DETONATION WAVE PROPAGATION IN SEMI-CONFINED LAYERS OF HYDROGEN-AIR AND HYDROGEN-OXYGEN MIXTURES

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ABSTRACT

This paper presents results of an experimental investigation on detonation wave propagation in semi-confined geometries. Large scale experiments were performed in layers up to 0.6 m filled with uniform and non-uniform hydrogen–air mixtures in a rectangular channel (width 3 m; length 9 m) which is open from below. A semi confined driver section is used to accelerate hydrogen flames from weak ignition to detonation. The detonation propagation was observed in a 7 m long unobstructed part of the channel. Pressure measurements, ionization probes, soot-records and high speed imaging were used to observe the detonation propagation. Critical conditions for detonation propagation in different layer thicknesses are presented for uniform H_2/air-mixtures, as well as experiments with uniform H_2/O_2 mixtures in a down scaled transparent channel. Finally detail investigations on the detonation wave propagation in H_2/air-mixtures with concentration gradients are shown.

1.0 INTRODUCTION

Semi-confined combustion scenarios are very important from the practical point of view. Accidentally released H_2 can accumulate below the ceiling of a room, garage, tunnel or other roofs like the containment of nuclear reactor. Such scenarios can create local pockets of reactive H_2/air-mixtures. In case of an ignition flames in obstructed areas can rapidly accelerate to sonic speed and a deflagration to detonation transition (DDT) cannot be excluded. Then the detonation wave (DW) might enter semi-confined areas with lower H_2/air concentrations. The resulting pressure loads of detonations are very dangerous and may exceed the design pressure of many industrial objects, sometimes by an order of magnitude. For safety analyses and accident-management it is very important to know the limits for the propagation of a DW in semi-confined geometries, especially in the presence of concentration gradients. Similar scenarios can occur in areas and housings of smaller industry facilities where H_2 and O_2 are handled or produced.

The transition from deflagration to detonation (DDT) and the shock inducted self-sustained DW propagation in premixed gas was intensively studied [1], but it still remain phenomena with open questions. There is no theory predicting the limits for detonation propagation. Detonation propagation limits were found to be dependent on the initial gas conditions and the boundary conditions (tube dimensions, geometry and wall surface). However, detonation limits are present and separate the propagation of detonations from failure of the detonation mode.

Experimental data of H_2/air combustions in semi-confined layer geometries are sparse and mostly performed by the author's experimental group [2–6]. Flame acceleration and DDT initiation and propagation in obstructed semi-confined channels were investigated in large scale [2] and small scale [4] for H_2/air mixtures. A study of flame propagation, detonation initiation and the shape of the detonation front for H_2/air mixtures with concentration gradients is presented in [5]. Critical conditions for hydrogen-air detonations in partially confined geometry for a uniform stoichiometric mixture and a mixture with a concentration gradient were formulated in [6]. For a uniform, stoichiometric hydrogen–air mixture it was found that a stable detonation propagation is possible for layer thicknesses of 3 cm or more. Other theoretical publications related to detonation propagation in semi-confined layer geometry can be found in [7]. The influence of a compressible boundary on the propagation of gaseous detonations is studied in small scale in [8] by the use of H_2-O_2 and N_2 as inert boundary.

Goal of this work is to investigate the critical conditions for a stable detonation wave propagation in horizontal semi-confined unobstructed flat layers for H_2/air and H_2/O_2 mixtures. Uniform mixtures and non-uniform mixtures were investigated. The variables for uniform mixtures are the layer thickness h and the fuel concentration, while the maximum H_2-concentration at the ceiling and the shape of the concentration profile are used as variables for layers with a natural fuel concentration gradient, which, in this case, is perpendicular to the flame propagation direction.

2.0 EXPERIMENTAL SET-UP

The large scale experiments were performed in a facility at the Karlsruhe Institute of Technology (KIT). The rectangular combustion channel (width 3 m; length 9 m) which is open from below was placed in a 100 m^3 cylindrical safety vessel. The facility is described in detail in [2-6].

2.1 Test channels

Fig. 1 shows the dimensions and basic configurations of the channels used in this work. The set up for the large scale experiments with uniform H_2/air mixtures shows Fig. 1 A. The 9 m long and 3 m wide channel is equipped with a highly obstructed effective flame acceleration section (X in Fig. 1 A) (booster (Fig. 2 a)). The height of the booster is 0.2 m in all experiments. The large facility additionally has a framed unobstructed observation section (Y in Fig. 1 A) of 1.3 m length. A polyethylene film (thickness 5.8 µm) separates the fuel mixture from the ambient air (Fig. 2 b), and also the open channel end was covered with the same foil. By replacing the initial air with pre-mixed mixture from the feed to the exhaust the channels were filled with the test mixture. To increase the mixture reactivity in the booster and observation section additional H_2 amounts were injected from a pressure vessel shortly before the ignition. The ignition via hot wire was placed in a perforated tube close to the ceiling in the booster section. The channel height is 0.6 m, different test mixture heights h were realized by varying the height level of the film (Fig. 2 b), which influences the geometrical shape of the observation section.

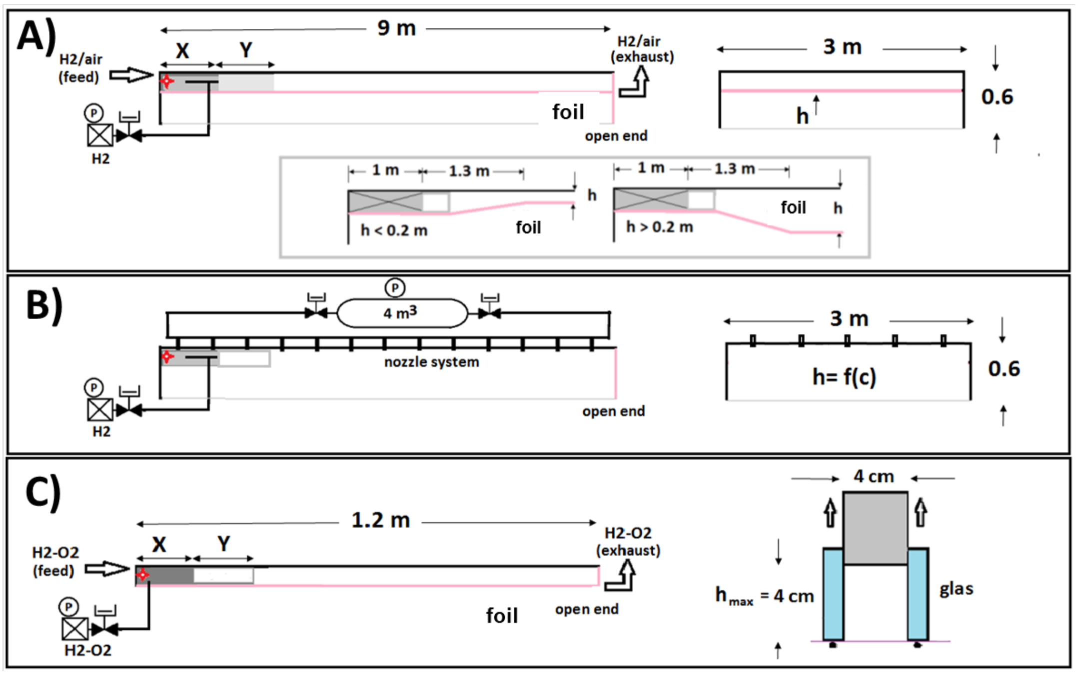

Figure 1: Scheme of the semi-confined channels.

Experiments with concentration gradients were only performed in the large scale facility. In this configuration (Fig. 1 B) no separation film between the fuel mixture and the ambient air was used. Again the channel was completely open from below. The main difference was the mixture preparation. A 4 m^3 pressure vessel was used as a reservoir from where defined H_2 or H_2/air amounts were injected through

75 nozzles into the channel in the directions of its ceiling. The injection lines are visible in Fig. 2 c, for more details see chapter 2.2.
The set up for small scale experiments with uniform H_2/O_2 mixtures shows Fig. 1 C. The 1.2 m long channel is a down scaled version of the large one described above. The width of the small channel is 0.04 m and its height h is variable by moving the transparent side walls up to 0.04 m (Fig. 1 C). The booster height is also variable (Fig. 2 e) and the observation section is not framed. Shortly before the spark ignition the initial test mixture in the booster section was replaced by stoichiometric H_2/O_2 mixtures.

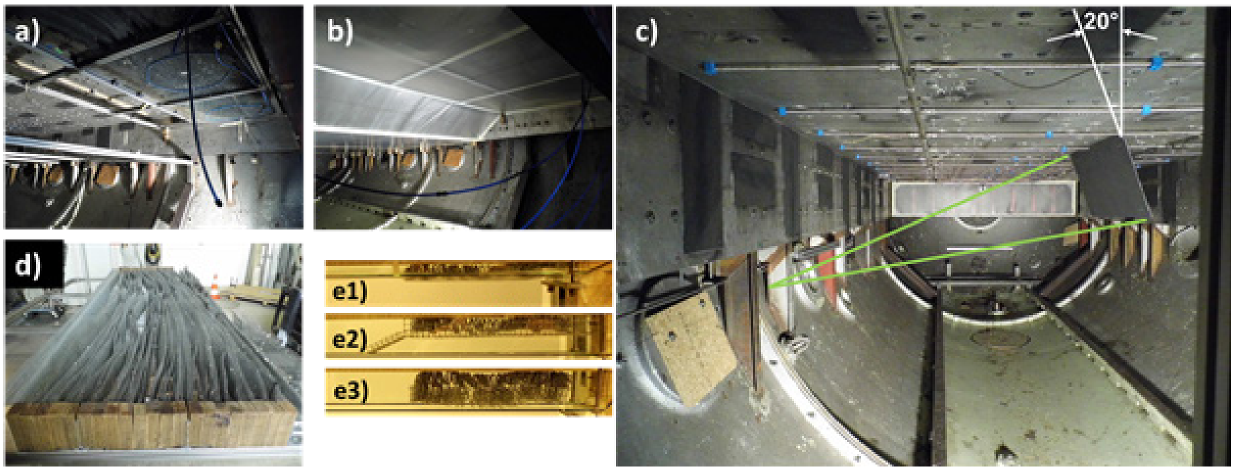

Figure 2: a) Booster in the large channel in uniform mixture configuration. b) Booster and observation section in the large channel covered with polyethylene film (uniform mixture configuration, layer height h = 60 cm, ready for ignition). c) View from the booster along the large channel (gradient mixture configuration, ready for ignition). d) Booster device: length 1 m, width 3 m and height 0.2 m. e) Examples for different booster heights in the small scale channel.

2.2 Mixture preparation

In general in all configurations the test section was filled with a well-defined test mixture, while a more reactive mixture was generated in the booster section to initiate a detonation. The main philosophy in the preparation of the experiments was to avoid any separations like a foil or diaphragms in the path of flame. The reactive mixture in the booster section consists of the same components as the test mixture and the combustion starts from a weak ignition and accelerates quickly in semi-confined conditions to a detonation.

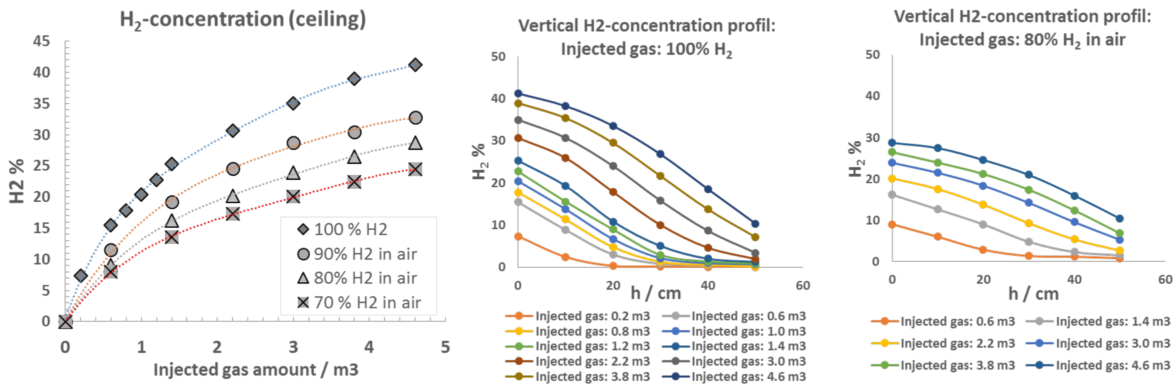

Figure 3: Properties of the H_2/air concentration gradients in air.

Due to the use of calibrated flow controllers and a concentration measurement in the exhaust flow the accuracy of the uniform test mixtures is better than +/- 0.15 % H_2 for H_2/air and +/- 0.25 % H_2 for H_2/O_2.

The preparation of the vertical concentration gradients with a high uniformity over the channel area is based on an extensively tested gas injection procedure. This procedure is well described in [5]. Fig. 3 summarizes the properties of the H_2/air concentration gradients in air used in this work. The left plot shows the influence of the gas amount and air dilution of the injected gas from the 4 m^3 tank (Fig. 1 B) on the maximum concentration close to the ceiling. The right two plots show the average values for the concentration gradients used in this work measured in many different locations in the channel. The dilution degree of the injected gas determines the slope of the gradient and the amount of the injected gas rules the maximum concentration below the ceiling. The accuracy of the gradient regularity is approx. +/- 1.2 % H_2. All concentration profiles can be fitted in good agreement by polynomial functions (2nd or 3rd order) or can be described as quasi linear dependency between channel level h and H_2-concentration. The values shown in Fig. 3 are measured 10 s after the end of the injection process which is also the ignition time in the combustion experiments. But the gradient shapes are also very stable. The maximum concentration at the ceiling decreases less than 10 % Vol. H_2 in 10 minutes. After the test mixture was prepared in the channel the second step of the mixture preparation is to enrich the reactivity of the basic test mixture in the booster section and partially in the observation section (Fig. 1). Therefore a fast injection of a defined amount of H_2 (large channel) or H_2/O_2 (small channel) from a pressure vessel (Fig. 1) was performed to reach near stoichiometric mixture conditions in the booster section as well as an additional vertical and horizontal mixture gradient (from stoichiometric mixture to the test mixture) in the observation section. In the large channel a system of perforated tubes was used to distribute the injected gas in the booster section. The gas injection time from constant volume (initial 10 bar) was between 0.3 s and 0.9 s, depending on the initial concentration of the test mixture. The ignition was initiated 5 s after the injection was started. Concentration measurements show that during this time portions of enriched mixture spread up to 3 m inside the channel in the uniform test mixture configuration, and 2 m for the gradient test mixture configuration. This injection procedure is tuned to the dimensions of the booster system (booster and observation section) with a volume of ~ 1 m^3 and allows a fast injection of pure H_2 to reach nearly stoichiometric H_2/air concentrations in the booster and half of the observation section without a separation film in the flame path. In the small channel experiments stoichiometric H_2/O_2 was used to replace the test mixture in the booster section.

2.3 Initiation and detection of detonations

The obstruction inside the booster section is built from layers of grids (Figure 1: d) and e)). It is known that such grids accelerate unconfined flames of stoichiometric H_2/air rapidly to supersonic speed [9]. The grid size of 6.3 mm x 0.63 mm is smaller than the detonation cell size of ~ 10 mm for a stoichiometric H_2/air mixture. This indicates that inside the highly obstructed grid system no classical detonation can be developed for H_2/air mixtures. But the flame velocity is rather high (> 1400 m/s) and at the end of the grid system the flame propagates in detonation mode. In [5] it was shown that one layer of this grid is able to transform a fast deflagration into a detonation. For stoichiometric H_2/O_2 mixtures the run-up distance to a detonation in such a semi-unconfined grid system lies in the range of a few centimeters and due to the small detonation cell size of < 2 mm a detonation can propagate. The main interesting point is the detonation wave transition from the stoichiometric mixture to the test mixture, which occurs in the observation section. The concentration gradient in this section is horizontal and also vertical. The shadow picture series in Fig. 4 a) shows a successful detonation propagation through the observation section starting from the end of the booster section (configuration Fig. 2 e2) to a planar detonation in the test section. The DW has a curved shape in the observation section but at its end the contour of the DW is planar. The shadow picture series in Fig. 4 b) shows a failed detonation propagation inside the observation section. The DW has a curved shape as it enters the observation section (picture 2). The first decupling of a shockwave (SW) from the DW starts on the open side while below the ceiling the DW still propagates (picture 3). Later the SW is fully separated from the flame front. The amplitude of the SW decays rapidly due to the energy losses through the open channel side. There is no possibility to reflect the SW and so a re-initiation of the detonation is not possible. The picture series in Fig. 4 c shows the luminescence of the failed detonation propagation inside the observation section (h = 40 mm; H_2 38 %; 30000 f/s) for the same booster configuration (Fig. 2 e 2). After quenching of the detonation, the flame propagates only in a narrow layer at the ceiling of the channel with sonic velocity. After an increase of the booster height (booster configuration (Fig. 2 e 3) the same behavior (Fig. 4 d) is observed for the same mixture (h = 40 mm; H_2 38 %; 30000 f/s). In the small scale experiments only optical measurements were used to monitor the DW propagation.

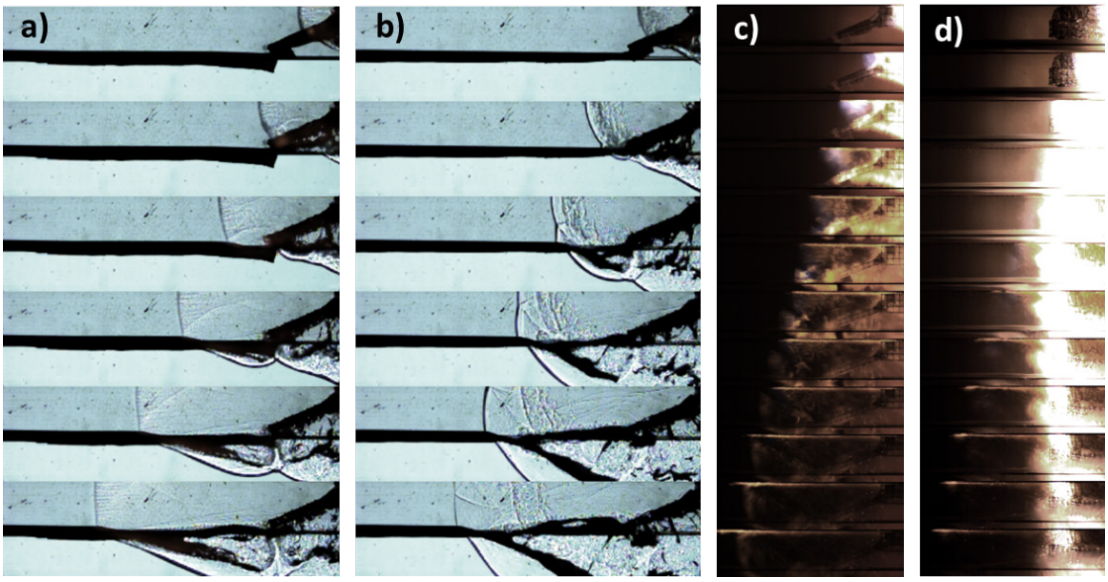

Figure 4: a) Successful detonation propagation in the observation section with formation of a planar detonation in the test section (h = 40 mm; H_2 45 %; 62500 f/s). b) Failed detonation propagation inside the observation section (h = 40 mm; H_2 38 %; 31250 f/s). c) Luminescence of a failed detonation propagation inside the observation section (h = 40 mm; H_2 38 %; 30000 f/s) with booster configuration (Fig. 2 e 2). d) Luminescence of a failed detonation propagation inside the observation section (h = 40 mm; H_2 38 %; 30000 f/s) with booster configuration (Fig. 2 e 3).

In the large scale tests the detonation transition inside the observation section was more complex due to the width of the channel and the lack of a direct optical access. In the experiments with uniform H_2/air mixtures the high speed video observation of the foil-wrapped observation section shows that the detonation propagates sometimes perpendicular to the main axis of the channel. So the detection of a successful experiment is based on soot records of the cellular structure of a DW propagation. Up to 48 soot plates were distributed at the ceiling and the side walls of the channel. The first line of plates was placed after the booster section in the observation section, on the left and right side wall (S1L and S1R) and on the top (4 plates T11 to T14). The second line of soot plates (S2; T2) was placed at the end of the observation section. Fig. 5 A) shows the soot plates of the first and second line after an experiment. If the first plate line is covered completely with the cellular structure and the second line at least partially structured the experiment was counted as successful. Fig. 5 B) shows the eight lines of soot plates arranged for post analyses on a table. If the detonation propagates through the test mixture all plates show structures as depicted in the example Fig. 5 C).

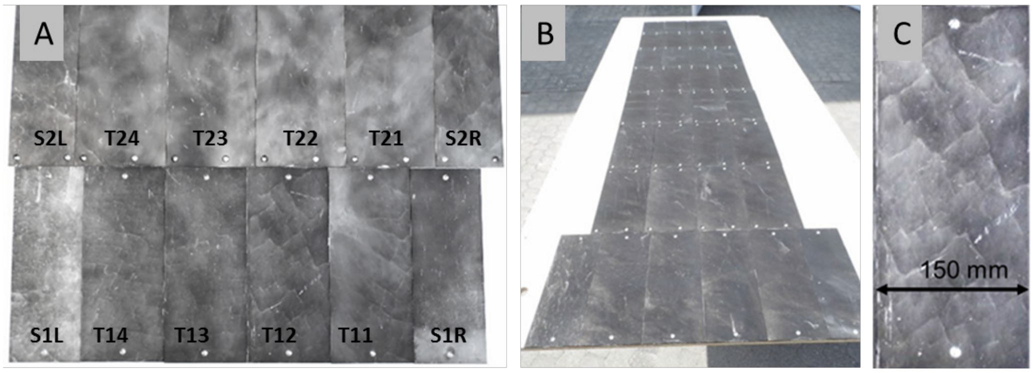

Figure 5: A) Soot plates of the first and second line after an experiment. B) Eight lines of soot plates arranged for post-test analyses on a table. C) Example for a soot record of a detonation.

The large channel was equipped with 14 fast dynamic pressure gauges (PCB type A24) to measure the shock waves and DW propagation with a sample rate of 10 µs inside the test section. The most gauges are positioned along the centerline of the channel, at x = 4.64 m and 8.6 m three gauges were placed in a line across the channel width. For the detection of the flame front ionisation probes (five in a line) were placed inside the observation section (x = 1.85 m) and at the end of the channel (x = 8.3 m). Fig. 6 shows exemplarily the distance-time history of the sensor signals as x-t-diagrams. Magenta signals represent overpressure, blue lines stand for signals from ionisation probes. The left side shows a DW propagation from the end of the booster section (x = 1 m) up to the end of the channel. The flame front arrives together with the DW at the end of the channel. In the right x-t-diagram the detonation propagates though the observation section and then quenches in a distance between x = 2.7 m and 3.9 m to the ignition point. The decoupling of shock wave and flame front is clearly visible at the channel end.

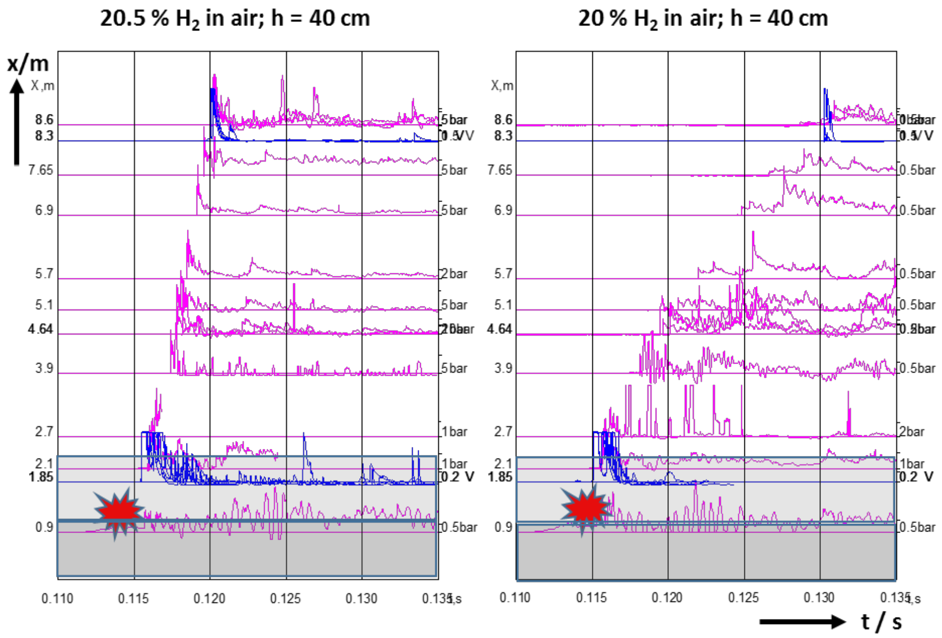

Figure 6: Examples in the form of x-t-diagrams. Left, detonation propagation inside the test mixture. Right, failed detonation propagation inside the test mixture.

To study the shape of the detonation front in the large scale experiments with concentration gradients a large soot plate (1 m x 0.5 m) was installed in the center of the channel (see Fig. 2 c). The plate was adjusted with an angle of 20 ° to have a perpendicular view in the high speed camera which was placed outside of the safety vessel. If the detonation wave is in contact with the carbon soot particles a very strong luminescence is observed. This allows to visualize the shape of the detonation front simultaneously with the soot record of the cellular detonation structure. Fig. 7 left shows the soot plate with the border of the cellular structure marked in red. The right side shows the corresponding detonation front propagation gained from the high speed movie (see also Fig. 13).

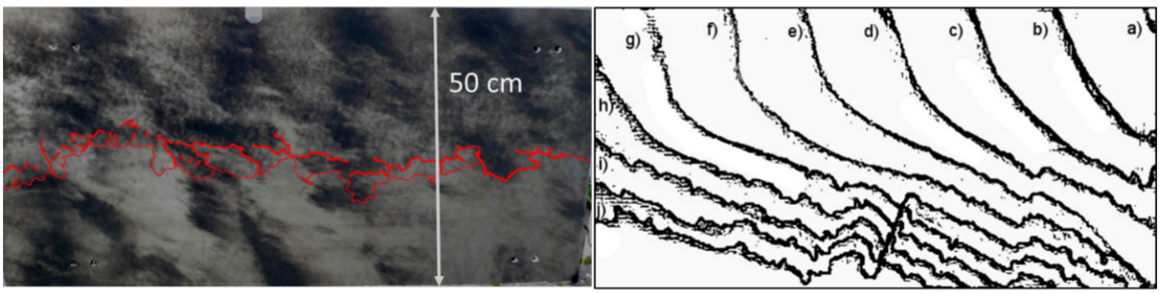

Figure 7: Large soot plate (1 m x 0.5 m) and corresponding detonation front propagation ($H_{2\,max}$ = 26.4 %; 15000 f/s).

3.0. EXPERIMENTAL RESULTS

In the following chapters the experimental results are presented and discussed. All used thermodynamic combustion properties of the gas mixtures are calculated with cantera code [10].

3.1 Large scale uniform H_2/air mixtures

The left plot in Fig. 8 summarizes the results for the large scale experiments with uniform H_2/air mixtures**.** Square symbols represent tests with no detonation propagation inside the test section while circular points indicate the detonation propagation through the test layer.

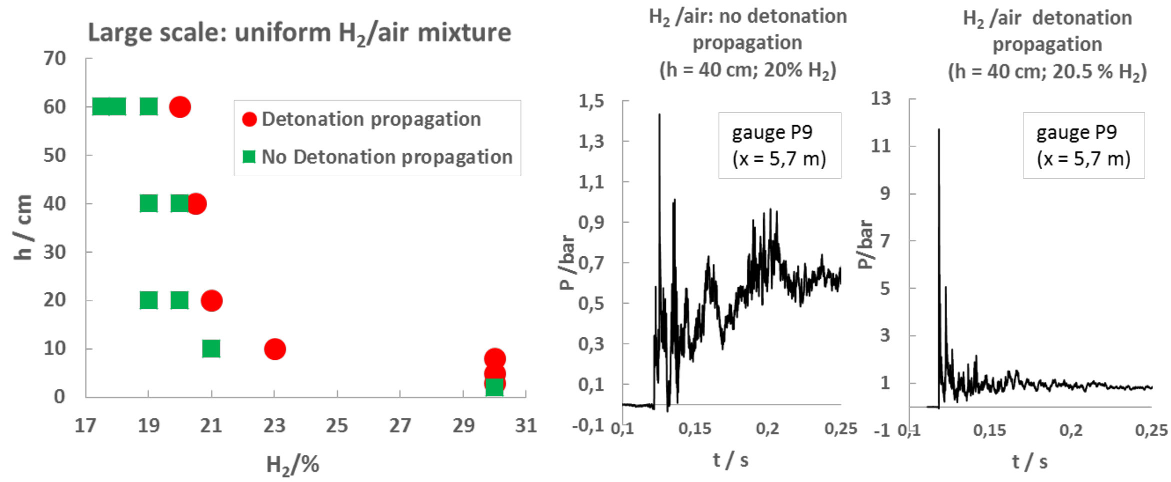

Figure 8: Left, results for the large scale experiments with uniform H_2/air mixtures**.** Right, examples of pressure histories for detonation and failed detonation propagation in the test mixture.

With increasing test layer height h the H_2-concentration for a successful DW propagation decreases. For the maximum layer height of h = 60 cm a detonation can propagate through a mixture of 20 % H_2 in air. The state of the flame propagation mode influences strongly the generated combustion overpressures. The right side of Fig. 8 shows pressure histories of the gauge P9 at x = 5.7 m for a layer thickness of h = 40 cm. For a mixture with 20 % H_2 in air no detonation propagation was observed and the amplitude of the overpressure lies below 1.4 bar. For a mixture with 20.5 % H_2 in air a detonation with an overpressure amplitude of 12 bar propagates through the channel. The measured detonation velocity, calculated using the DW arrival times at x = 5.7 m and 7.65 m, are in good agreement with the theoretical CJ velocity.

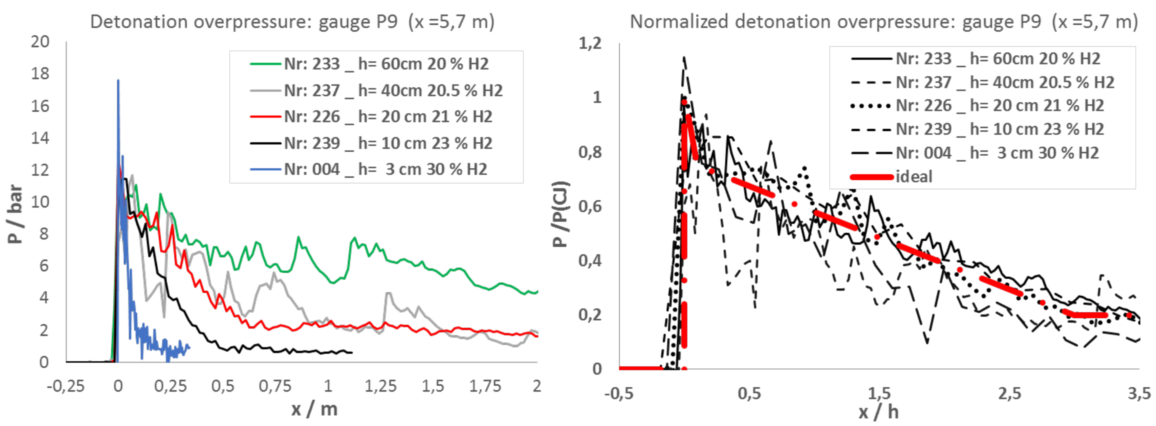

Figure 9: Left, pressure distance histories calculated from gauge 9 (x = 5.7 m). Right, normalized dimensionless detonation overpressure profiles for uniform H_2/air layers.

Fig 9 left compares the DW overpressure for different layer heights. The measured pressure time histories were transferred into pressure distance plots using the DW-velocity. This gives an impression of the impact pressure load on the structure of the channel. Thin layers generate only a narrow strip of overpressure. For 3 cm layer height and 30 % H_2 in air the Taylor wave is less than 25 cm, and for 60 cm layer height and 20 % H_2 in air the Taylor wave is longer than 2 m. The pressure distance histories (Fig. 9 left) can be plotted as dimensionless detonation overpressure diagram (Fig. 9 right). The pressure is scaled with the theoretical detonation overpressure P_{CJ}, and the length of the Taylor wave is scaled by the reciprocal layer height h. All pressure histories fall together with good agreement. With approx. 25 % of the P_{CJ} the pressure behind the Taylor wave in this semi-confined conditions is lower than in closed systems, where the pressure behind the Taylor wave is approx. 50 % of P_{CJ} [11].

3.2 Small scale uniform H_2/O_2 mixtures

The left plot in Fig. 10 summarizes the results for the small scale experiments with uniform H_2/O_2 mixtures**.** Square symbols represent tests with no detonation propagation inside the test section, while circular symbols indicate detonation propagation through the test layer. Solid points represent data from this work while open points are data taken from reference [8]. With increasing test layer height h the H_2-concentration for a successful DW propagation decreases.

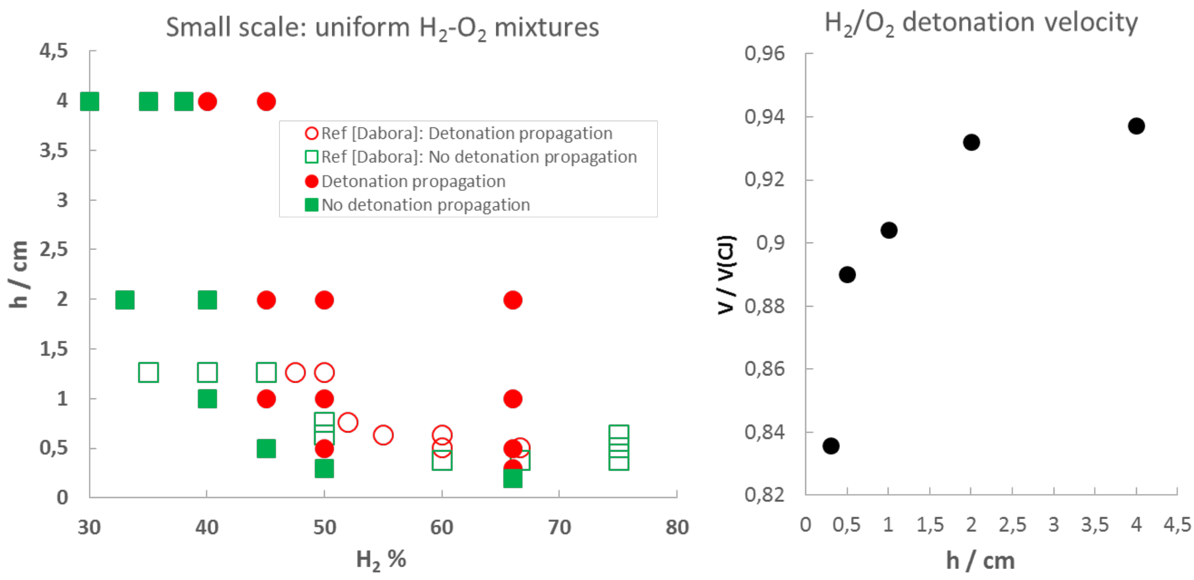

Figure 10: Left, results for the small scale experiments with uniform H_2/O_2 mixtures**.** Right, ratio of the deficit between measured DW-velocity and theoretical DW-velocity.

For the maximum layer height of h = 4 cm a detonation can propagate through a mixture of 40 % H_2 in O_2. The limiting height for a stoichiometric mixture was found to be 0.3 cm. The data from this work and the reference date fit well together. The detonation velocity was measured optically using high speed movies. Examples for different layer heights and concentrations are shown in Fig. 11. In contrast to the large scale experiments with uniform mixtures a remarkable deficit of the measured DW-velocity to its theoretical DW-velocity was found, Fig. 10 right. With increasing layer height the deficit to the theoretical DW-velocity decreases. This tendency is consistent with the near limit behavior of detonation velocities in closed channels [12].

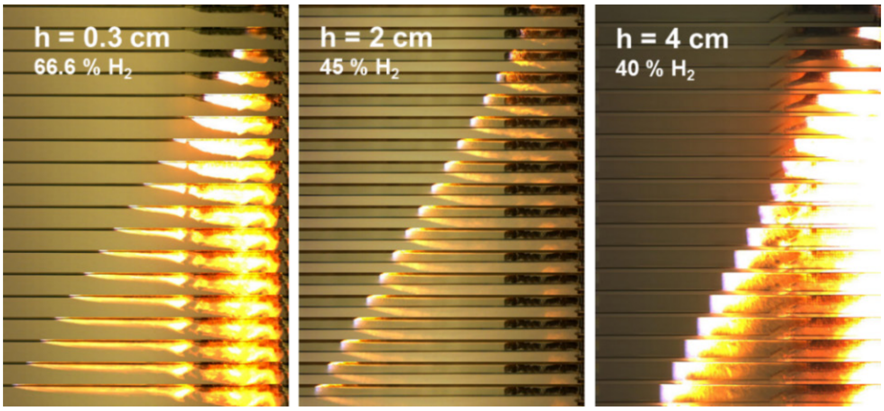

Figure 11: Detonation propagation in a H_2/O_2 mixture in the small scale channel.

3.3 Large scale H_2/air mixtures with concentration gradients

The left plot in Fig. 12 summarizes the results of the large scale experiments with H_2/air mixtures with concentration gradients**.** Square symbols represent tests with no detonation propagation inside the test section while circular symbols indicate detonation propagation through the test layer.

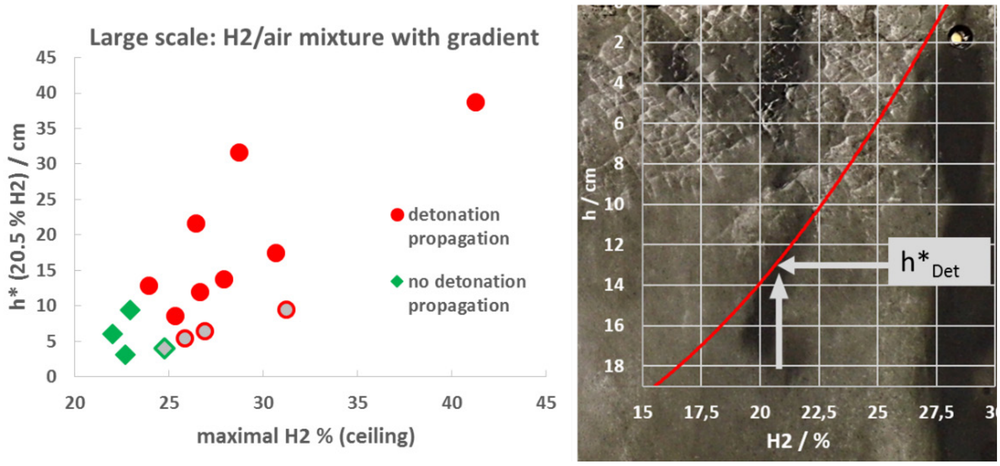

Figure 12: Left, results of large scale experiments with H_2/air mixtures with concentration gradients**.** Right, example of a soot plate from the side wall as background for the corresponding H_2-concentration.

The results in Fig. 12 were plotted with the maximum H_2 concentration at the channel ceiling over the layer height h* where the concentration in the gradient lies above a value of 20.5 % H_2 in air. In the left plot in Fig. 12 the two different slopes (solid symbols) of concentration gradients used in this work are visible. Data with open symbols taken from reference [6]. Below a maximum concentration of 23.7 % H_2 at the channel ceiling no detonation propagation was observed. Fig. 12 right shows as an example a soot plate from the side wall as background for the corresponding H_2-concentration diagram. The cellular structure of the soot record extends downwards to a concentration level that lies between 17 % and 24 %. But there is a large scattering in the height of the structure in the sidewall plates in one experiments. Another method to define the detonated gas layer h* for the experiments for H_2/air mixtures with concentration gradients is the large soot plate (Fig. 2 c) together with the high speed carbon luminescence movie, as shown in Fig. 7. The soot plate in Fig.7 also shows no a well-defined border of cellular structure from the detonation. Fig. 13 shows an example for a detonated gas layer with a maximum H_2 concentration of 26.6 %. The corresponding concentration profile is plotted on the right side, the left side shows a snapshot of the detonation front (60000 f/s), above a visualization of the detonation front propagation along the soot plate (30000 f/s). The distance between the contour lines of the detonation front reflects directly the velocity. The velocity decays on a level h $_{det}$ at which the corresponding concentration is 20.5 %. Remarkable is, that the mixture with 20.5 % propagates with the same detonation velocity as the mixture with the highest concentration at the ceiling.

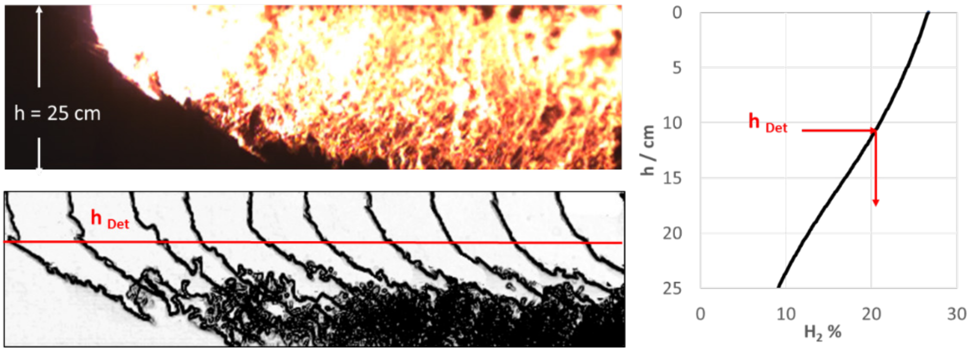

Figure 13: Left, snapshot of the detonation front and visualization of the detonation front propagation along the soot plate. Right, corresponding H2-concentration profile.

Due to the non-planar detonation front with an elliptical shape the regions with lower H_2-concentrations burn with an overdriven detonation velocity. But due to the larger detonation surface the energy consumption per volume unit increases and should lead to an overdriven detonation velocity [13]. The measured detonation velocities correspond well with the theoretical DW-velocities calculated for the maximum concentration, Fig. 14 right.

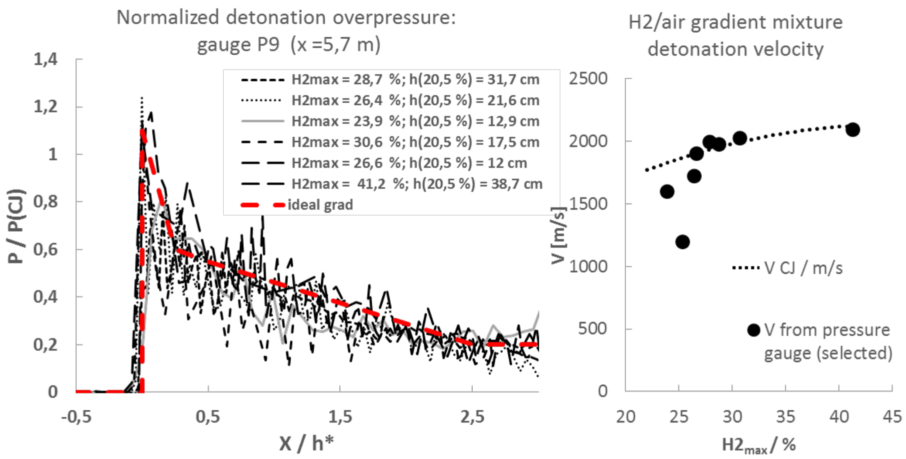

Figure 14: Left, normalized dimensionless detonation overpressure profiles for layers with H_2 concentration gradients in air. Right, measured DW-velocity and theoretical DW-velocity.

Near the detonation limit a velocity deficit was measured, although the measured amplitude of the detonation pressure corresponds to the theoretical P_{CJ} of the maximum H_2-concentration at the channel ceiling. The left side in Fig. 14 shows the normalized dimensionless detonation overpressure profiles for the experiments with H_2-concentration gradients in air (see also Fig. 9). Here the P_{CJ} values were calculated for the maximum H_2 concentration and the height of the detonated gas layer is h*. The pressure behind the Taylor wave in this semi-confined conditions is approx. 25 % of the P_{CJ}, which is the same as in the experiments with uniform H_2/air mixtures. But the length of the pressure wave is shorter.

4.0. LIMITS OF DETONATION PROPAGATION IN SEMI-CONFINED LAYERS

All observed soot records in this work show highly irregular detonation cell structures. But nevertheless the detonation cell size λ is a probate scale to link detonation properties. Using calculated detonation cell size values λ the limits of detonation propagation in semi-confirmed layers can be formulated by using the layer thickness h or h* for the geometrical conditions and the detonation cell size λ for the mixture properties.

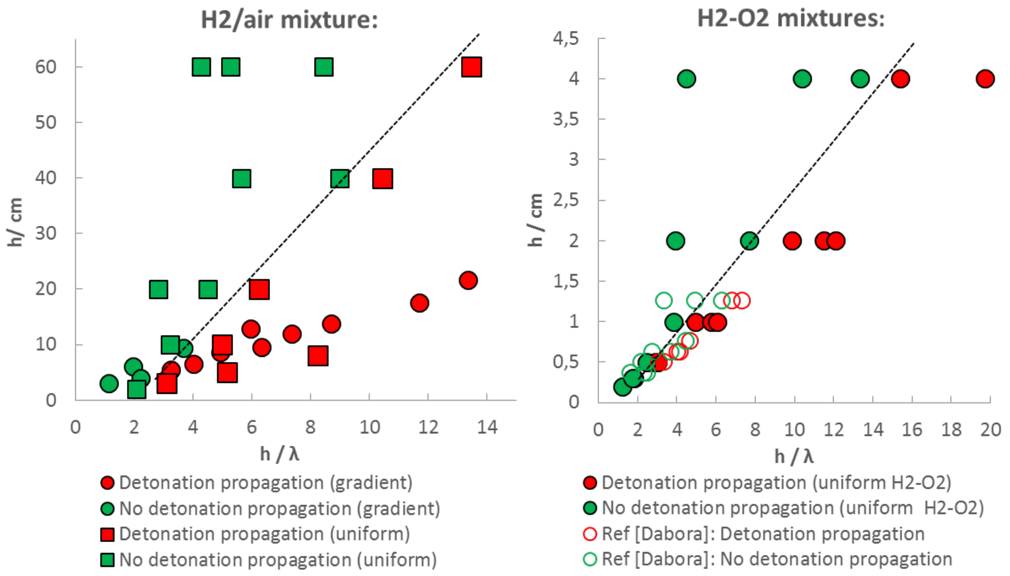

Figure 15: Limits of detonation propagation in semi-confirmed layers for H_2/air-mixtures and H_2/O_2-mixtures.

In Fig. 15 left the ratio of layer h to the detonation cell size λ of the mixture is plotted against the layer thickness h. Square symbols represent experiments with uniform H_2/air-mixtures and circular symbols represent experiments with H_2/air-mixtures with concentration gradients. For the mixtures with concentration gradients the layer h*(h > 20.5 % H_2) and the detonation cell size λ corresponding to the maximum H_2-concentration at the ceiling of the channel were used. The diagram separates observed detonation propagation from observed failed detonation propagation. With increasing layer height h the ratio of h/λ also increases. In Fig. 15 the dependency looks linear. The plot for uniform H_2/O_2-mixtures, (Fig. 15 right), shows the same tendency. Solid points correspond to this work and open points to reference [8]. The main differences between these two diagrams are the geometrical conditions expressed as the layer height h. The difference of the layer height h (H_2/air) to h (H_2/O_2) can be linked with the ratio of the detonation cell size λ from both mixtures for stoichiometric conditions.

5.0. Conclusions

This work presents an experimental investigation on detonation wave propagation in semi-confined layer geometries. Large scale experiments in layers up to a height of 0.6 m filled with uniform and non-uniform H_2/air-mixtures as well as small scale experiments with uniform H_2/O_2-mixtures were performed in rectangular channels. Hydrogen flames were accelerated from weak ignition inside a semi confined driver section to the state of detonation. The detonation propagation from the driver section to the test section was realized without diaphragm. Critical conditions for detonation propagation were investigated for the test section.

The variables for uniform-mixtures are the layer height h and the H_2-concentration while the variables for mixtures with concentration gradients were the maximum H_2-concentration at the ceiling and the height h* where the concentration profile reaches 20.5 % H_2. A mixture with 20 % H_2 in air was found as critical conditions for a detonation propagation in a layer of h = 0.6 m. This corresponds to a ratio h/λ = 13. For a layer height of h = 0.03 m the critical conditions for a detonation propagation correspond to stoichiometric H_2/air-mixture, which leads to a ratio of h/λ = 3. With increasing layer height h the ratio of h/λ also increases. The dependency is linear in the investigated ranges. Comparative studies in small scale experiments with H_2/O_2-mixtures show the same trend. The main differences are the geometrical conditions of the layer height h. Critical condition for a detonation propagation for a stoichiometric H_2/O_2-mixture was a layer height h = 0.003 m, corresponding to a ratio of h/λ = 2.

Investigations with non-uniform H_2/air-mixtures with a defined concentration gradient show that only in the part of the mixture with concentrations higher 20.5 % H_2 flames can propagate in detonation regime. The layer height h*, from the ceiling to the level of 20.5 % H_2, and the maximum concentration of the mixture C_{max} determine the critical conditions for detonation propagation. As critical conditions for a detonation propagation a mixture with a maximum concentration C_{max} = 23.7 % H_2 at the channel ceiling and a layer height h* of 0.13 m was found. This corresponds to a ratio of $h/\lambda = 5$. For H_2/air-mixtures with concentration gradients detonation velocities and detonation overpressures are determined from the maximum H_2-concentration at the ceiling of the channel.

Acknowledgments
The large scale experiments were funded by the German Federal Ministry of Economics and Technology on the basis of a decision by the German Bundestag (Project No. 1501426) which is gratefully acknowledged.

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