteristic pattern (experiment HLT10, $\delta = 0.30$ m, C(H_2) = 25% vol.). Arrows show direction of the detonation propagation.

As can be seen from both diagrams, the use of the acceleration section and additional obstacles leads to higher flame velocities. More important is that an increase of the layer thickness produces faster combustion regimes. While the flame propagation velocities are low for the experiments with 0.15 m and slightly higher with 0.3 m layer, considerably higher flame velocities were observed in the experiments with $\delta = 0.6$ m. For experiment HLT01 (15% H_2) mean velocity of 195 m/s, with a maximum velocity of more than 300 m/s, and for experiment HLT02 (only 17.5% vol. H_2) mean velocity of 512 m/s was found.

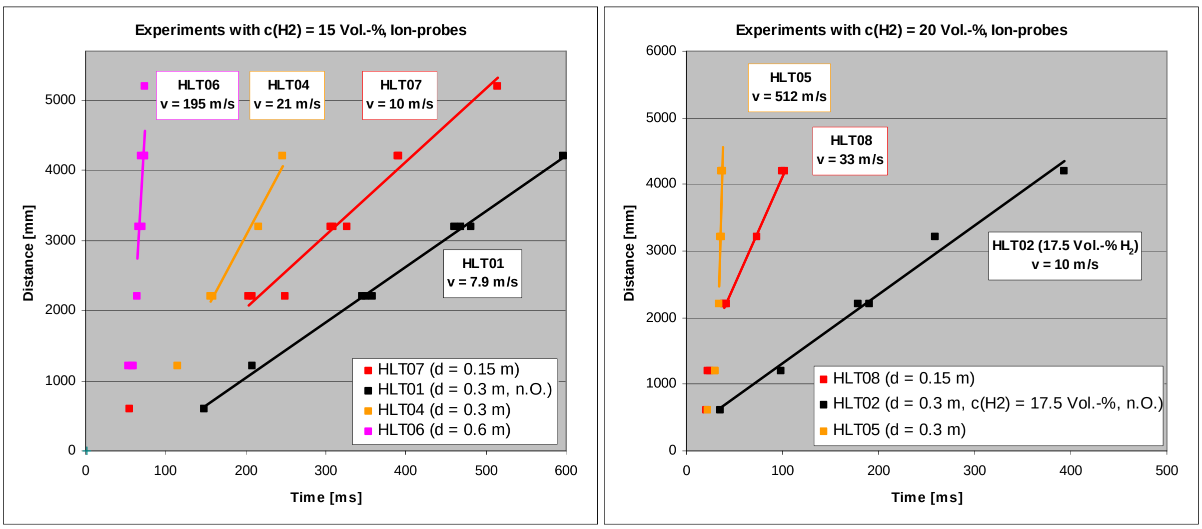

Figure 11. Comparison of all experiments with H_2 concentration of 15% (left) and of 20% (right). Black colour is used for the tests with unobstructed channel, HLT02 in right diagram only 17.5%.

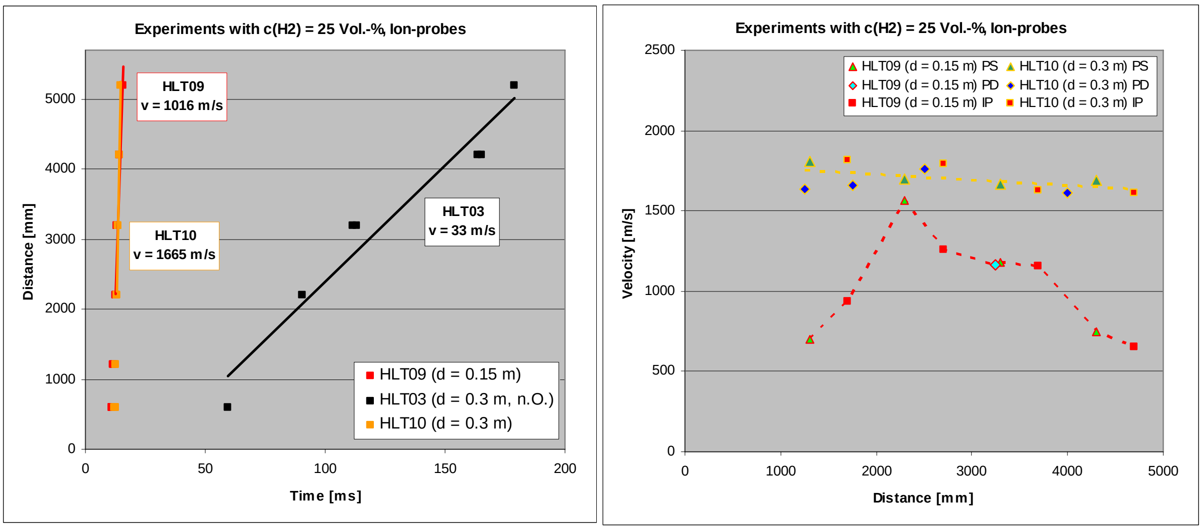

Figure 12. Comparison of all experiments with H_2 concentration of 25% vol. (black curve represents experiment HLT03 in the unobstructed channel) (left), and v-x-diagram for the experiments HLT09 and HLT10 (right).

The comparison of the observed combustion regimes in the experiments with hydrogen concentration of 25% are presented in Figure 12. Similarly as with lower concentrations, the higher flame speeds were registered in the experiments with the presence of the acceleration section and additional obstacles. The two experiments in the obstructed channel demonstrated, that with increase of the layer thickness the flame speed also increases: in the experiment HLT09 (δ = 0.3 m) a decaying detonation with a maximum velocity of approx. 1600 m/s was detected, while in experiment HLT10 (δ = 0.3 m) the steady detonation velocity of approx. 1650 m/s was observed over the whole length of the channel.

4.0 SUMMARY

In total ten combustion experiments have been performed in the facility. Three of them were curried out in the unobstructed channel, while seven were done with booster section and obstacles in the channel. All unobstructed experiments resulted in slow flame propagation regimes with a maximum flame velocity of approximately 33 m/s.

Table 3. Combustion regime in flat layer of hydrogen-air mixture depending on layer thickness and hydrogen concentration in the mixture.

C(H_2), [% VOL.]	LAYER HEIGHT δ, [M]: 0.15	0.30	0.60
15	**SLOW DEFLAGRATION**	**SLOW DEFLAGRATION**	**FAST DEFLAGRATION**
20	**FAST DEFLAGRATION**	**FAST DEFLAGRATION**	*FAST DEFLAGRATION*
25	**DECAYING DETONATION**	**DETONATION**	*DETONATION*

In the experiments with the obstructed channel three different combustion regimes were distinctly distinguished: slow deflagration, fast deflagrations and detonation. The results of the conducted experiments are summarized in Table 3. Two cells in the matrix were not proven experimentally since the facility was destroyed in experiment HLT10 with a layer height of 0.3 m and a hydrogen concentration of 25%. However, the trend derived from the experiments let make a good guess that for the layer thickness of 0.6 m with hydrogen concentration more than 20% the fast deflagration or detonation can be expected.

The analysis of the results of the experiments permit to conclude that the possibility of the fast regimes of deflagration as well as the possibility of self-sustained detonation in the wide flat layers of hydrogen-air mixtures is defined by the layer thickness. The critical layer thickness was evaluated on the basis of the results of the tests in two different geometry scales. From the experiments in small-scale facility the critical value was evaluated as 7 – 20 detonation cell widths. On the basis of the results obtained from the experiments in the large-scale facility the range of the value for critical thickness was limited to 7.5 - 15 detonation cell widths.

This work was performed in the frames of internal project HyTunnel carried out in EC NoE HySafe.

REFRENCES

1. Knystautas R., J.H. Lee, and C.M. Guirao. The critical tube diameter for detonation failure in hydrocarbon-air mixtures. Combust. Flame, 48(1):63-83, 1982.
2. S. B. Dorofeev, V. P. Sidorov, M. S. Kuznetsov, I. D. Matsukov, and V. I. Alekseev. Effect of scale on the onset of detonations. Shock Waves, 2000, v. 10, pp. 137-149
3. Lee, J.H.S., Moen, I.O.: The mechanism of transition from deflagration to detonation in vapor cloud explosion. Prog. Energy Combustion Sci. 16, pp. 359-389 (1980)
4. Dorofeev S. B., M. S. Kuznetsov, V. I. Alekseev, A. A. Efimenko, and W. Breitung. Evaluation of limits for effective flame acceleration in hydrogen mixtures. J. Loss Prev. Proces. Ind., 14, 583 (2001).
5. Dorofeev S., V. Sidorov, A. Dvoinishnikov, and W. Breitung. Deflagration to Detonation Transition in Large Confined Volume of Lean Hydrogen-Air Mixtures. Combustion and Flame, 104: 95-110 (1996)
6. Ciccarelly G., J. Boccio. T. Ginsberg, C. Finfrock, L. Gerlach, H. Tagava, and A. Malliakos. The Effect of Initial Temperature on Flame Acceleration and Deflagration-to-Detonation Transition Phenomenon. NUREG/CR-6509, BNL-NUREG-52515, 1998.
7. Sherman M., M. Berman, and R. Beyer. Experimental Investigation of Pressure and Blockage Effects on Combustion Limits in H2-Air-Steam Mixtures. SAND 91-0252, 1993.
8. Sherman M., S. Tieszen, and W. Benedick. The Effect of Obstacles and Transverse Venting on Flame Acceleration and Transition to Detonation for Hydrogen-Air Mixtures at Large Scale. NUREG/CR-5275, SAND 85-1264, 1989.
9. Ciccarelli, G., Boccio, J., Ginsberg, T., Finfrock, C., Gerlach, L., Tagava, H., & Malliakos, A. (1998). The effect of lateral venting on deflagration-to-detonation transition in hydrogen\u2013air steam mixtures at various initial temperatures. NUREG/CR-6524, BNLNUREG- 52518. Washington, DC: US NRC.
10. Alekseev V.I., Kuznetsov M.S., Yankin Yu.G., Dorofeev S.B. Experimental study of flame acceleration and DDT under conditions of transverse venting. J. Loss Prev. Proc. Ind., 2001, Vol 14/6, pp. 591-596