

Influence of Concentration Gradients on Detonation Velocities in Hydrogen-Air Mixtures

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Measurements of detonation velocities in hydrogen-air mixtures with concentration gradients perpendicular to the main direction of flame propagation are presented. Average volumetric hydrogen contents between 25% and 45% at ambient pressure and temperature are examined at concentration gradients of different slope. Experiments are conducted in a rectangular closed channel which is equipped with obstacles for flame acceleration to reach DDT. Signals from pressure transducers and photodiodes are checked against each other to reach a high reliability in the final conclusions. It can be shown that concentration gradients lead to systematically lower detonation velocities than measured in homogeneous mixtures. In addition, the behavior strongly depends on the average hydrogen content.

Keywords: *inhomogeneous mixture, concentration gradient, detonation velocity*

1. Introduction

Detonations in hydrogen-air mixtures pose a major threat to the integrity of nuclear power plants. In experiments on flame acceleration, DDT and detonation at laboratory scale usually homogeneous mixtures have been investigated in the past. However, a more realistic formation of hydrogen distribution in case of a severe accident scenario in a nuclear power plant is the evolution of concentration gradients due to the low density of hydrogen compared to air. It has already been shown by Ishii and Kojima [1] that detonation velocities in stoichiometric mixtures with gradients differ from those in homogeneous mixtures. The present investigation aims at providing additional insight into the effect of concentration gradients on detonation velocity. Average volumetric hydrogen contents from 25% to 45% are experimentally examined in a detonation channel at ambient pressure and temperature.

2. Experimental setup

The experiments are conducted in a closed detonation channel with a rectangular cross section of 300mm x 60mm and a length of 5.4m. At the ignition plate, a spark plug is used to weakly ignite the mixture. The section between 0.25m and 2.05m is equipped with obstacles to provoke effective flame acceleration until DDT. Relevant mechanisms for flame acceleration and transition to detonation in ducts are extensively described by Ciccarelli and Dorofeev [2]. In this study, horizontal flat plate obstacles with a blockage ratio (BR) of 30% and spacing (S) of 100mm or 300mm are installed inside the channel. For hydrogen injection and gradient formation, a mechanism developed and characterized

by Vollmer [3] is integrated into the facility. It allows reproducible creation of vertical S-shaped concentration gradients prior to ignition. After injection through the top plate of the channel, hydrogen is deflected by injection plates into parallel direction to the channel top. Thus, a compact horizontal layer of hydrogen is formed. By setting a characteristic diffusion time between injection and ignition, downwards-diffusion of hydrogen leads to vertical concentration gradients of characteristic shape. A diffusion time of 60s leads to a homogeneous mixture, whereas shorter times down to 3s imply high local concentrations at the top and the inverse situation at the bottom. For instance, a diffusion time of 3s at an average hydrogen concentration of 25% yields a local concentration of about 45% at the top and 7.5% at the bottom. Raising the average concentration to 45% causes a local concentration at the top of 65% and 20% at the bottom. Further details about the concentration gradients are given by Vollmer [3].

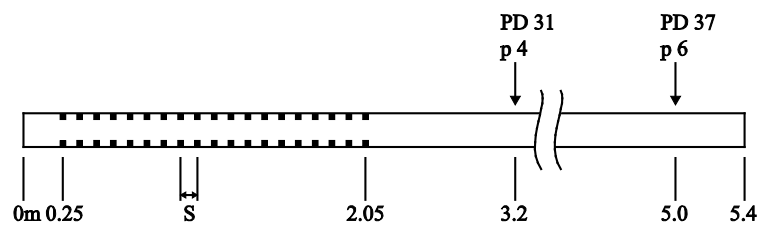


Figure 1: Channel configuration BR30S100

The channel is equipped with seven pressure transducers (type Kistler 601A) and 30 photodiodes (type Hamamatsu S1336-18BQ). Six pressure transducers are located in the top plate flush with the channel wall and another one in the end plate to record reflected pressures. For data acquisition, simultaneous measurement devices at a sampling rate of 250kS/s are used. Arrival times of shock wave (pressure transducers) and flame (photodiodes) are determined by an algorithm which applies a threshold value for the measured voltage of each sensor. When this voltage is reached, the time of arrival is defined. The finite sampling rate allows measurement of a minimum time difference of $4\mu\text{s}$. By linear interpolation between the two closest points around the threshold voltage the precision is further enhanced.

3. Results and discussion

In order to measure detonation velocities in this facility at a high accuracy, the first step is to determine the region in the channel where a detonation can be established. Areas close to the DDT location with over-driven wave behavior or segments in which run-up to DDT is not yet completed must be excluded from the section of measurement. For this purpose, measured velocities from pressure transducers and photodiodes for a critical case are evaluated. In the variety of average concentrations and gradients to be tested, the cases for 25% hydrogen are the most critical ones due to the highest run-up distances to DDT. Figure 2 exemplarily shows the measured velocity evolution from photodiodes and pressure transducers between ignition and reflection at the end plate. For a coupled detonation, shock wave and flame velocity must be equal. This behavior can be found in the section between 3.2m and 5.0m, where the pressure measurements show very good agreement with the one-dimensional CJ theory (calculated CJ speed 1867m/s, measured 1823m/s), whereas the photodiode analysis shows significant oscillations. This is mainly due to small differences in the responding behavior of the operational amplifiers used to intensify the photodiode signals. Also the possibility of contamination of the diodes with residues inside the channel increases the uncertainty of measurement. The following data for detonation velocities is recorded by analyzing only the sensors at 3.2m (photodiode no. 31, pressure transducer no. 4) and 5.0m (photodiode no. 37, pressure transducer

no. 6). Thus, these velocities are averages between 3.2m and 5.0m. Each measurement is repeated five times.

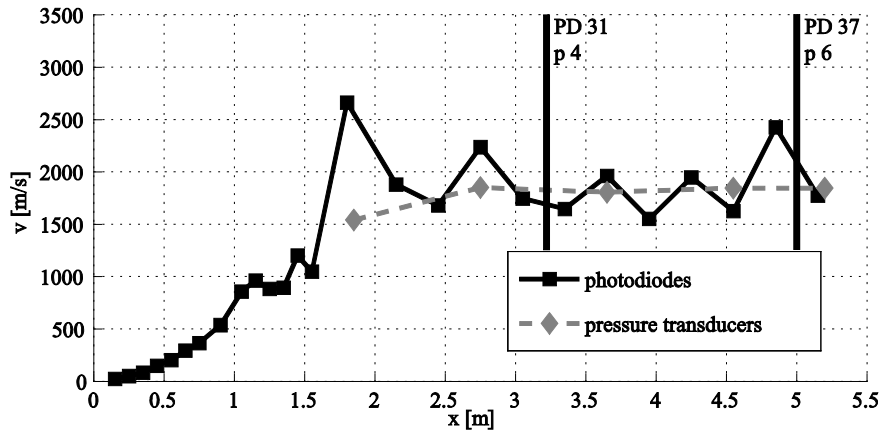


Figure 2: Shock wave and flame velocities, BR30S100, 25% hydrogen, 60s diffusion time

A further comparison of photodiodes and pressure transducers for homogeneous mixtures shows that the standard deviation of velocities gained from pressure transducers for each group of five experiments is lower than the one gained from photodiodes. This is why solely information from the pressure transducers is used for further analysis. Table 1 contains results for homogeneous mixtures including the arithmetic averages of five measurements of detonation velocity from photodiodes v_{photo} and pressure transducers v_{pres} , corresponding standard deviations σ and a comparison with CJ velocities calculated using Cantera [4]. The measured velocities remain closely below the calculated values which might be due to momentum losses, especially arising from the hydrogen injection plates which effect a BR of 0.02 at $S=100\text{mm}$. The obstacle configurations BR30S100 and BR30S300 show only minor differences. It can be concluded that the way how to achieve DDT and detonation is not an influencing factor for the analysis.

X_{H2} [%]	BR30S100					BR30S300	
	v_{photo} [m/s]	σ_{photo} [%]	v_{pres} [m/s]	σ_{pres} [%]	$\frac{v_{pres}}{D_{CJ}}$	v_{pres} [m/s]	$\frac{v_{pres}}{D_{CJ}}$
25	1796	0.99	1823	0.46	0.977	1839	0.984
30	1924	0.54	1939	0.12	0.978	1951	0.985
35	2038	1.54	2016	0.27	0.982	2024	0.987
40	2046	0.95	2065	0.07	0.984	2072	0.987
45	2080	0.36	2101	0.04	0.983		

Table 1: Characteristic parameters of detonations in homogeneous mixtures

Finally, concentration gradients are introduced by setting diffusion times between 3s and 15s. The results are illustrated in Figure 3 using a dimensionless description of the occurring velocity deficits. All arithmetically averaged velocities show standard deviations lower than 1% for each group of five measurements. It can clearly be seen that increasing the gradient slope by decreasing diffusion time results in lower detonation velocities normalized by the detonation velocity measured in the homogeneous mixture. A rise in the average volumetric hydrogen content from 25% up to 45% leads to a decline of the velocity deficit. The authors suggest that this trend can be explained by delayed reaction of significant portions of mixture. Especially for low average concentrations at short diffusion times, the region along the channel bottom only offers very low local hydrogen concentrations. Delayed reaction would result in lower heat release and thus lower volumetric expansion, which leads

to lower detonation velocities. For the highest average concentration examined (45%), the local hydrogen concentration at the bottom is still about 20% at 3s diffusion time, which facilitates reaction across the entire channel height resulting in a low velocity deficit.

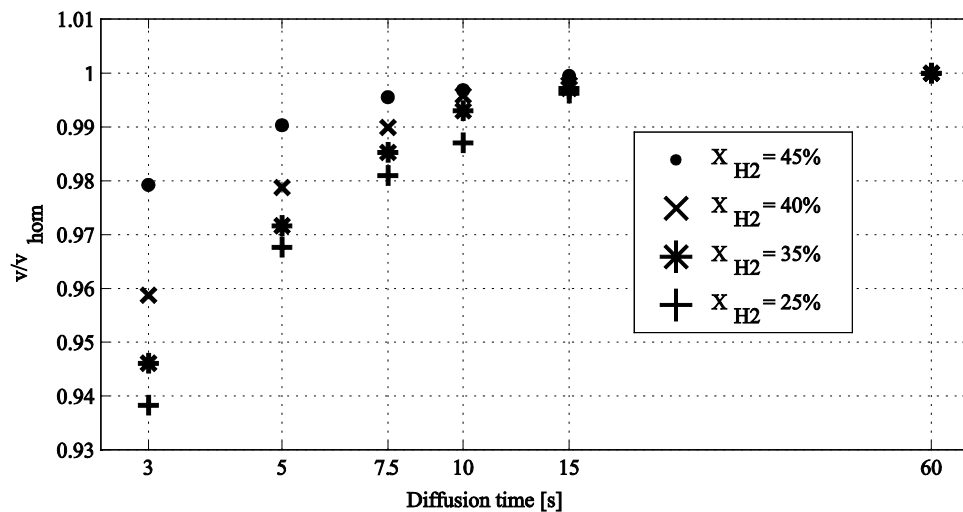


Figure 3: Velocity deficit of detonations with concentration gradients, BR30S100

4. Conclusions

The measurements presented reveal the influence of vertical concentration gradients in hydrogen-air mixtures on detonation velocities. Different average hydrogen contents were examined. Before taking the final data, it was investigated whether the described test facility is suitable for detonation velocity measurements. The applicability was demonstrated by analyzing signals from pressure transducers and photodiodes at different obstacle configurations. No impact of the configuration on detonation velocities could be found. Especially using pressure transducers for velocity measurement offers a very low standard deviation and underlines the high repeatability of experiments. The results show a clear dependence of detonation velocity on the gradient slope as well as on the average hydrogen concentration. Steeper gradients cause a higher velocity deficit, whereas higher average concentrations lead to lower deficits. Regions in the mixture with delayed reaction seem to play a major role, which is going to be investigated by the authors in further studies.

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