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Abstract:

Schlieren has been used in the visualization of shock waves since the beginning of the 20th century and is still highly actual in the research of shock waves and DDT. The goal of this study was to build a schlieren setup to use in high speed photography of hydrogen and air explosions in a channel with one obstacle in order to photograph deflagration to detonation transition.

A 3 meter long open-ended test channel with one obstacle and closed in the end of ignition with cross-section of 0.1x0.1 m was used. The channel was filmed with a high-speed camera at three different positions all after the obstacle with pressure recordings at different position in the channel.

The results from experiments with mixtures of 25%vol. H_2 to 35%vol. H_2 and blockage ratio of 0.75 are presented in this report with pressure recordings and schlieren photos. Detonation occurred in mixtures from 28 to 35%vol. H_2. Shock waves were observed for all mixtures at various distances from the obstacle and DDT was seen in two tests with 30%vol. H_2 at a distance between 0.4 and 0.45 m from the obstacle. The run-up distance is observed to be shorter as the mixtures get richer, this is observed from both the schlieren photographs and the pressure recordings. The shock wave velocities were estimated from the pressure recordings and for mixtures that detonated they are above the CJ-velocity in all cases. The flame velocities were estimated from the photographs for two tests that detonated and in both cases were about 40% of the CJ-velocity.

The schlieren setup was successful in the way that it was able to make photographs of well observable shock waves along with the deflagration to detonation transition, however further experiments are recommended with higher frame rate to gain understanding of the DDT phenomena.

Telemark University College accepts no responsibility for results and conclusions presented in this report.

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Preface

This thesis was carried out during the autumn of 2013 as a part of a two year master degree program at Telemark University College.

The main purpose of this thesis was to build a schlieren setup that is able to take high-speed photographs of shock waves from gas explosions in a channel and set the basis for further research with a new high-speed camera. This work is connected to the PhD work of André V. Gaathaug that will be submitted in 2014.

An appendix is included at the end of this report with the task description, equipment that is not described in the report, overview over all tests done, procedure for the experiments, pressure plots from all tests, matlab codes and calibration data of flow-meters.

This thesis was made possible by excellent guidance provided during the lab work and the work of this thesis by Professor Dag Bjerketvedt, Assoc. Professor Knut Vågsæther and Assistant Professor André V. Gaathaug.

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Porsgrunn, December 2013

Larus Bjarnason

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1 Introduction

This project is a part of Telemark University College's research of shock waves and hydrogen safety in cooperation with IEA-HIA task 31. Hydrogen safety is and will be increasingly important in many aspects of our society. The study of shock waves is important in order to understand the mechanisms that lead deflagration to detonation transition in gas explosions.

1.1 Background

Schlieren imaging has been used in various forms in shock wave research since the beginning of the 20th century. There are many possibilities in the configuration of equipment and setups, but they mostly originate in the idea of parallel light and a knife cut-off (Settles, 2001).

There exist many studies on the use of schlieren in combustion research from early on with various goals, such as temperature measurements of flames and flame propagation in tubes (Garner, Long, & Thorley, 1953), (Schmidt, Steinicke, & Neubert, 1953). Schlieren is still widely being used in shock wave research like more resent research of (Kuznetsov, Liberman, & Matsukov, 2010) were a study of deflagration to detonation transition (DDT) is done with schlieren used as a tool to investigate critical parameters of DDT.

Much research has been done of DDT and the conditions that lead to DDT. There are many different factors to consider and there still are uncertainties regarding the onset of DDT. It is understood that flame acceleration sets the condition for the onset which then occurs in a small volume and that both areas need further investigation (Ciccarelli & Dorofeev, 2007).

1.2 Goal/Aim

The main goal of this project is to build a schlieren setup in order to observe the deflagration to detonation transition in a channel with a single obstacle. Hydrogen and air mixtures will be ignited before the obstacle and the section after the obstacle will be filmed with a high-speed camera. A literature review of the applications of schlieren imaging technique in gas explosion research will be done and of the advantages and drawbacks of different light sources in such research.

1.3 Organization of the report

Chapter 1: Introduction with background and the goal of the report.

Chapter 2: Litterature review were use of schlieren in similar research along with performance of different light sources.

Chapter 3: Materials and methods with description of the main equipment that was used and the different setups.

Chapter 4: Results divided into three sub chapters according to the three different setups are presented.

Chapter 5: Discussion of the results.

Chapter 6: Conclusion of the discussion.

2 Litterature review

Schlieren has been used in a varity in lab scale experiments on shock waves and different combustion phenomena as this technique is able to visualize density gradients with high sensitivity. In this chapter the use of schlieren in such research and the performance of different light sources is investigatet. It was hard to find any exact price of the different light sources, but in general laser and arc producing light sources are consideret expensive when compared to conventional light sources and LED's.

2.1 Schlieren in combustion and shockwave research

There are many different ways of seting up and arranging the equipment when filming with the schlieren technique, z-type schlieren setup is perhaps one of the most common ways to arrange equipment. Many detonation and shock wave studies have been made with a z-type arrangement, (Oppenheim, Urtiew, & Weinberg, 1966), (Obara, Yajima, Yoshihashi, & Ohyagi, 1996) and (Mariani, Kontis, & Gongora-Orozco, 2013) among many more used that arrangement in their studies.

(Oppenheim, Urtiew, & Weinberg, 1966) also show a type of setup were coma (appears when a parabolic mirror with on-axis focus is focused off-axis, that will smear out the focus) is avoided by not having the parabolic mirrors in an angle, istead a plane mirror is placed in the middle of the test region reflecting the light to the first parabolic mirror which reflects parallel light to the second parabolic mirror and then to a plane mirror and to the recording device. This however occupies a large section of the image area and coma is generally avoided in z-type arrangement if the two mirrors have the same angle in opposite directions (Settles, 2001).

Some more complicated and less used techniques have also been used such as a z-type schlieren setup with a beam splitter and two different cameras to record the same schlieren view was used in the study of combustion in irregular detonation waves by (Kiyanda & Higgins, 2012).

(Hargather & Settles, 2012) compared three schlieren techniques to use in temperature measurement of flows. Calibrated schlieren were a lens next to the schlieren object is used to get reference refraction to compare to the object subject to temperature measurement. Rainbow schlieren were a colored filter is used instead of the knife cut-off before the camera, the refracted light will then pass through the colored filter at different places and result in different colors in the picture. That way it is possible to determine the magnitude of reflection. Another possibility is the use of BOS(background oriented schlieren), were a background with random pixels is placed behind the schlieren object and used as calibration for the image that will occour when filming the schlieren object. This requires software processing to get an schlieren image (Hargather & Settles, 2012).

2.2 Light sources for use in schlieren

Conventional continuous wave lamps have been used in schlieren photography for a long time with advantages of low price, high availability and a variety of shapes and brightness. They may though not be suited for high speed photography due to lack of brightness.

Arc lamps exist in a great variety. They exist in a variety of setups and brightness with different size, shape and temperatures of the arc. They can produce sparks with short pulse duration at high frequency which is an advantage for high speed photography. There are some drawbacks with such lamps as they are relative expensive compared to conventional light sources and some instability in the arc that is produced may give some change in illumination from pulse to pulse.

The lasers advantages are their high brightness, ability for high frequency pulsing and monochromatic light which eliminates chromatic aberration. The most obvious drawbacks for lasers are their coherent light and high price compared to other sources. Since lasers emit coherent light (light waves in the same phase) diffraction will occur. Laser induced air breakdown is a possibility to eliminate coherence were a laser is used to produce a spark by focusing the laser to a point (Estevadeordal, Gogineni, Kimmel, & Hayes, 2007), (Oppenheim, Urtiew, & Weinberg, 1966).

LED's exist in a range of size, brightness and price. With their monochromatic incoherent light problems with diffraction and chromatic aberration is eliminated. They can be pulsed or used in continuous operation. They can be found in different prize ranges colors and shapes. They are cheap compared to lasers and arc lamps. The main drawback is low brightness. It is possible to make clusters of many LED's to increase the brightness. It is possible to overdrive the LED's for short pulses. LED overdriven ten times its specification gives enough brightness. They respond instantaneously compared to xenon flash lamps. The geometry of the LED is suitable for schlieren as it is a point source. Space requirements are reduces since no lens and knife is necessary for the light source. It can be operated in continues mode at lower intensity for alignment of the equipment. However a drawback is that is necessary to operate in pulse mode to avoid damage if one wants to overdrive the LED's. Should be noted that a conventional continuous light source is as suitable as a LED as long as the brightness is good enough and problems with chromatic aberration is eliminated. A key advantage is possibilities of flexibility with LED's when thinking about pulse rate, width, brightness and price (Estevadeordal, Gogineni, Kimmel, & Hayes, 2007), (Willert, Mitchell, & Soria, 2012).

3 Materials and Methods

In this chapter the equipment, the different setups and the experimental procedure are presented. The schlieren setup is presented in its own section though it was a part of the overall set-up and the calibration process is described in its own section. The setup of the schlieren equipment was partly a "trial and error" process to be able to find an effective position of the equipment. In the actual experiments three different setup series were used with different location of pressure sensors and picture location. The setups are presented as P101, P102 and P103. An experimental overview is seen in Figure 3-1.
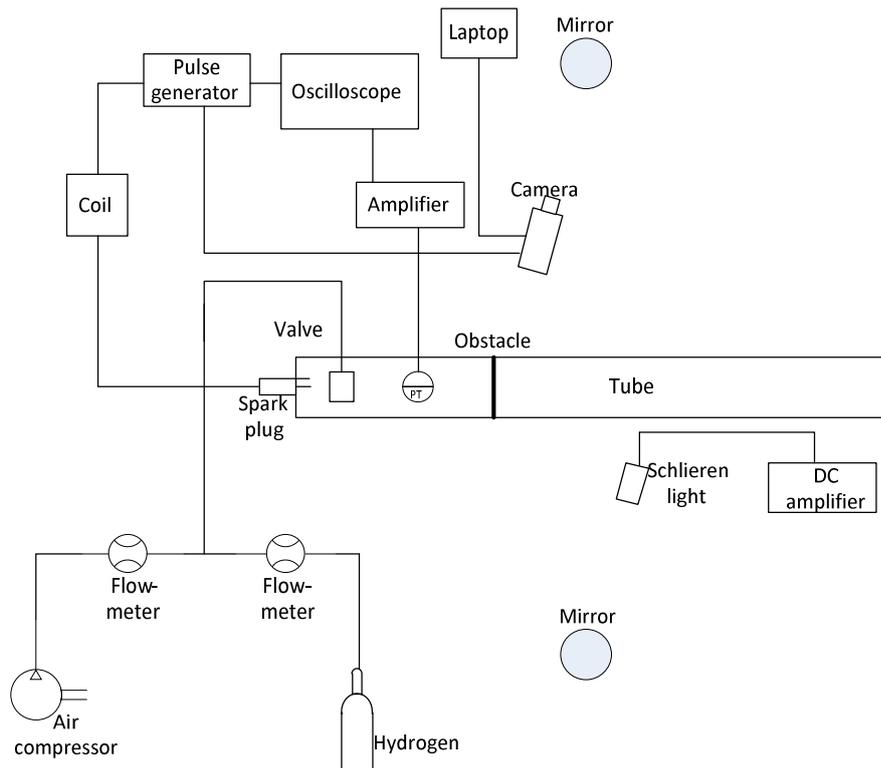
Figure 3-1 Main overview of the experimental setup.

3.1 Equipment

The test channel:

The channel that was used in the experiments was a rectangular tube closed in the end of ignition with an obstacle 1m from ignition and open in the other end with width of 0.1m and height of 0.1m. The obstruction was adjustable so that the blockage ratio could be changed.

Figure 3-2 The test channel.

High speed camera:

The camera used is a Photron FASTCAM-APX RS high speed camera. It has a IEEE 1394 connection for data transfer with a max resolution of 1024x1024 with 3000FPS at that resolution. Max FPS is 250000 at resolution 128x16. The shutter of the camera is open at the end of each frame. It was used in testing of the schlieren setup and for recording the experiments.

Figure 3-3 High-speed camera.

Halogen lamp:

A 20Volt/150watt halogen lamp was used as a light source for the fiber optical slit during the experiments. Fiber optics seen in Figure 3-5 that directed the light from the lamp to a slit that was connected in front of the lamp.
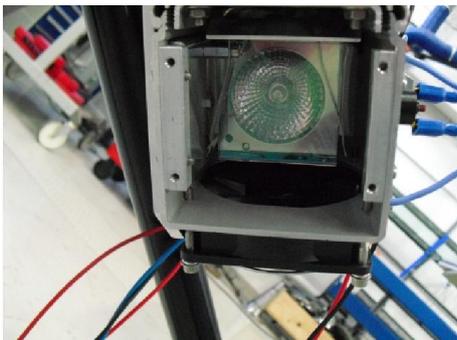

Figure 3-4 150watt halogen lamp.

Fiber optical slit:

The optical slit was used as schlieren light source during the experiments. Because of the slit being close to a vertical point source no focusing lens or a knife cut-off was in need after the light.

Figure 3-5 Fiber optical slit connected to the halogen lamp.

Mirrors:

Two on-axis parabolic mirrors with diameter 0.25m and focus length 2.5m were used. They were mounted on a housing that gave possibilities of regulating the angle of the mirrors in all directions and to adjust the position of the mirror in one direction.


Figure 3-6 On-axis parabolic mirrors.

Pulse generator:

The pulse generator was Quantum composer 9518. It was used to trigger the oscilloscope, camera and the ignition source.

Figure 3-7 The pulse generator.

Pressure sensors:

Kistler 603b:

This is a quartz crystal sensor that transforms pressure into an electric charge which is amplified with the Kistler amplifiers. This type was used for ch.3 to 8. Its range is from vacuum to 200 bar.

Kistler 7001:

This type was used for ch.2 due to problems with the 603b sensor that was originally planned

for use. This type has measuring range from vacuum to 250 bar, but has lower frequency response time than the 603b sensors.

Amplifiers:

Kistler Type 5011 amplifiers were used to amplify the signal from the pressure sensors. The pressure sensors had individual calibration data given that was typed into the amplifier for that sensor and an appropriate amplification was chosen. Amplification is given as bar per volt.

Figure 3-8 The amplifiers for the pressure sensors.

Oscilloscope:

The oscilloscope has 8 channels in, channel 1 was connected to the pulse generator which triggered the oscilloscope, channel 2-8 were connected to the amplifiers which gave signals from the pressure sensors. The sampling rate was 0.5μs with 1 million total samples.

Figure 3-9 Sigma Oscilloscope.

Camera lens:

A Nikon 80-200mm lens was attached to the high speed camera with the focus length set to infinity.

Figure 3-10 The camera lens used on the high speed camera.

3.2 Experimental Setup

All experiments were done with a plug in the open end during filling to minimize flow of external air into the channel. The pulse generator was connected to the oscilloscope, camera and the igniter. Channel 1 on the oscilloscope was connected to the pulse generator and the pressure sensors to channel 2-8. The obstruction was one meter from ignition and had a blockage ratio (total are divided by blocked are) of 0.75 was used for all tests. The DC amplifiers gave power to the light and were controlled by adjusting the voltage. DC power was used to give continuous emitting light, they were set to 10V each giving a total of 20V. Full voltage was given in a shortest possible amount of time to avoid damage to the image sensor of the high-speed camera. Two separate air compressors were used, one to operate the valve on top of the channel and one to supply air into the channel to mix with the hydrogen. The compressor for the valve gave pressure of about 16bar, and the oil-free compressor for the air supply into the channel gave about 4bars. There was a valve between the air supply compressor and the flow-meters that controlled the air pressure to be 1.5 bars into the flow-meter. The pressure from the hydrogen cylinder was set to 1.5 bar. Equal or higher pressure from the air compressor than from the hydrogen cylinder was important to minimize the risk of hydrogen flowing into the compressor. The valve on top of the channel was controlled by a switch at the control panel for the flow-meters. The channel was filled by ten times its volume before ignition to ensure homogenous mixture. In the selection of flow-meters for the hydrogen and air supply the criteria was to be able to fill ten times the channels volume in a few minutes and the volume ratio of hydrogen and air was important. A flow of about three times the flow of hydrogen was used as reference in the test of different flow-meters. The calibration was done by a Ritter - TG 10/1 gas-meter with volume of 10 liters.

3.2.1 Schlieren setup

The schlieren setup was a z-type alignment as shown in Figure 3-11. The focal distance of the mirrors was checked by measuring the diameter of the circular parallel light from the mirrors at two distances, when the diameter is the same in two distances the light rays are parallel.

That means the light source is at the focal spot of the first mirror and the focal length will be the distance between the light source and the mirror. It was 2.5 meters. Then the channel was placed between the mirrors and the second mirror (the one that focuses parallel light to the camera knife cut-off) was put in place in such a distance that the camera setup was able to fit in. Then the light, camera, mirrors and channel were leveled with the cross line laser leveler. In the placement of the camera a simple but effective approach was done. The light was kept at its fixed location and the focus point of the second mirror was found. The camera and knife cut-off for were placed in the focus point of the second mirror. To avoid comatic aberration (an effect that occurs when light hits an on-axis mirror or a lens from an angle) the angle of the mirrors relative to the light source and camera should be equal in opposite directions (Settles, 2001). Because of space problems the angles of the camera and light were not equal relative to the mirrors in this setup. Since the light source was a slit a free lens after the light and a knife edge to make a point-source was not used. A camera lens was used to focus the light after the knife cut-off.
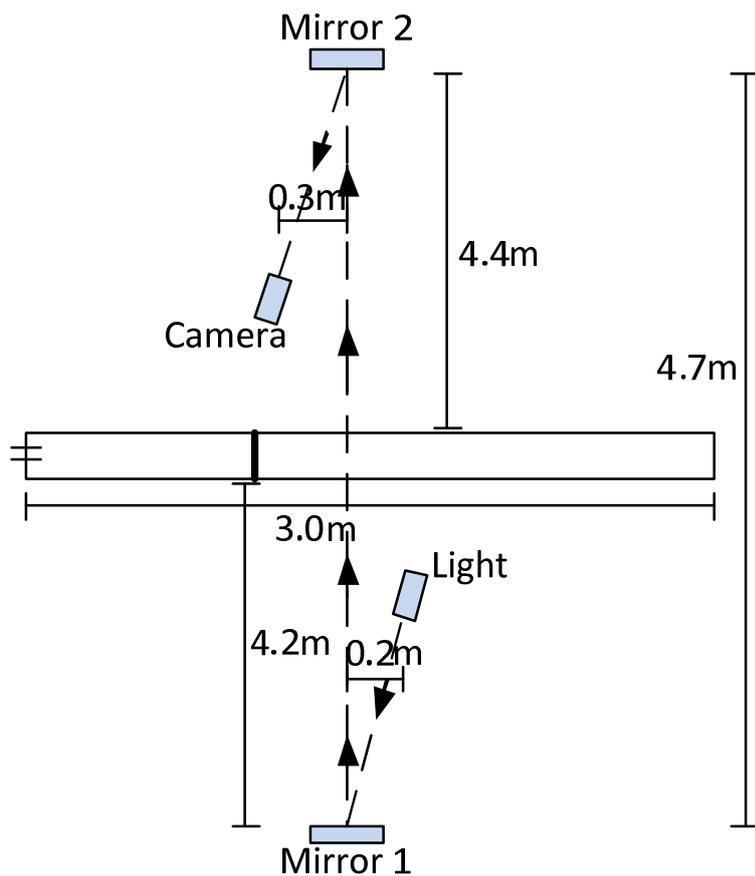
Figure 3-11 Overview of the schlieren setup (Seen from top of the channel).

3.2.2 P101
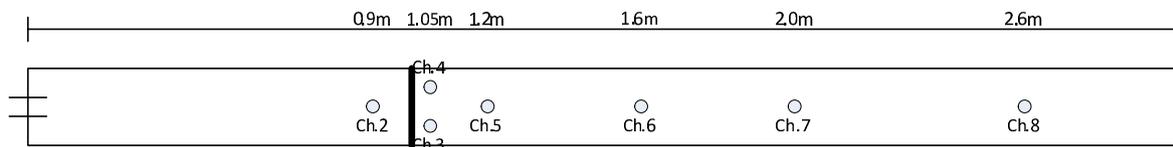
Figure 3-12 Drawing of the set-up of pressure sensors with length from ignition shown for each sensor, view is from top of the channel.
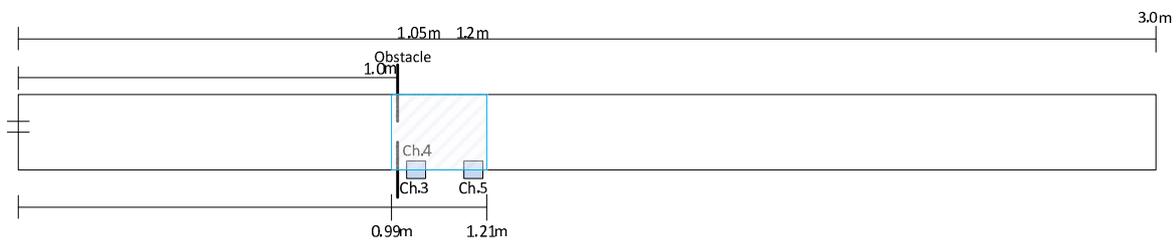

Figure 3-13 Drawing of the area that was recorded with the high-speed camera.

The pressure sensors were given names that correspond to the channels they were connected to on the oscilloscope. The sensor closest to ignition was connected to channel 2 on the oscilloscope and then given the name Ch2. The sensors for the P101 test series were placed as seen in Figure 3-12. Sensor 3 and 4 were placed parallel to each other in the width. The area

that was filmed is shown in Figure 3-13. The frame rate in the P101 series was 20000FPS, the resolution used was 512x256pixels with pixel size 0.431mm and the width of the filming area was 221mm. Pixel 0 was 0.99 m from ignition. The shutter time for all tests done in all series was 1/1000000 seconds. To obtain the pixel size an object of known width was placed in the filming area and the number of pixels measures with the Photron FASTCAM viewer software.

3.2.3   P102
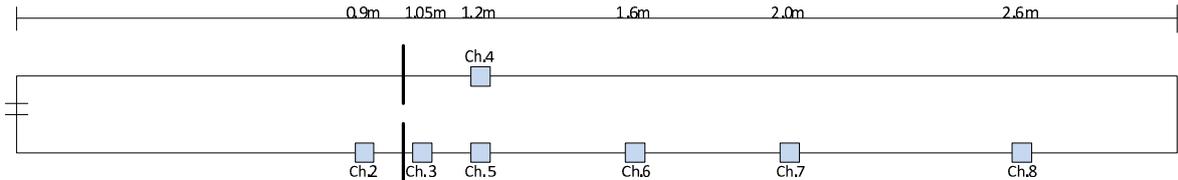
Figure 3-14 Drawing of the set-up of pressure sensors with length from ignition for each sensor, view is from the right side of the channel.
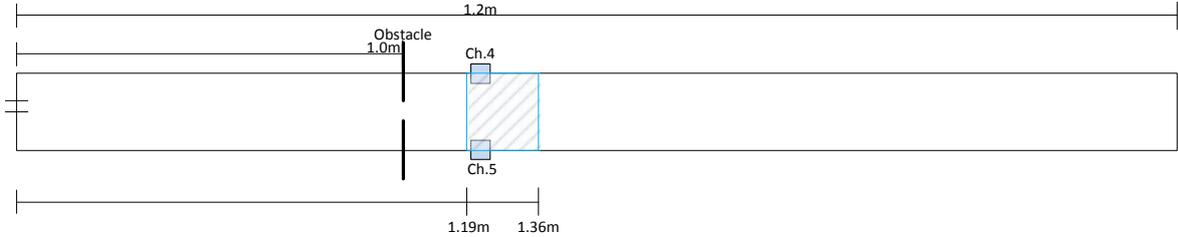

Figure 3-15 Drawing of the area that was recorded with the high-speed camera for tests done in the P102 series.

The pressure sensor setup for the experiments done in the P102 series is shown in Figure 3-14. Ch. 4 and 5 are at the same length with 5 at the bottom and 4 at the top of the channel. The area of the channel that was filmed is shown in Figure 3-15. The frame rate here was 22500FPS and the resolution was 384X256pixels with same pixel size of 0.431mm as before. The width of the filming area was then 165.5mm. Pixel 0 was 1.19 m from ignition.

3.2.4 P103
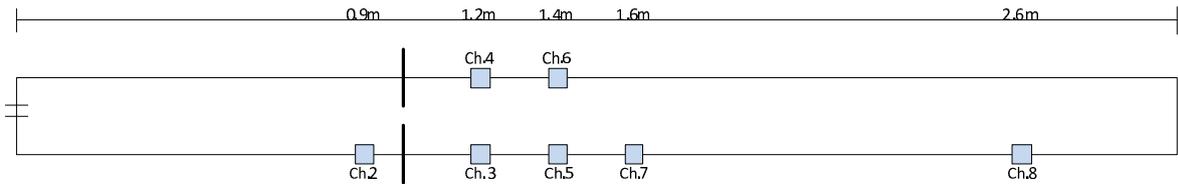
Figure 3-16 Drawing of the set-up of pressure sensors with length from ignition shown for each sensor, view is from the right side of the channel.
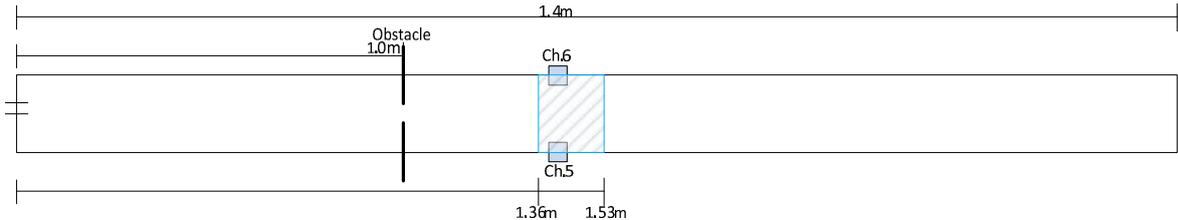

Figure 3-17 Drawing of the area that was recorded with the high-speed camera for tests done in the P103 series.

For the P103 series the pressure sensor placement is shown in Figure 3-16, Ch. 3 and 4 are at the same length of 1.2m from ignition. Ch. 5 and 6 are at the same length of 1.4m from ignition. The filming area is shown in Figure 3-17, pixel 0 was 1.36m from ignition and with the same resolution and FPS as in the P102 tests.

4 Results

Table 4-1 shows an overview of the tests presented in this report, an overview and pressure plots for all experiments that were done can be found in appendix 3 and 5.

Three different main setups were made with different placement of pressure sensors and different locations of the tube filmed. Tests were done with H_2 vol% from 15-40% and all tests were done with BR (blockage ratio of the obstacle) = 0.75. Table 4-1 shows all the tests presented in this section, a complete tests table for all tests done is included in the appendix. The tests are presented with a sequential of five pictures and then two pressure plots for each test. The blue vertical lines in the pressure plots correspond to start and end times of the frames shown for that test. The shutter of the high-speed camera is open at the end of each frame. Since the shutter time is 1µs, frame 1 is taken 1µs before the second vertical line.

All the pressure plots show time in seconds at the x-axes and position and pressure in dm and bars at the y-axes. The pressure sensors actual position from ignition is shown in dm at the y-axes along with the pressure in bars. By plotting this way it is easy to see the shock wave travel. All photos shown are taken with schlieren. The pressure plots are presented with time intervals of 0.5 ms and 2 ms.

It should be noted that there were some oscillation problems with the test channel during the tests conducted in the P103 series which may have given unreliable pressure results for those tests.

The shock wave velocities were estimated by tracing the rapid pressure increase between pressure sensors, this may give some error as the shock waves are rather irregular in shape and some sensors were placed at the top and bottom wall of the test channel. The flame-tip velocities that were estimated may also deviate from the actual velocity as they are traced with help of the photos taken.

Table 4-1 Shows the tests presented in this report with volume percentage H_2, CJ-Detonation velocity and overview over which tests did detonate. Project refers to the pressure sensor and film location setup, BR is blockage ratio of the obstacle.

Project	Test	BR	Vol%H2	CJ-Det. Velocity m/s	Detonation
101	5	0.75	25	1858	No
101	6	0.75	30	1976	Yes
101	7	0.75	35	2048	Yes
102	3	0.75	25	1858	No
102	4	0.75	30	1976	Yes
102	5	0.75	35	2048	Yes
103	3	0.75	28	1935	Yes
103	4	0.75	28	1935	No
103	5	0.75	30	1976	Yes
103	6	0.75	30	1976	Yes

4.1 P101

In the setup for tests done in P101 ch. 3 and 4 are placed parallel to each other at 50 mm from the obstacle and ch. 5 is at 200 mm (ch. is pressure sensor).
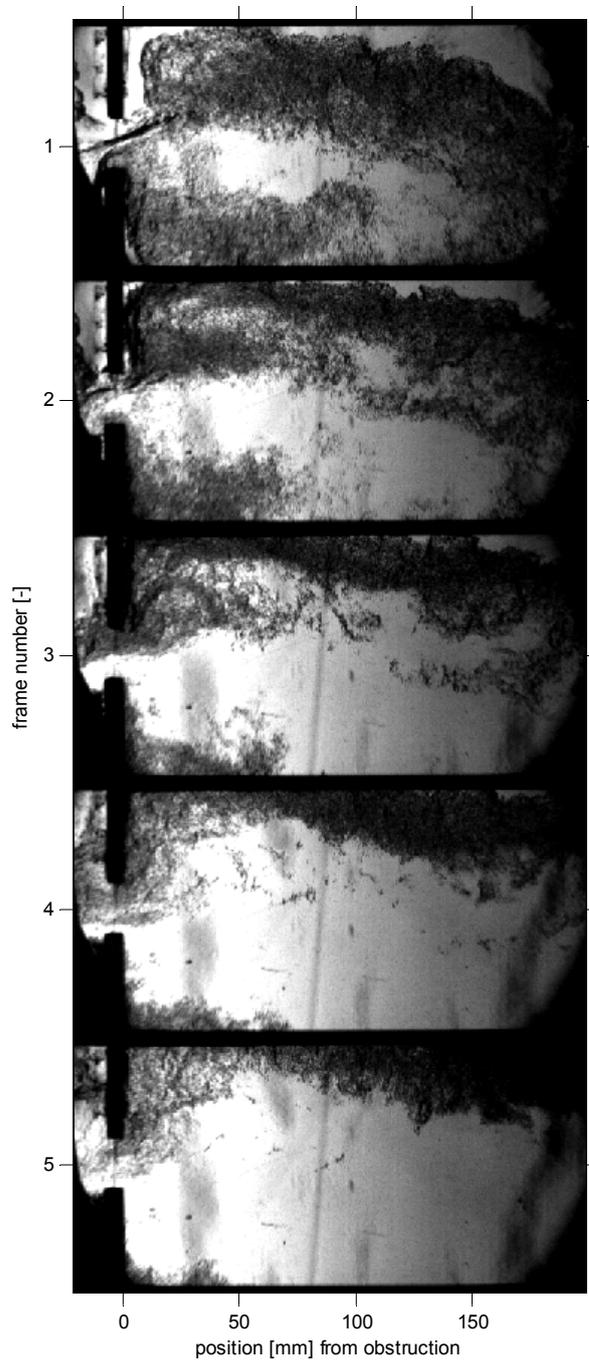

Figure 4-1 P101-5 25%vol. H₂, filmed at 20000FPS.

Test 5 did not detonate and no shock wave is visible in the schlieren photos for that test. The pressure plots shown in Figure 4-2 and Figure 4-3 for that test indicate a shock wave visible at ch. 6 propagating with about 1000 m/s.
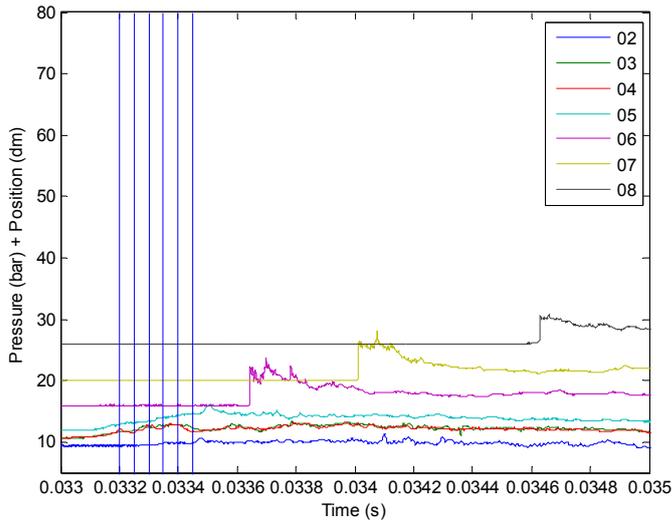
Figure 4-2 P101-5 25%vol. H₂. A time interval of 2ms is shown. The velocity of the shock wave from sensor 6-7 is estimated to be 1080 m/s and from sensor 7-8 to be 970m/s.
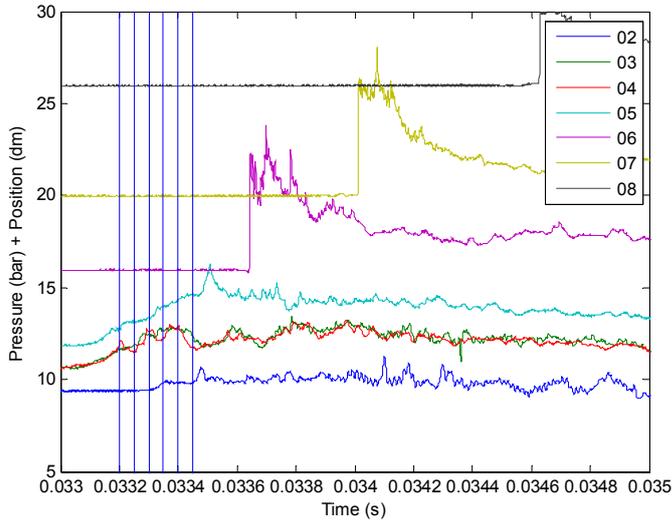

Figure 4-3 P101-5 25%vol. H₂. The time interval is 2ms. The velocity of the shock wave from sensor 6-7 is estimated to be 1080 m/s and from sensor 7-8 to be 970m/s.
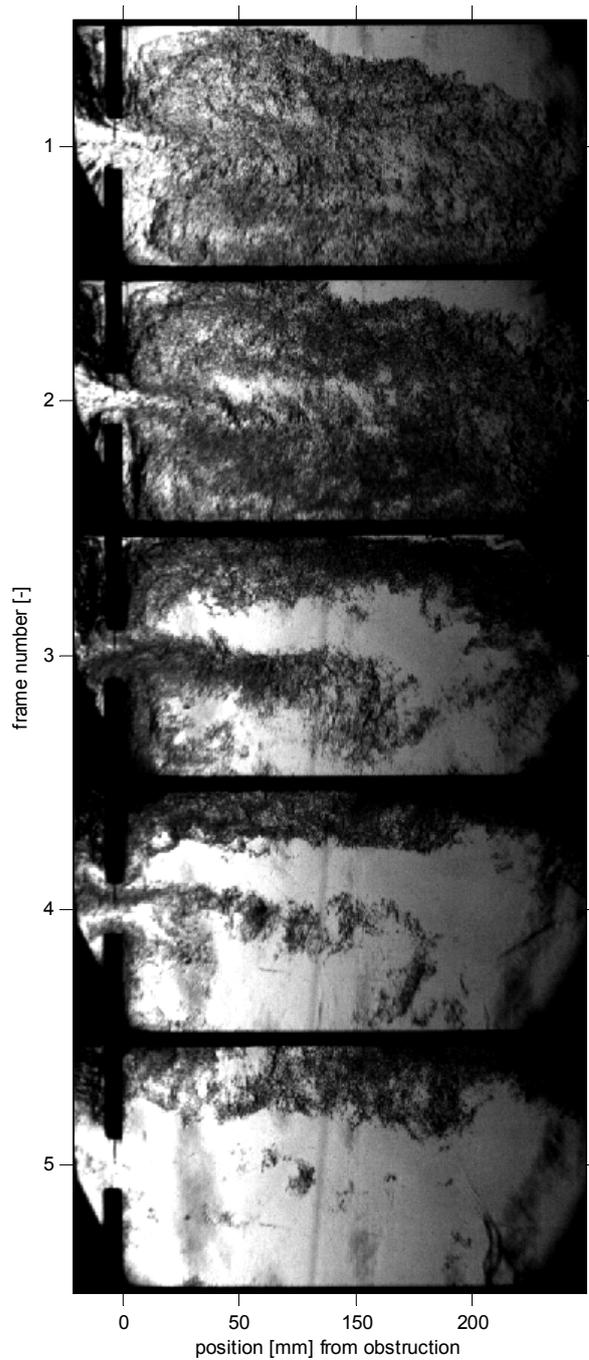
Figure 4-4 P101-6 30%vol. H$_2$ filmed at 20000FPS.

In frame 5 in Figure 4-4 for test 6 a shock wave is visible in the bottom at about 200 mm from obstacle. This mixture did detonate as indicated by the pressure plots with pressure at ch. 6 above 20 bar.
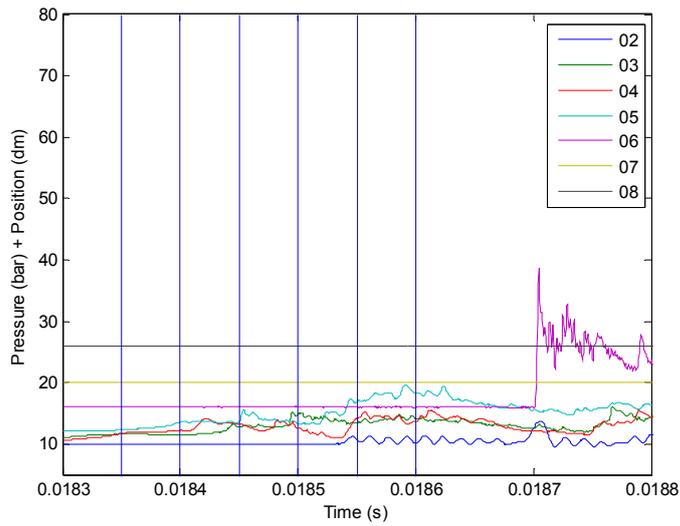
Figure 4-5 P101-6 30%vol. H₂. Time interval of 0.5ms. The velocity of the shock wave from sensor 6-7 is estimated to be 2100 m/s and from 7-8 2070m/s.
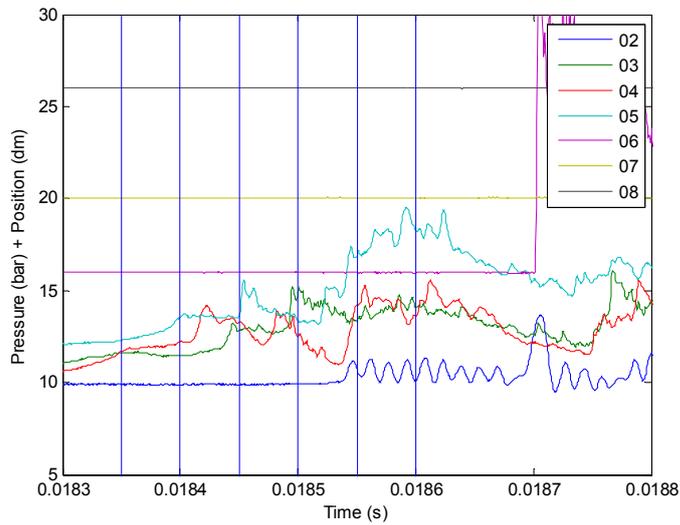

Figure 4-6 P101-6 30%vol. H₂. Time interval of 0.5ms. The velocity of the shock wave from sensor 6-7 is estimated to be 2100 m/s and from 7-8 2070m/s.
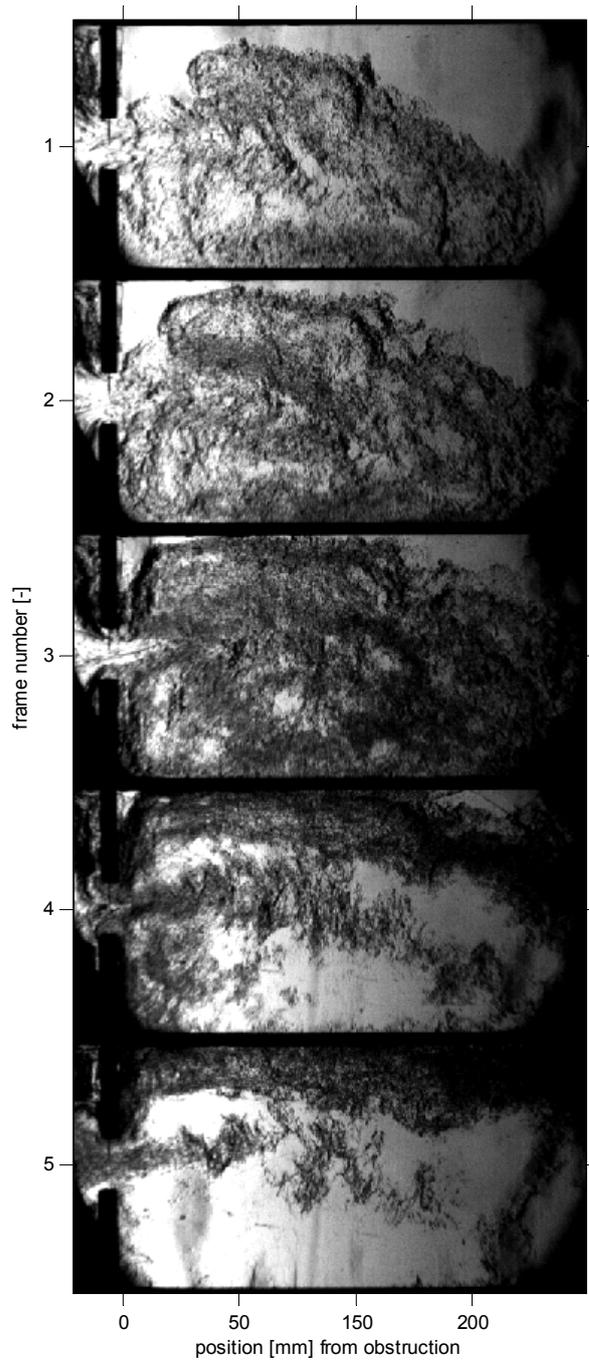
Figure 4-7 P101-7 35%vol. H_2 filmed at 20000 FPS.

In test 7 a shock wave and its reflection is visible in frame 4 in Figure 4-7 at the top wall at about 200 mm, this mixture detonated with pressure above 20 bar as seen in the pressure plots for that test.
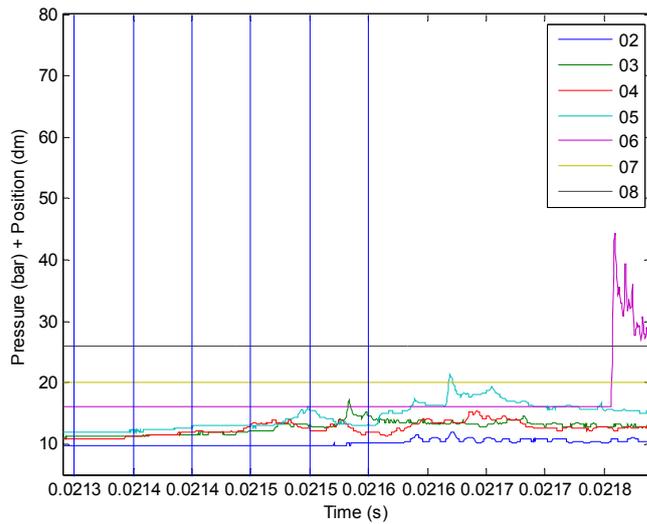
Figure 4-8 P101-7 35%vol. H₂. Time interval of 0.5ms. The shock wave velocity from sensor 6-7 is estimated to be 2350 m/s and from 7-8 2140 m/s.
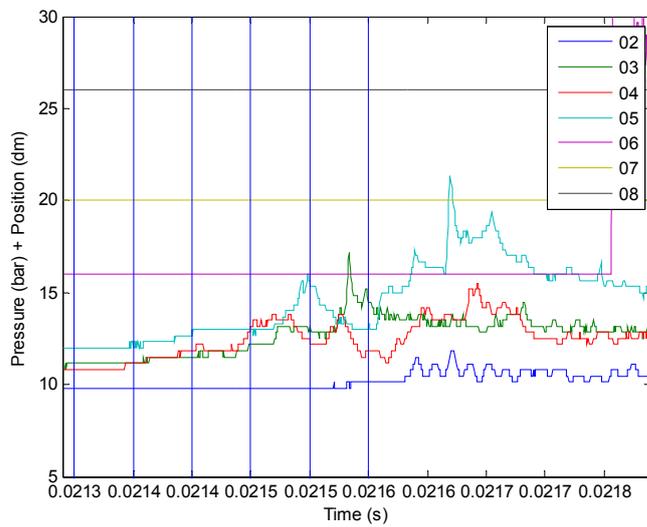
Figure 4-9 P101-7 35%vol. H₂. Time interval of 0.5ms. The shock wave velocity from sensor 6-7 is estimated to be 2350 m/s and from 7-8 2140 m/s.

4.2 P102

In the P102 setup ch. 4 and 5 are at the same length of 200 mm from the obstacle, ch. 4 is at the top and 5 at the bottom.
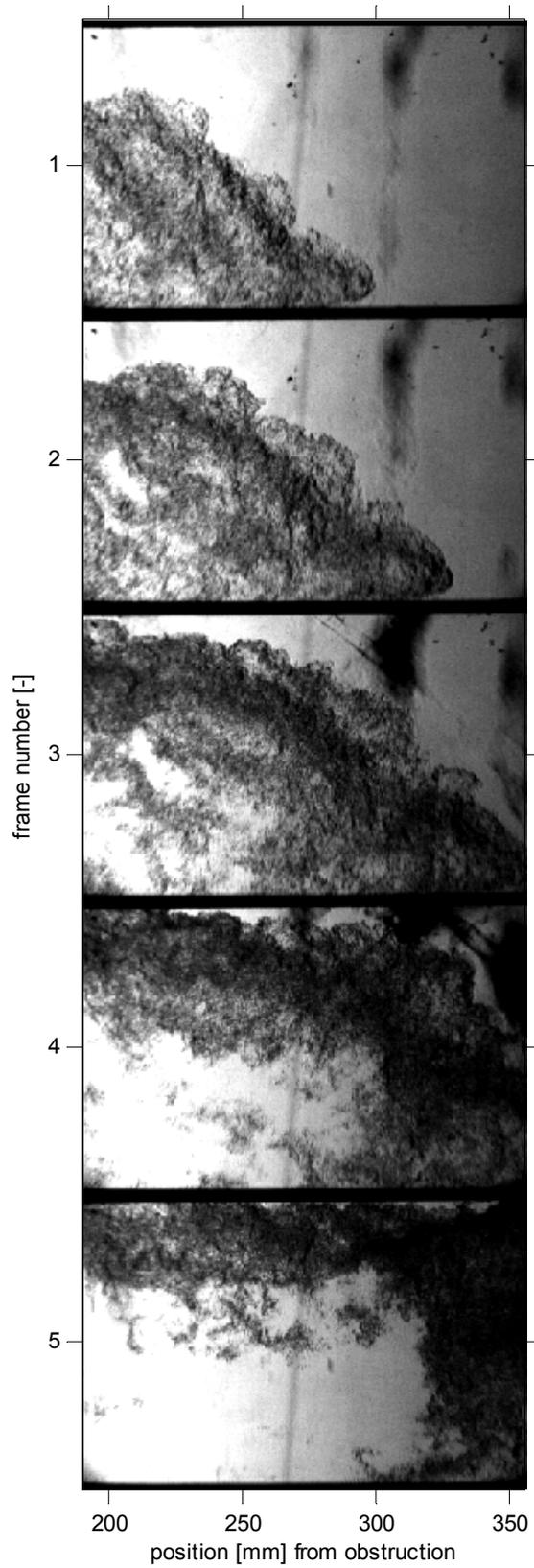
Figure 4-10 P102-3 25%vol. H_2 filmed at 22500 FPS. The velocity of the tip of the flame front from frame 1-2 is estimated to be 660 m/s.

In Figure 4-10 the contours of a shock wave is visible in frame 2 and in frame 3 and 4 what appears to more than 1 shock wave is visible. From the pressure plot in Figure 4-12 it is seen that the pressure increases in the top at ch. 4 and then is followed by an increase at the bottom (ch. 5). This occurs at the same time as frame 2 to 5 in Figure 4-10. This mixture did not detonate.
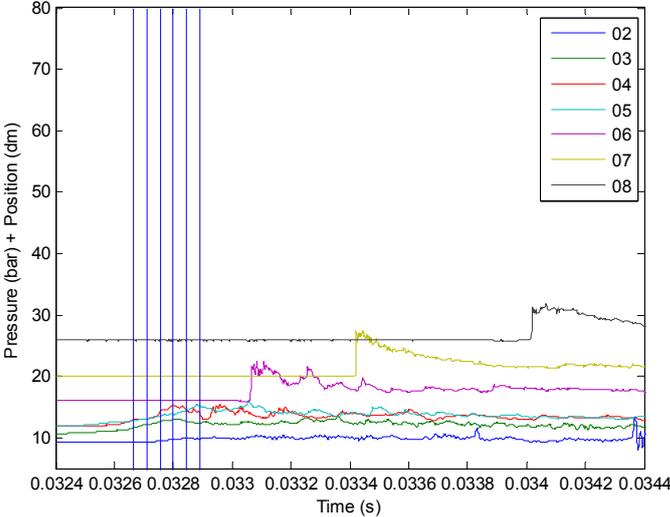
Figure 4-11 P102-3 25%vol. H₂ with time interval of 2ms. The shock wave velocity from sensor 6-7 is estimated to be 1110 m/s and from 7-8 1000 m/s.
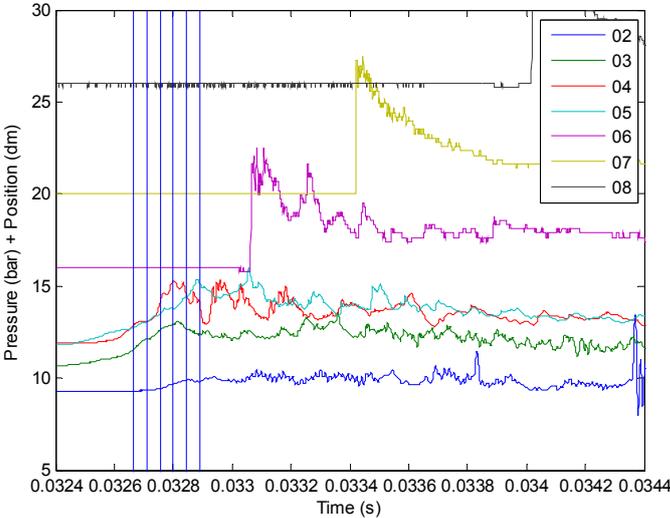

Figure 4-12 P102-3 25%vol. H₂ with time interval of 2ms. The shock wave velocity from sensor 6-7 is estimated to be 1110 m/s and from 7-8 1000 m/s.
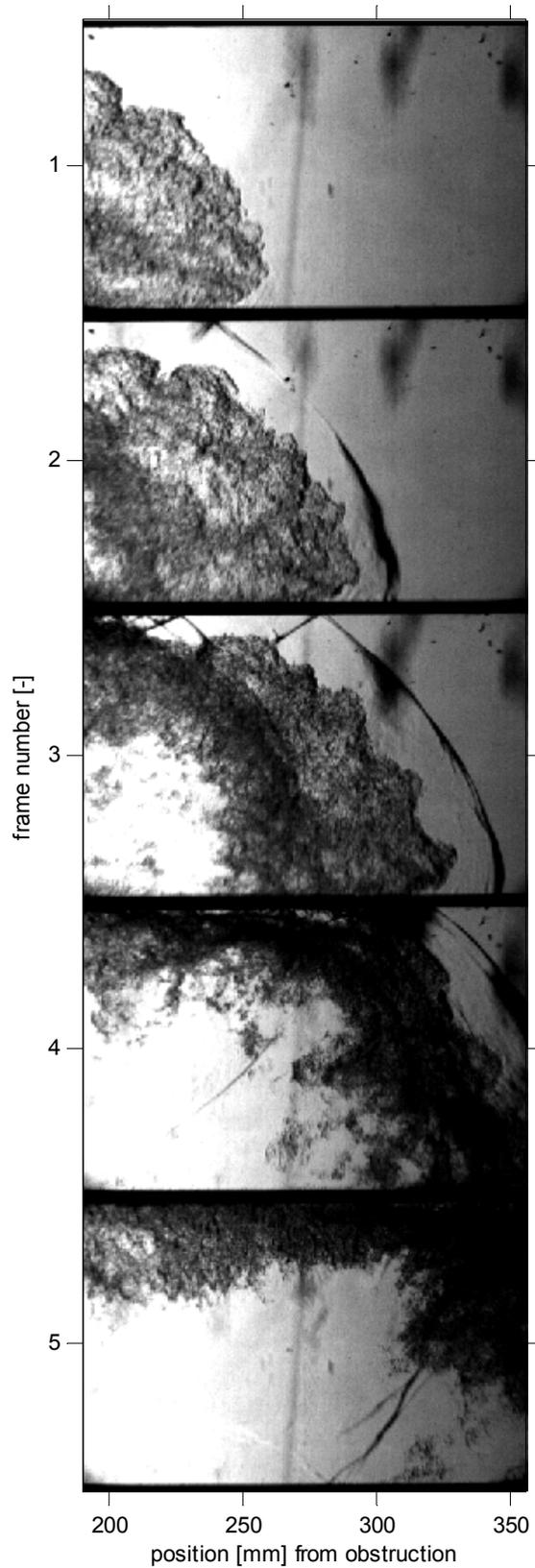
Figure 4-13 P102-4 30%vol. H_2 filmed at 22500 FPS. The velocity of the tip of the flame front from frame 1-2 is estimated to be 750 m/s and from frame 2-3 823 m/s.

Figure 4-13 shows 5 frames for test 4 which detonated further out in the channel than is seen here. In frame 2 a shock wave is seen and its reflection at the top wall of about 250 mm from the obstacle and in frame 3 what appears to be the formation of more shock waves occurs. The pressure plot in Figure 4-14 shows a pressure top of 50 bar at ch. 6, the pressure was actually higher but due to limitations in the amplification setup for this test the recordings stopped at 50 bar for that pressure sensor. As seen in Figure 4-15 the pressure increases first at the top wall (ch. 4) and then at the bottom wall (ch. 5). The velocity of the flame tip from frame 1 to 2 was about 750 m/s and the shock wave was propagating above 2000 m/s.
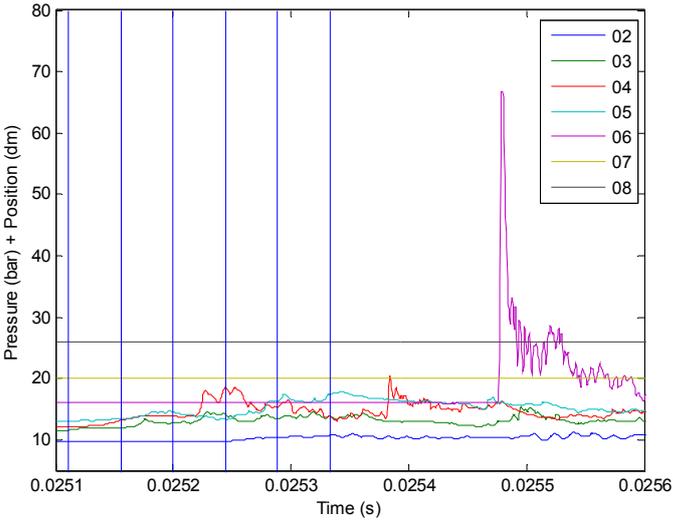
Figure 4-14 P102-4 30%vol. H_2 with time interval of 0.5ms. The shock wave velocity from sensor 6-7 is estimated to be 2350 m/s and from 7-8 2070 m/s.
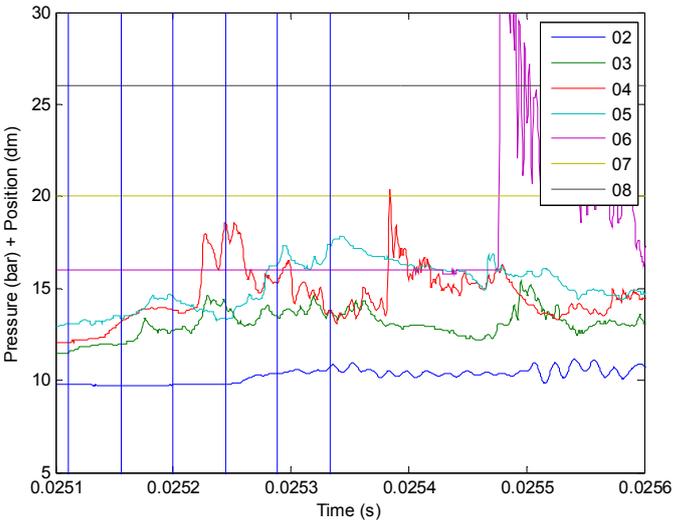
Figure 4-15 P102-4 30%vol. H_2 with time interval of 0.5ms. The shock wave velocity from sensor 6-7 is estimated to be 2350 m/s and from 7-8 2070 m/s.
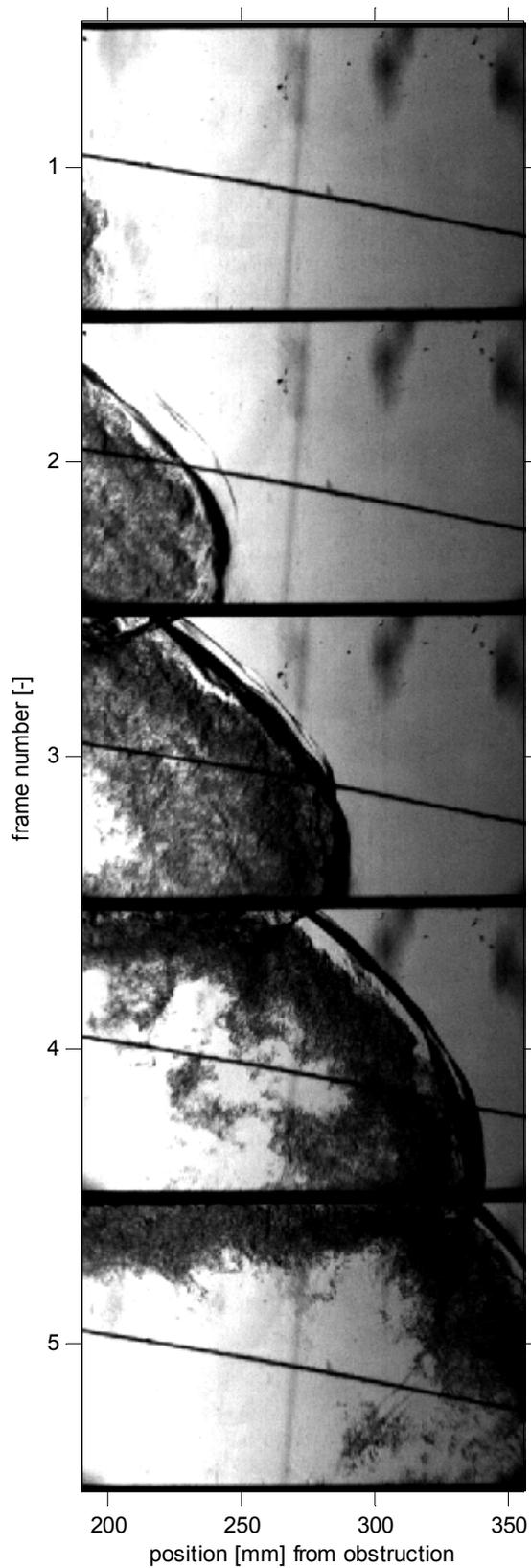
Figure 4-16 P102-5 35%vol. H_2 filmed at 22500 FPS. The velocity of the tip of the flame front from frame 1-2 is estimated to be 900 m/s. The straight line stretching across the photos is an error in the filming.

In Figure 4-16 a shock wave is clearly visible in frame 2 as a thick dark line in front of the flame, what appears to be a weaker shock wave in front is seen in frame 2 and 3. In the down left corner of frame 1 multiple lines are seen in front of the flame which indicates high density and low density relative to each other. The flame velocity from frame 1 to 2 is about 900 m/s.
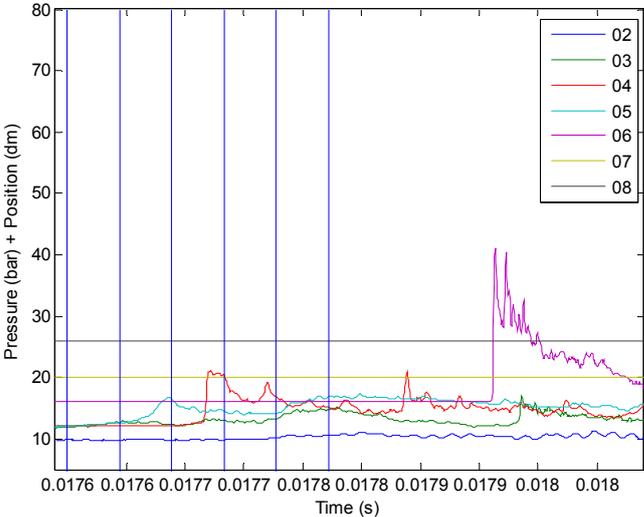

Figure 4-17 P102-5 35%vol. H_2 with time interval of 0.5ms. The shock wave velocity from sensor 6-7 is estimated to be 2220 m/s and from 7-8 2140 m/s.
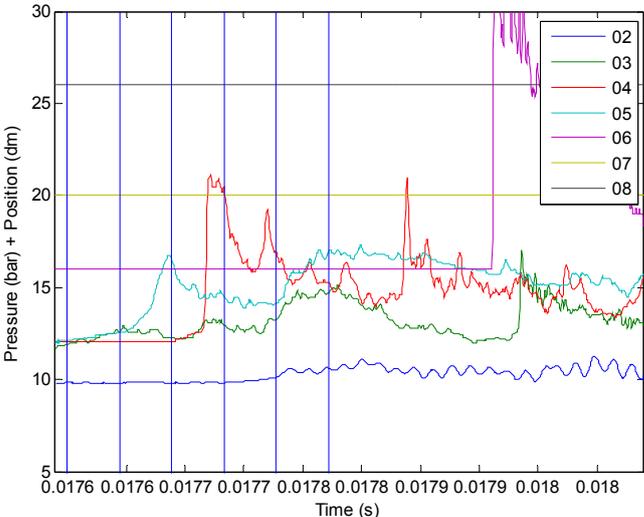
Figure 4-18 P102-5 35%vol. H_2 with time interval of 0.5ms. The shock wave velocity from sensor 6-7 is estimated to be 2220 m/s and from 7-8 2140 m/s.

4.3 P103

Ch. 5 and 6 are placed at 400 mm from the obstacle with ch. 5 at the bottom and 6 at the top wall. Both test 3 and 4 had 28%vol. H_2, test 3 detonated but not test4.
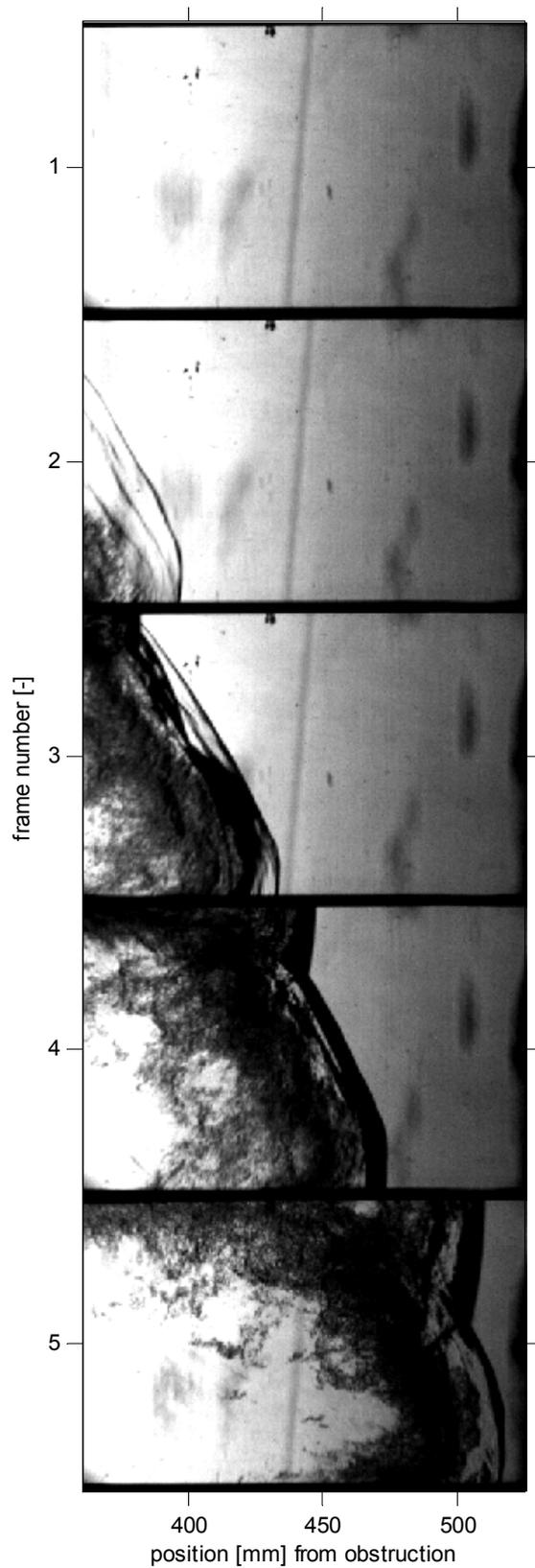
Figure 4-19 P103-3 28%vol. H_2 filmed at 22500 FPS.

Frame 2 in Figure 4-19 indicates the appearance of more than one shock wave and in frame 4 a strong shock wave and its reflection. The pressure plots in Figure 4-20 and Figure 4-21

show that the pressure at ch. 6 which was in the top wall at 400 mm from obstacle is above 25 bar for a relative long time compared to other tests and with a peak pressure of about 35 bar.
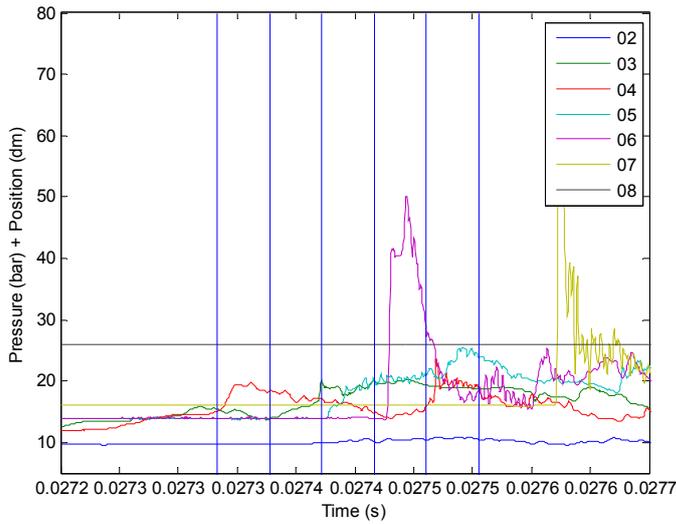
Figure 4-20 P103-3 28%vol. H₂ with time interval of 0.5ms. The shock wave velocity from sensor 6-7 is estimated to be 1430 m/s and from 7-8 2130 m/s.
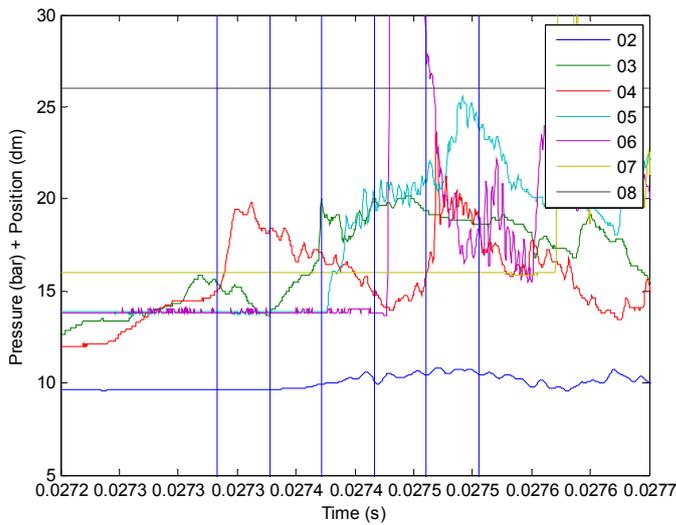

Figure 4-21 P103-3 28%vol. H₂ with time interval of 0.5ms. The shock wave velocity from sensor 6-7 is estimated to be 1430 m/s and from 7-8 2130 m/s.
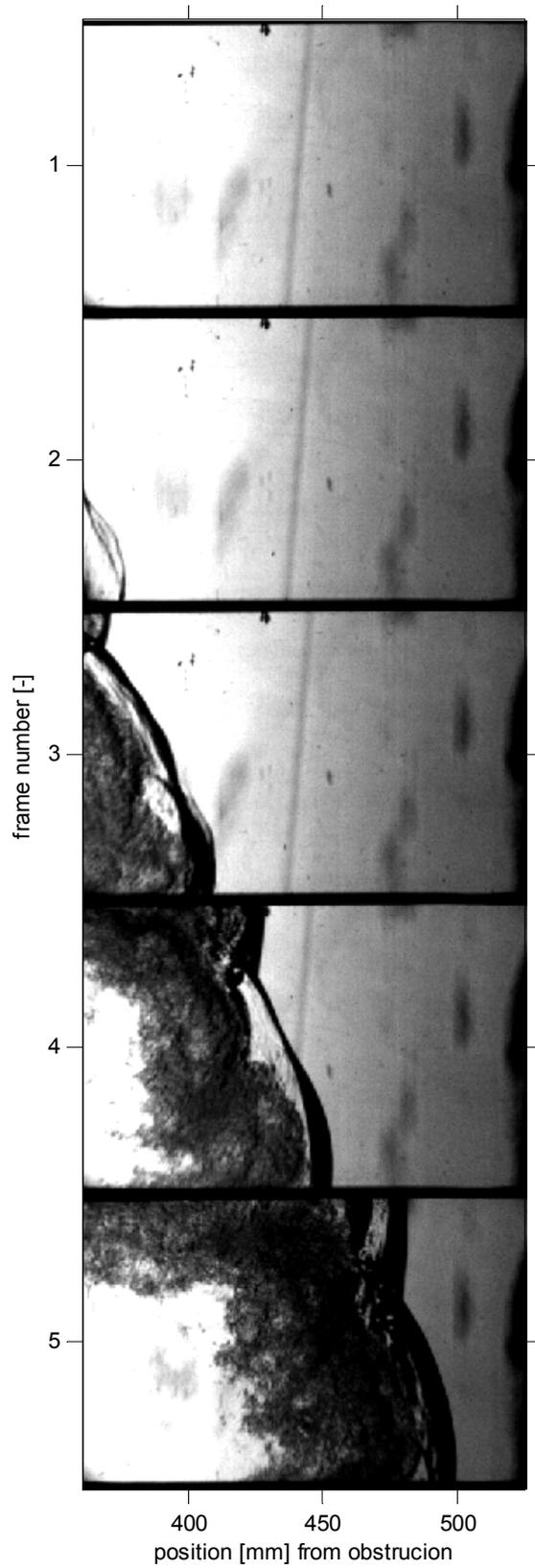
Figure 4-22 P103-4 28%vol. H₂ filmed at 22500 FPS.
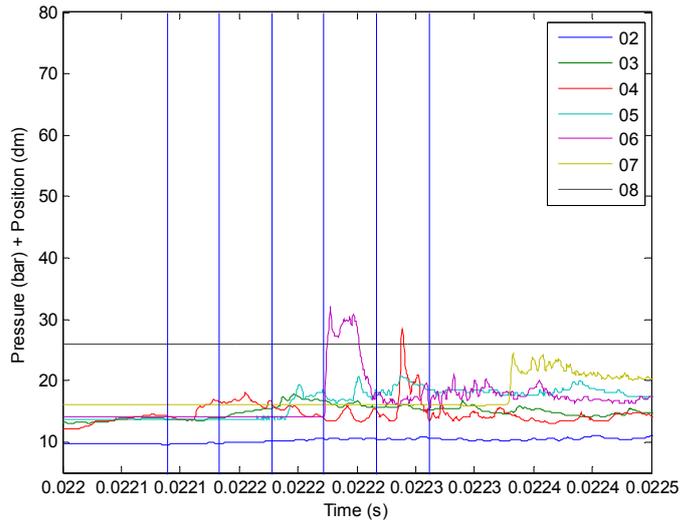
Figure 4-23 P103-4 28%vol. H₂ with time interval of 0.5ms. The shock wave velocity from sensor 6-7 is estimated to be 1250 m/s and from 7-8 1160 m/s.
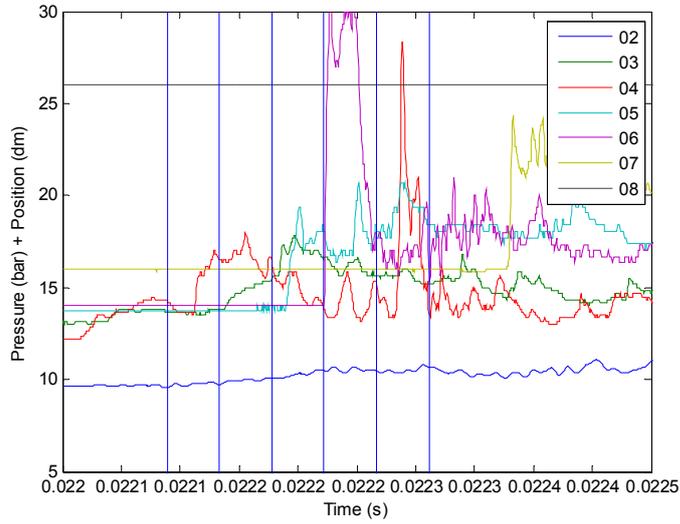
Figure 4-24 P103-4 28%vol. H₂ with time interval of 0.5ms. The shock wave velocity from sensor 6-7 is estimated to be 1250 m/s and from 7-8 1160 m/s.
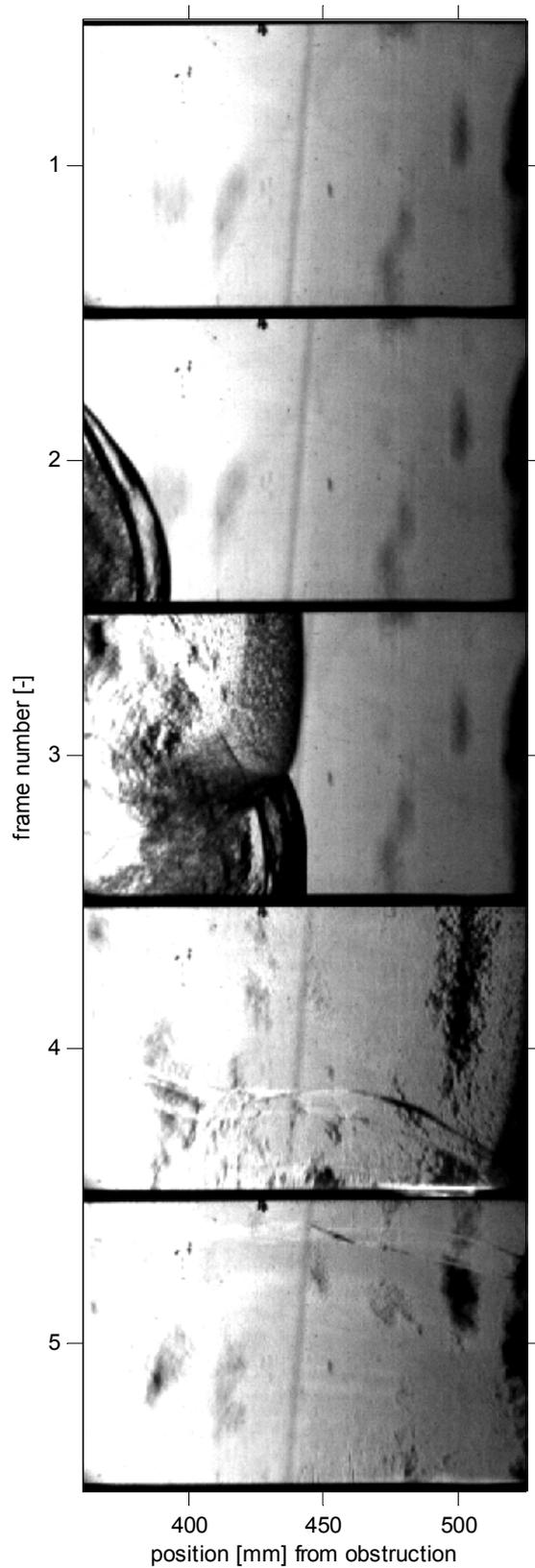
Figure 4-25 P103-5 30%vol. H₂ filmed at 22500 FPS.

Photos for test 3 with 30%vol. H₂ are shown in Figure 4-25, the shock wave and flame front are seen in frame 2 and a deflagration to detonation transition (DDT) is seen in frame 3. From

the pressure plots in Figure 4-26 and Figure 4-27 the velocity of the shock wave is calculated to be above 2000 m/s.
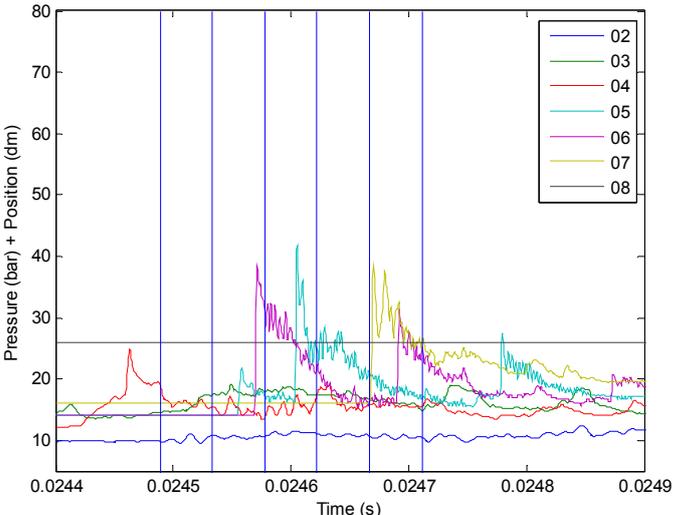
Figure 4-26 P103-5 30%vol H₂ with time interval of 0.5ms. The shock wave velocity from sensor 6-7 is estimated to be 2000 m/s and from 7-8 2130 m/s.
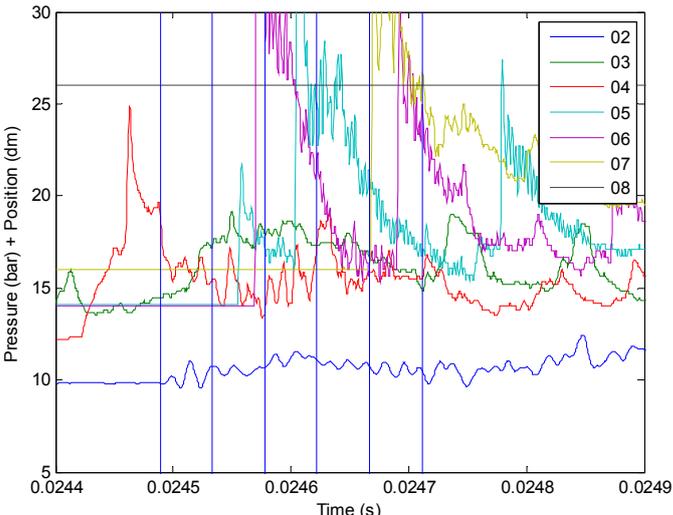
Figure 4-27 P103-5 30%vol. H₂ with time interval of 0.5ms. The shock wave velocity from sensor 6-7 is estimated to be 2000 m/s and from 7-8 2130 m/s.
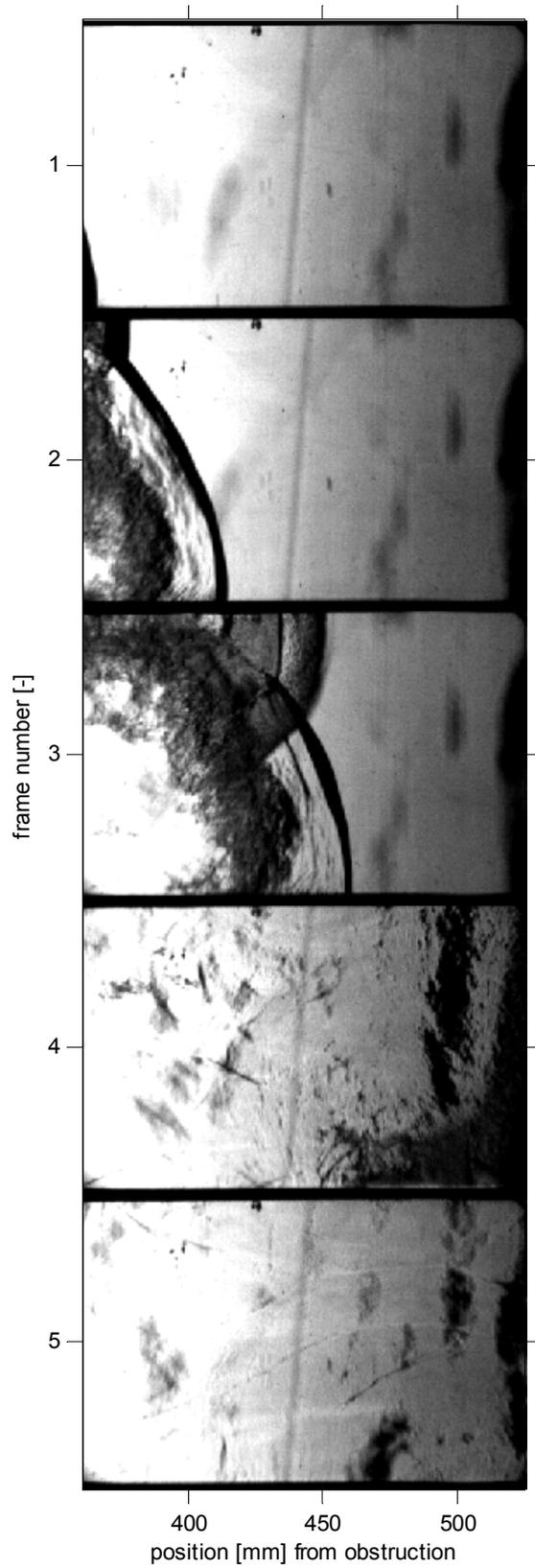
Figure 4-28 P103-6 30%vol. H_2 filmed at 22500 FPS.

Photos from test 6 with the same mixture as test 5 of 30%vol. H_2 are shown in Figure 4-28. In frame 2 the shock wave and flame front are seen and in frame 3 DDT is seen from the top wall. The pressure plot in Figure 4-29 shows a peak pressure of about 60 bar at ch. 6.
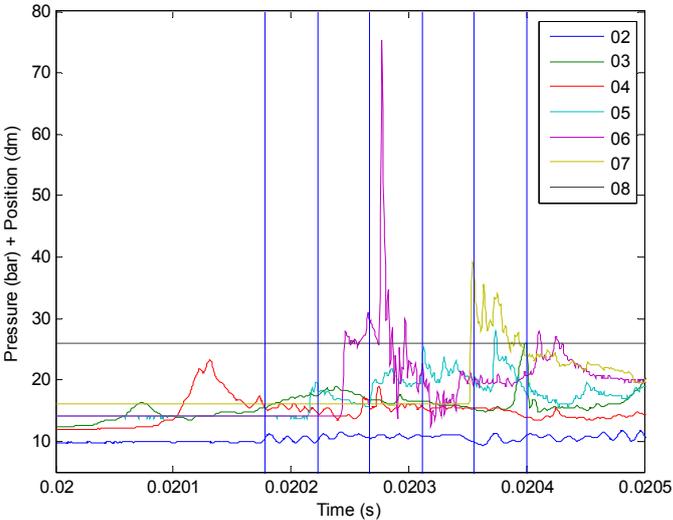
Figure 4-29 P103-6 30%vol. H_2 with time interval of 0.5ms. The shock wave velocity from sensor 6-7 is estimated to 1820 m/s and from 7-8 to be 2130 m/s.
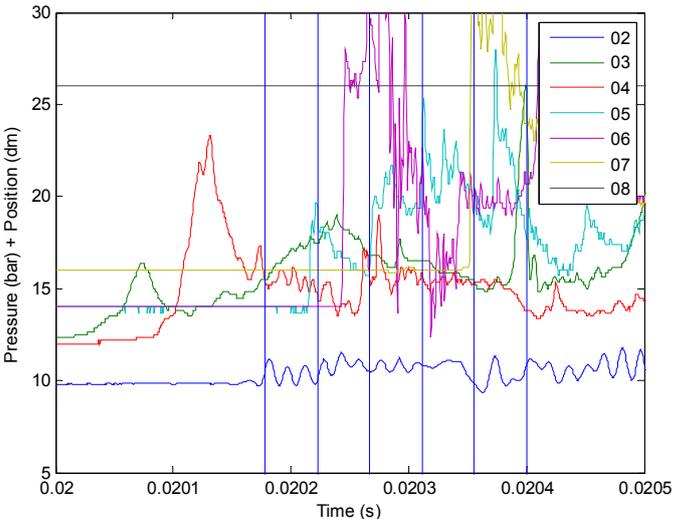
*Figure 4-30 P103-6 30%vol. H_2 with time interval of 0.5ms. The shock wave velocity from sensor 6-7 is estimated to 1820 m/s and from 7-8 to be 2130 m/s.*

5 Discussion

The main objective of this study was to build a schlieren setup in order to do high speed photography of deflagration to detonation transition of a hydrogen and air mixture in a channel with one obstacle.

The schlieren setup was able to take photographs of the whole cross section of the test channel at 22500 FPS with shutter time of 1μs. The sensitivity of the system was sufficient to observe shock waves well along with the DDT. The 150watt halogen lamp and the optical slit used as a light source provided enough light to get acceptable schlieren pictures. A camera that can take pictures at 1μs interval (1 million FPS) should be able to use the same schlieren setup with the same light source as well.

Three different experimental series were carried out, were location of pressure sensors and position of the channel that were filmed was different for each series. Results from mixtures ranging from 25 to 35%vol. H_2 with blockage ratio of 0.75 are presented in this report. Shock wave velocities were traced from the pressure plots and flame-tip velocities from photographs were that was possible.

Two tests were done with 25%vol. H_2, they did not detonate. Two tests with 28%vol. H_2 were conducted were one did detonate and one did not. This suggests that for blockage ratio of 0.75 with the used cross section area a 28%vol. H_2 mixture is the lean limit for a mix that will detonate, this is in accordance with (Gaathaug, 2014) earlier experiments with the same test channel. All tests done with 30 and 35%vol. H_2 detonated. In some cases multiple shock waves seem to appear as seen in Figure 4-13 and Figure 4-19. This is not considered to be entirely due to reflections of the front wave as they appear simultaneously as seen in frame 3 in Figure 4-13.

In Figure 4-1 which shows photos taken with a 25%vol. H_2 mixture no shock waves are observed. The same location is filmed with a 30 and 35 % mixture and shown in Figure 4-4 and Figure 4-7 were shock waves are observed, this may indicate a shorter run-up distance for the richer mixtures. The same is observed in the photographs taken further out in the channel as seen in Figure 4-10 and Figure 4-13 were tests with 25 and 30%vol. H_2 are shown, a shock wave is formed closer to the obstacle for the richer tests.

The tests in the P103 series were filmed in the length of 36 to 53 cm from the obstacle and a transition from deflagration to detonation was observed at the top wall for the two tests with 30%vol. H_2, these tests are shown in Figure 4-25 and Figure 4-28 were a clear change in the structure from the top wall is seen were the transition occurs. The run-up distance for these tests was between 400 and 450mm from the obstacle. The 28%vol. H_2 mixture that detonated is filmed at the same position in the channel and shown in Figure 4-19, DDT for that mixture occurred further away from the obstacle than the 30%vol. H_2 mixture and is not seen in the photos.

The shock wave velocities shown in Table 5-1 were estimated between pressure sensor 6 and 7 and sensor 7 and 8. The velocities for the P103 tests are not directly comparable to the P101 and P102 tests since sensor 6 and 7 were at 1.4 and 1.6 m from ignition in the P103 setup and at 1.6 and 2 m in the P101 and P102 setups as seen in Figure 3-14 and Figure 3-16. The tests that showed a detonation all had estimated shock wave velocities greater than the CJ-velocity for that mixture.

A highly possible error source for the P103 velocities between sensor 6 and 7 may be that sensor 6 was at the top wall and sensor 7 at the bottom wall, since the shock waves were not planar this may have given inaccurate estimation of velocities.

Table 5-1 Shows estimated velocity from the pressure plots along with CJ-Velocity (Gaathaug, 2014) for each mixture. Possible error source in estimated velocities for the P103 tests since ch. 6 was placed at the top wall and ch. 7 at the bottom wall.

Project	Test	Vol%H2	CJ-Det. Velocity	Est. Velocity ch.6-7	Est. Velocity ch.7-8
101	5	25	1858 m/s	1080 m/s	970 m/s
101	6	30	1976 m/s	2100 m/s	2070 m/s
101	7	35	2048 m/s	2350 m/s	2140 m/s
102	3	25	1858 m/s	1110 m/s	1000m/s
102	4	30	1976 m/s	2350 m/s	2070 m/s
102	5	35	2048 m/s	2220 m/s	2140 m/s
103	3	28	1935 m/s	1430 m/s	2130 m/s
103	4	28	1935 m/s	1250 m/s	1160 m/s
103	5	30	1976 m/s	2000 m/s	2130 m/s
103	6	30	1976 m/s	1820 m/s	2130 m/s

Flame tip velocities for test P102-4 and P102-5 which both detonated were estimated to 820 m/s for P102-4 at about 300 mm from obstacle and 900 m/s for P102-5 at about 200 mm from obstacle. This is about 40% of the CJ-velocity for these mixtures as seen in Table 5-1.

6 Conclusion

A schlieren setup was built and 150watt halogen lamp was used with an optical slit as light source. The setup with that light source system was able to get photos of shock waves at 22500 FPS and shutter time of 1μs at different positions and with different mixtures in the test channel. Multiple shock waves were observed in some cases were reflections of the front wave could not explain all shock waves observed. Photographs of a deflagration to detonation transition were captured in two different tests with the same mixture of 30%vol. H_2 between 400 and 450 mm from the obstacle. The pictures show that shock waves occur further away from the obstacle as the mixture gets leaner. The results suggest that with a blockage ratio of 0.75 as was used for all tests, the leaner mixture limit for a detonation to occur is 28%vol. H_2 and mixtures as rich as 35%vol. H_2 detonate. The shock wave velocities that are estimated for tests that detonated are all above the CJ-velocity for that mixture, and flame velocities that are about 40% of the CJ-velocity at approximately 300 mm from the obstacle for a test with 30%vol. H_2 and approximately 200 mm from the obstacle for at test with 35%vol. H_2 mixture.

There are still unsolved questions regarding shock wave behavior and the onset of detonation and continuation of similar experiments is recommended as a new high speed camera is going to be acquired that can take pictures in the range of millions per second rather than thousands. A brighter light source may be considered in that case as the current light source has only been tested for exposure times of 1μs.

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Appendices

Appendix 1: Task description

Appendix 2: Other equipment

Appendix 3: Test tables

Appendix 4: Experiment procedure

Appendix 5: Pressure plots

Appendix 6: Matlab code pressure plots

Appendix 7: Matlab code schlieren photographs

Appendix 8: Calibration flow-meters

Appendix 1: Task description

Telemark University College
Faculty of Technology

FMH606 Master Thesis

Title: Experimental investigation of hydrogen-air explosions with a schlieren set-up

Student: Larus Bjarnason

College supervisor: Professor Dag Bjerketvedt
Assoc. Professor Knut Vågsæther
Assistent Professor André V. Gaathaug

External partners: IEA (International Energy Agency)-HIA Task 31 – Hydrogen safety

Task description:

a) Make a literature review on schlieren imaging with focus on i) applications of this technique and ii) performance of different types of light sources

b) Build and test a schlieren set-up

c) Perform experiments with gas explosions in a channel with a single obstacle where the main diagnostics will be the schlieren set-up.

Task background:

This project will be part of our work on shock waves and hydrogen safety in cooperation with IEA-HIA Task 31 (http://ieahia.org/pdfs/Canada/PRES_Task31_Toronto_June2012.pdf). Main objective is to develop a schlieren set-up and use this to observe transition from deflagration to detonation in hydrogen-air explosion in a lab scale experiment

Practical information (where, how, available equipment etc.):
The work will be performed at Telemark University College

Formal acceptance by the student (with ultimate task description as stated above):

Student's signature and date: 8/8–13

Supervisor's signature and date: 8/8-2013

Appendix 2: Other equipment

Palflash 501:

The Palflash 501 was used in the setup of the schlieren equipment. It is an arc light source specially designed for schlieren, but due to problems only the focus light was used in the alignment and testing of the schlieren equipment.

DC amplifiers:

The amplifiers used for the halogen lamp are two Gossen KONSTANTIER DC amplifiers. They gave 10V each.
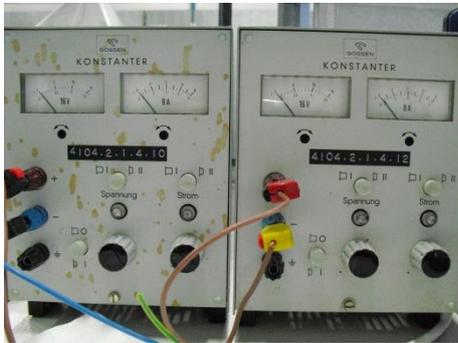
Leveling:

For alignment of the mirrors, the light source, camera and the test channel a Bosch GLL3-80P Professional cross line laser was used.

Flow-meters:

Two Fischer and Porter flow-meters were used. The tube in the air flow-meter was a FP-1/4-25-G-5, the tube for the hydrogen was a FP-1/8_16-G-5.

Air compressors:

Two air compressors were used, one for the tube-valve and one for air supply to flow-meter. An Oil free compressor for the air supply to the channel was used so no oil would contaminate the system.

Tube valve:

On the top of the channel was a valve used to remote control the flow in to the channel, it was controlled with air pressure.

Gas-meter:

A Ritter – TG 10/1 gas-meter was used in the calibration of the flow-meters.

Appendix 3: Test tables

Project	Test	Vol%H2	Pix. 0	Ch.2	Ch.3	Ch.4	Ch.5	Ch.6	Ch.7	Ch.8
101	3	15	0.99	10	10	10	10	10	10	10
101	4	20	0.99	10	10	10	10	10	10	10
101	5	25	0.99	10	10	10	10	10	10	10
101	6	30	0.99	10	10	10	10	10	10	10
101	7	35	0.99	10	10	10	10	10	10	10
101	8	40	0.99	10	10	10	10	10	10	10
102	1	15	1.19	1	3	3	3	7	7	7
102	2	20	1.19	1	3	3	3	7	7	7
102	3	25	1.19	1	1	1	1	7	7	7
102	4	30	1.19	1	3	3	3	7	7	7
102	5	35	1.19	1	3	3	3	7	7	7
102	6	40	1.19	1	3	3	3	7	7	7
103	1	25	1.36	1	3	3	3	3	5	5
103	2	27	1.36	1	3	3	3	3	5	5
103	3	28	1.36	1	5	5	5	5	5	5
103	4	28	1.36	2	5	5	5	5	5	5
103	5	30	1.36	2	5	5	5	5	5	5
103	6	30	1.36	2	5	5	5	5	5	5

Project	Test	Vol%H2	Pix. 0	BR	CJ-Det. Velocity m/s	Detonation
101	3	15	0.99	0.75	1517	No
101	4	20	0.99	0.75	1703	No
101	5	25	0.99	0.75	1858	No
101	6	30	0.99	0.75	1976	Yes
101	7	35	0.99	0.75	2048	Yes
101	8	40	0.99	0.75	2096	No
102	1	15	1.19	0.75	1517	No
102	2	20	1.19	0.75	1703	No
102	3	25	1.19	0.75	1858	No
102	4	30	1.19	0.75	1976	Yes
102	5	35	1.19	0.75	2048	Yes
102	6	40	1.19	0.75	2096	No
103	1	25	1.36	0.75	1858	No
103	2	27	1.36	0.75	1911	No
103	3	28	1.36	0.75	1935	Yes
103	4	28	1.36	0.75	1935	No
103	5	30	1.36	0.75	1976	Yes
103	6	30	1.36	0.75	1976	Yes

Appendix 4: Experiment procedure

Before filling:

1.   Note experiment in excel file, test nr. etc..

2.   Turn on the VENTILATION.

3.   Check that all persons in the room have safety glasses, hearing protection and are behind safety glass.

4.   PULSE GENERATOR on, adjusted, connected and set to ready.

5.   OSCILLOSCOPE on, adjusted, connected and set to ready.

6.   AMPLIFIERS on and set to operate.

7.   Turn on the schlieren LIGHT and take cover off mirrors. Keep at low voltage.

8.   Check connection to CAMERA and set to ready.

9.   Flow meters OFF.

10.   Lock the doors manually and turn on alarm light.

Filling:

11.   Air compressor ON and check pressure.

12.   Open hydrogen gas cylinder.

13.   Open tube-valve.

14.   Set flow-meters to the desired mix.

15.   Turn the light up to full voltage (2 min before ign.).

16.   Turn ON the alarm (30sec before ign.).

**Ignition:**

17.   Close tube-valve.

18.   Pull out plug.

19.   Ignition.

After ignition:

20.   Flow meters off and close hydrogen cylinder.

21.   Turn off alarm.

22.   Save pressure and video data.

Appendix 5: Pressure plots

P101-3

P101-4

P101-5

P102-1

P102-2

P102-3

P102-4

P102-5

P102-6

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P103-1

P103-2

P103-3

P103-4

P103-5

P103-6

55
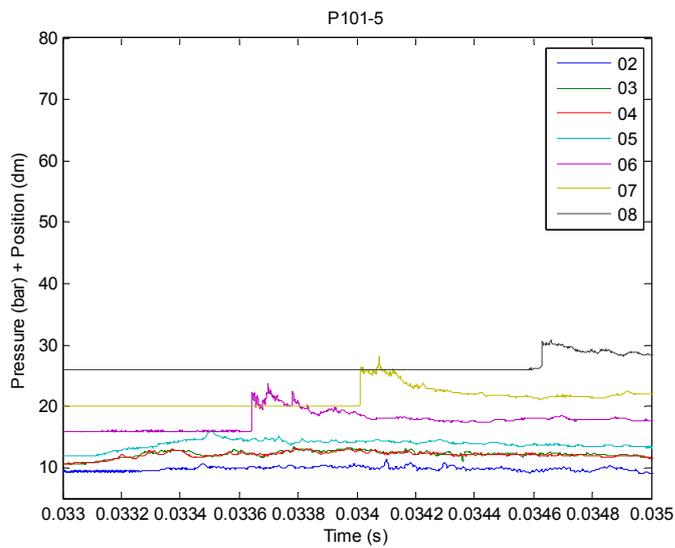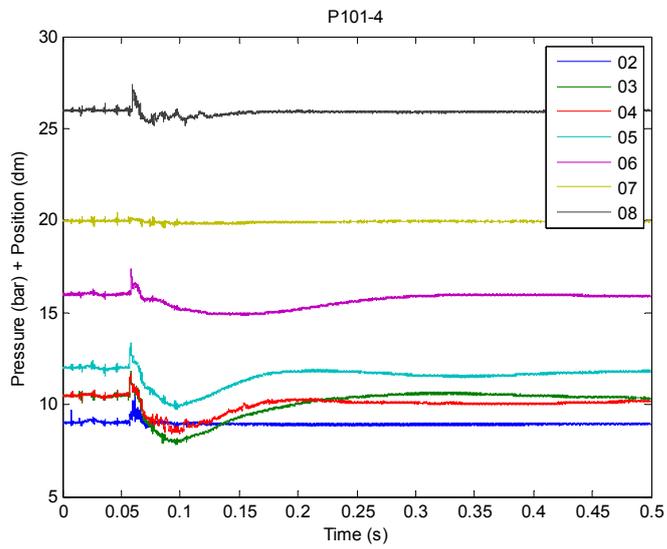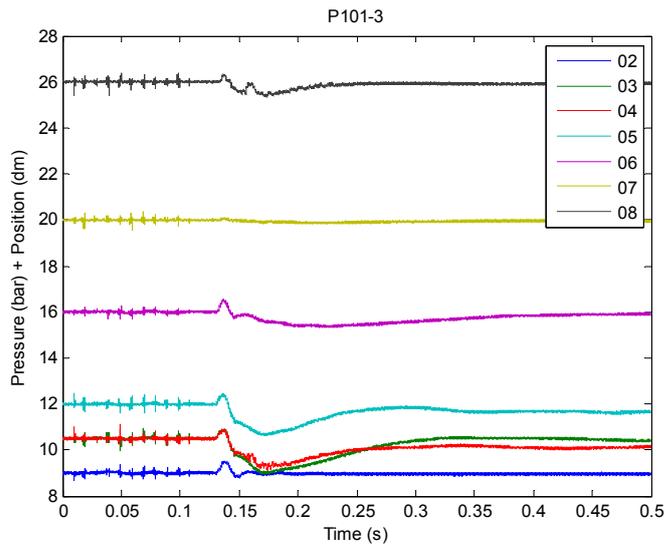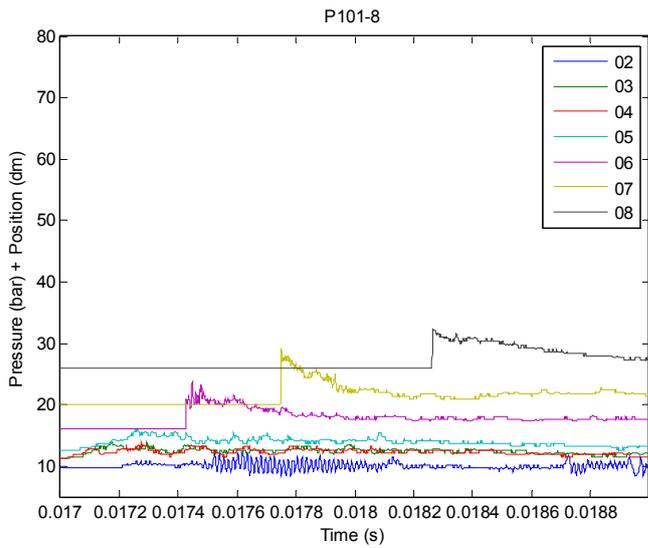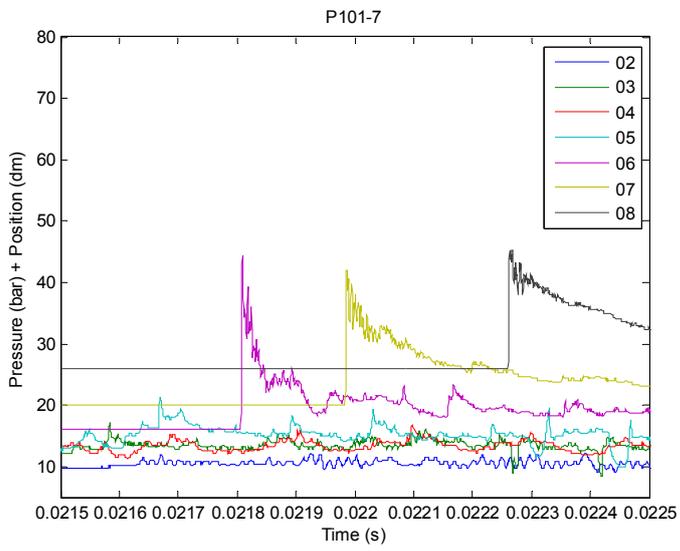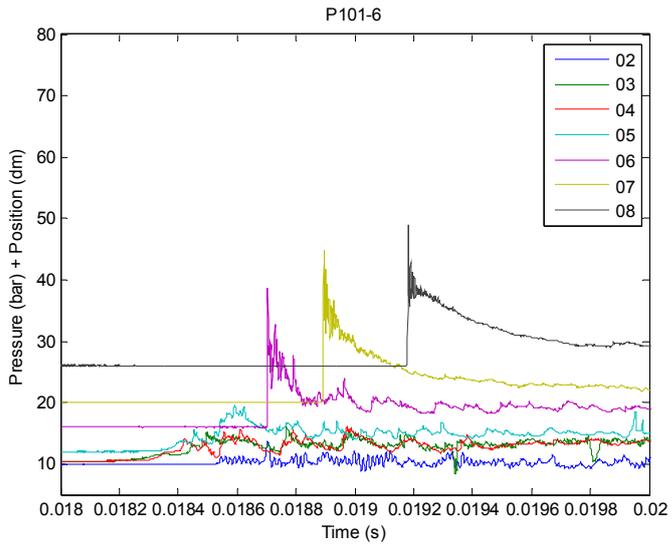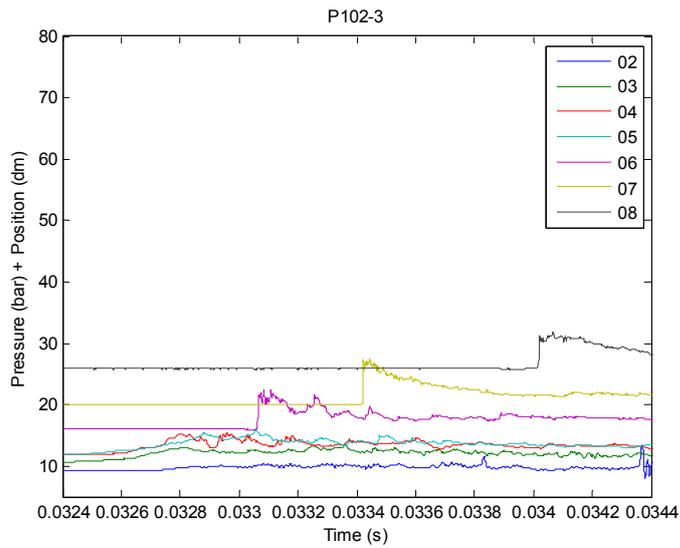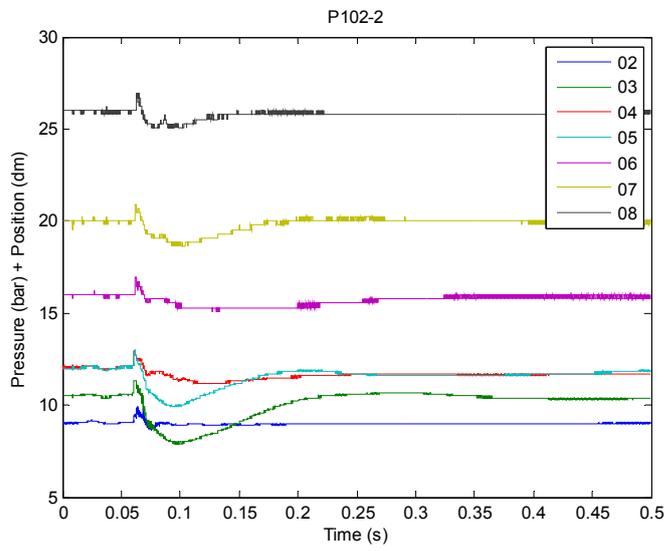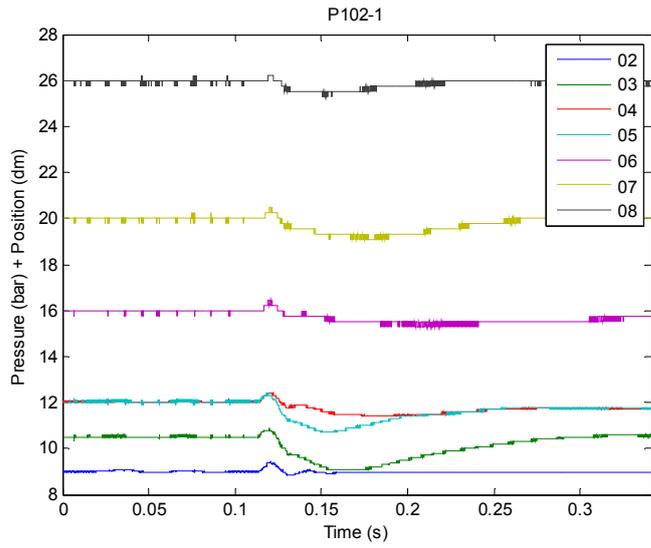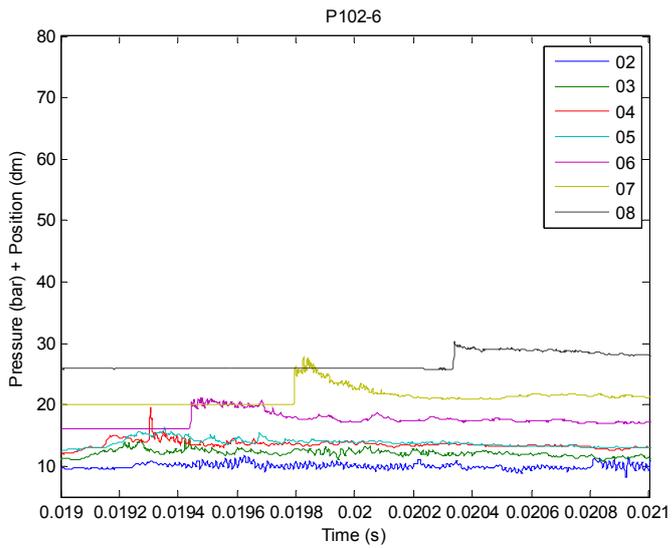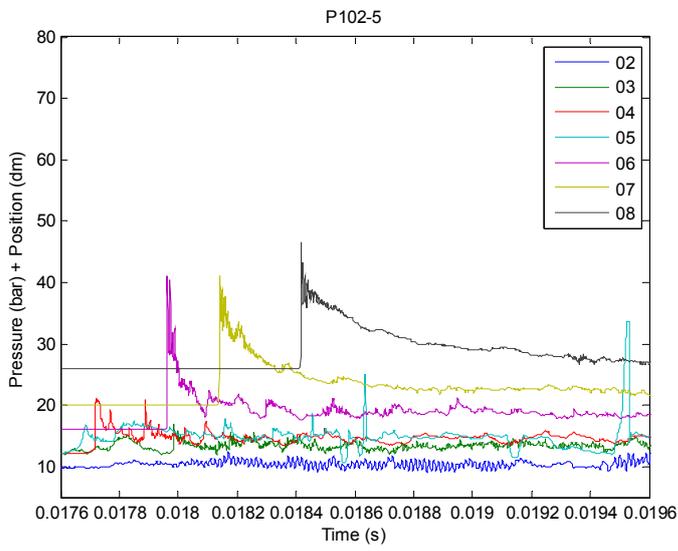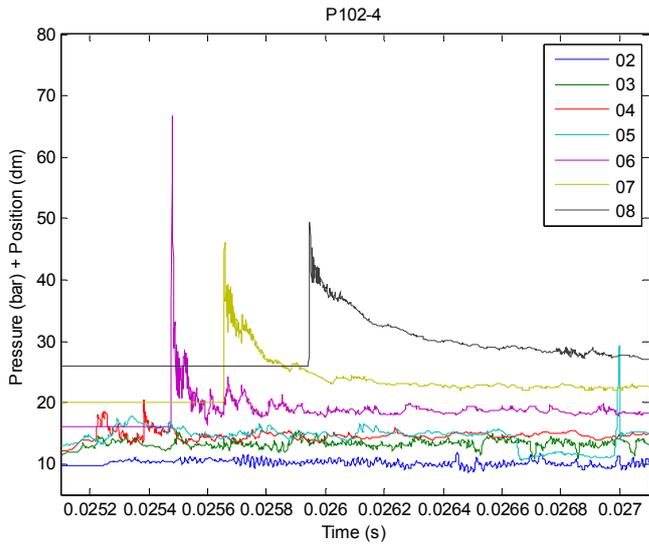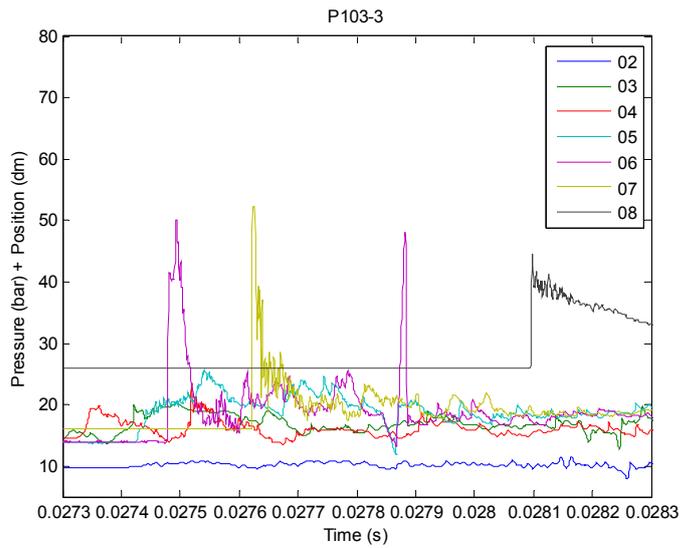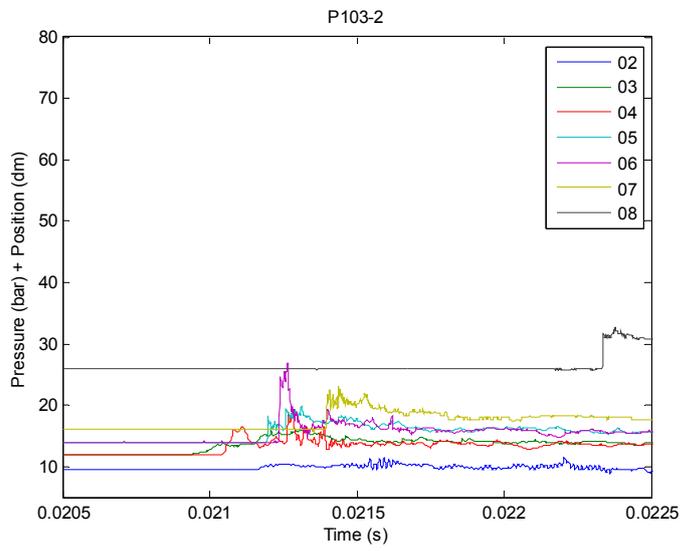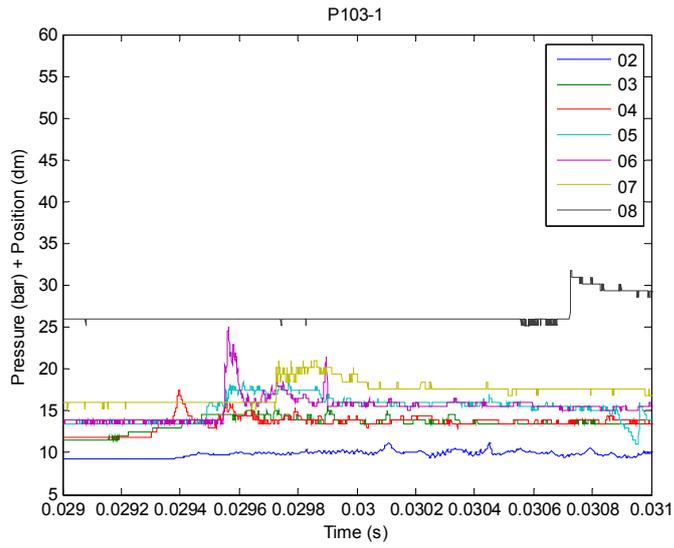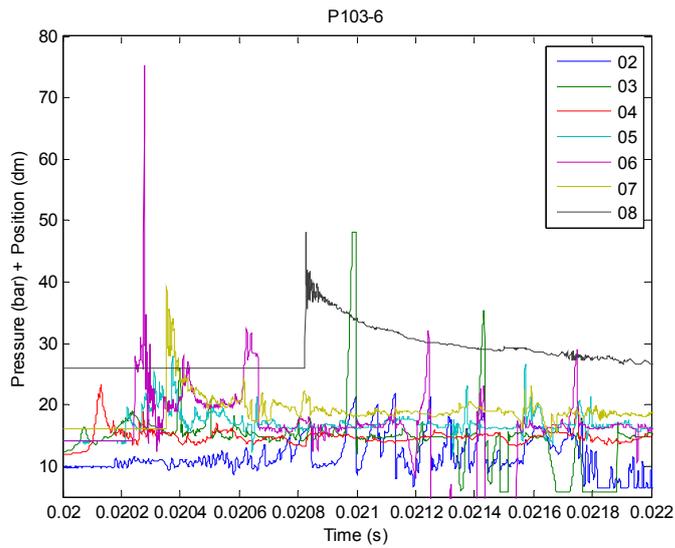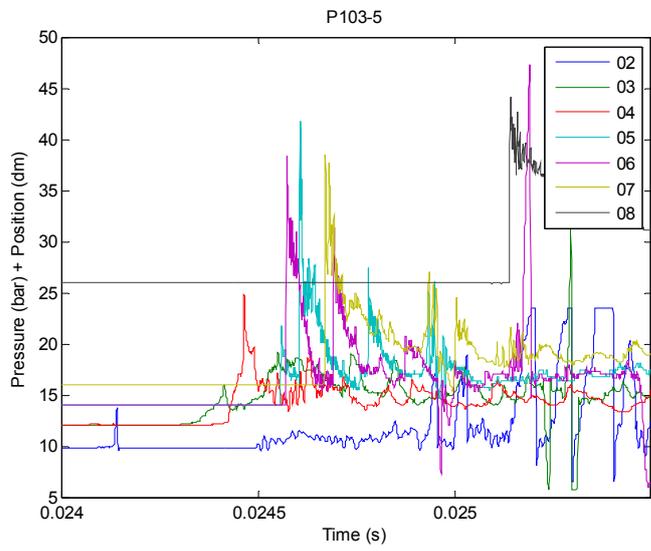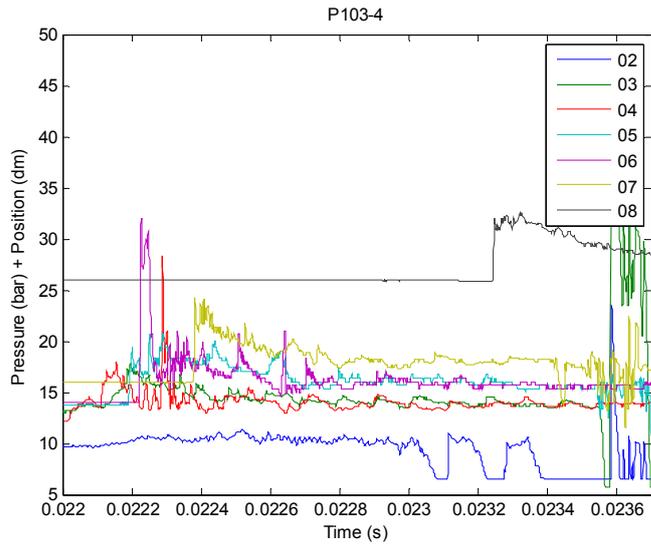
Appendix 6: Matlab code pressure plots

```
clear all
% HiT gas esplosion  data files : 108_DBj_P001_T 0009/CH1_01h.TXT
%                                 12345678901234567890123456789   0
Project    = input('Project number: ');
if isempty(Project)
    'No project number given'
end
test       = input('Test number: ');
if isempty(test)
    'No test number given'
end

% ch=input('channels ex. [4 5 6 7 8] ');
% if isempty(ch)
    ch = [2 3 4 5 6 7 8] ;
    %ch = [6 7 8] ;


%
% ASCII/TXT file from Nicolet Sigma 90 - DATA START at line 14
%
%   1   Nicolet Sigma 90
%       15:21:59 Trigger Time
%       Trace Type
%       YT
%   5   Time of First sample wrt trigger (s)
%       -1
%       Time per sample (s)
%       1e-005
%       Units
%   10  V
%       Number of Samples08_AVG_P207_T 00006_A/CH1_06h.TXT';
%       1000000
%   13  DATA START
%       -0.007161
%       -0.005078
%       -0.004036
%       -0.008203
%
filename = '13_LBJ_P111_T 00001/CH1_06h.TXT';
%           123456789012345678901234567890

pn = num2str(Project);
filename(9:11) = pn;


tn = num2str(test);
filename((20-length(tn)):19) = (tn(1:length(tn)));


headline = [2 6 8 14];
% Read headerlines [# # .....]in ACSII file filename.txt
% ASCII/TXT file from Nicolet Sigma 90 - DATA START at line 14
hl = [headline(1)-1 (diff (headline))]; %

chans=ch;


for i = 1:length(chans);


    filename(23) = num2str(chans(i));
```

```matlab
    filename(26) = num2str(chans(i));

    fid = fopen(filename, 'r');
    nstart = 1;
    nstop = 1000000;

    TTime = textscan(fid, '%f ',8, 'headerlines', hl(1));
    TT = TTime{:}';

    FSTime = textscan(fid, '%f ',1, 'headerlines', hl(2));
    FST = FSTime{:};

    STime = textscan(fid, '%f ',1, 'headerlines', hl(3));
    ST = STime{:};

    volt = textscan(fid, '%f ',nstop, 'headerlines', hl(4) + nstart); %
hl(max) = headlines
    V(:,i) = volt{:};

    T(:,i) = FST + ST.*((1):(length(V(:,i))))');%

    M(i,1:2)= (filename(25:26));   % legend(M)


end

%Denne maa endres
% [amp,BR,H2conc,DDT,XD,XD2,SensorPos]=scaleextr2(Project,test,chans);
[scale,BR,H2conc,SensorPos,filmfile,FTT]=scaleextr2(Project,test,ch)

        V0=mean(V(1:15,:));

        for k=1:length(V(1,:))
            PRes(:,k)=(V(:,k)-V0(k)).* scale(k)+(SensorPos(k))*10;
        end


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

plot (T,PRes);
% xlabel('Time (s)')
% ylabel('Pressure (MPa)')
% title([' Nicolet Sigma 90 ', filename(4:7),' ',filename(8:11),'
',filename(13:17),' Trigger Time: ',TT]);
%axis([0 50e-3 -100 1000])
legend(M)
% axis([0.02,0.022,5,80])
YYY=[zeros(length(FTT),1),ones(length(FTT),1)*100];

%   hold on
%     for k=1:length(FTT)
%         plot(FTT(k,:),YYY(k,:))
%     end
%   hold off
title('P103-6')
xlabel('Time (s)')
ylabel('Pressure (bar) + Position (dm)')
```

```matlab
% dette gir forsterkningen pÃ¥ hvert experiment

% function [scale,BR,H2conc,DET,XD,XD2,SenPos,CJdetVel,Prod_speed_sound,filmfile]=scal
eextr2(Project,test,ch)
function [scale,BR,H2conc,SenPos,filmfile,FTT]=scaleextr2(Project,test,ch)

    basescale=ones(length(ch));


    [num,txt,raw]=xlsread('D:\lalli\HiT\Energy&Environmental\Master Thesis
2013\Documents\Experiments\Experimental_matrix_LarusThesis.xlsx', 1,
'A2:AJ58');

    line = find(num(:,2)==Project & num(:,3)==test);

    line

    film_time=[];

    scale = num(line,ch+6);
    BR    = num(line,4);
    H2conc= num(line,5);
%    DET   = num(line,17);
%    XD    = num(line,20);
%    XD2   = num(line,21);
%    CJdetVel = num( line, 22);
%    Prod_speed_sound = num(line,37);
     filmfile = txt( line,26);
%filmfile='ingen info';


    film_start= num(line,34);
    film_fps = num(line,35);
    film_slutt = num(line,36);


    for i = 1:length(ch)

        SenPos(i) = num(line,25+ch(i));

    end

    SenPos = SenPos;

     Film_time_length = (film_slutt - film_start)/film_fps;
     FTT=[];
     if isempty(film_start)==0
         FT = film_start:1/film_fps:film_slutt;
         for i=1:length(FT)
             FTT = [FTT;[FT(i),FT(i)]];
         end
     else
         FT = [];
     end

    display({'scale = ',num2str(scale);...
            'BR = ',num2str(BR);...
            'H2conc = ',num2str(H2conc);...
```

```matlab
            'SensorPos = ',num2str(SenPos)});

% basescale=scale;
% antchan=5;

% ch=[4 5 6 7 8];
%
% scale=zeros(1,antchan);
%
% for p=1:antchan
%
%     channumb=ch(p)-3;
%     scale(p)=basescale(ch(p)-3);
% end

end
```

Appendix 7: Matlab code schlieren photographs

```matlab
function [X,C]=Les_raw_BW(fn, width, height, startframe, sluttframe)
k=0;

% cihfile=ls('*.cih');
% fid = fopen(cihfile, 'r');
% % TEST= textscan(fid, '%f ',1, 'headerlines', 1));
% TEST=textscan(fid, '%s' ,200);
% fclose(fid);
%
% width=TEST{1}(88);
% width=str2num(width{1});
% height=TEST{1}(92);
% height=str2num(height{1});

for j=startframe:sluttframe
%[filename,'_C001H001S0001','\',changename,'_C001H001S0001','.cih'];

clear f B C


%
imagefile=[fn,'_C001H001S0001','\',cn,'_C001H001S0001',filenumbers{j},'.raw
w'];

cd(fn); %setter folderen
list=ls('*.raww'); %finner alle .raww filene

id = fopen(list(j,:), 'r'); %åpner filene

% Read in the data.
% x = fread(id, [width,height],'int8')';
x = fread(id,'int16')'; %leser binærdata til 16bit

% Close file
fclose(id);

B=reshape(x',[width height]);    %lager matrisen med dataene

bittall=2^16;

k=k+1;
X{k} = uint16(B'.*255);  %lager bilde X fra heltallsvariabelen
figure(1)
imshow(X{k})    %viser bildet
h=getframe();
title(num2str(j));
pause
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%
%   Setter så sammen bildene til en figur med akser
%
%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%


C=[];
```

```matlab
for i = 1 : length(X)

        C = [C;X{i}];

end

    figure(2)

    imshow (C)

    ax1 = gca;

    pxl_m = 1/0.431;

    w0=1.19*1000-1000;

    w1=ceil(w0/100)*100;

    w3=round((w1-w0)*pxl_m);

    x_marks = w3: round( 1/0.431*50):(w1-w0)+4*round( 1/0.431*50);

%    for h=1:4
%        xtl{h}=num2cell(w1+(h-1)*50);
%    end
%
set(ax1,'Visible','on','XTick',x_marks,'XTickLabel',{'200','250','300','350
'});
%
    y_marks = height/2:height:height/2+length(X)*height;


set(ax1,'Visible','on','YTick',y_marks,'YTickLabel',{'1','2','3','4','5','6
','7','8','9'});
    xlabel('position [mm] from obstruction')
    ylabel('frame number [-]')

    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

Appendix 8: Calibration flow-meters

Read from bottom of the ball

Hydrogen

1,5Bar
Hydrogen:

Flowmeter(Scale) \ Liters	10	20	30	40	50	60	Actual total time (Not the sum of row) min.	sec.	Total sec.	L/sec.	L/min.
6 Time(sec)	125	125	125	125	125	127	12	32	752	0.079787	4.787234
9 Time(sec)	74	74	74	74	74	74	7	23	443	0.13544	8.126411
12 Time(sec)	51	52	51	51	52	52	5	9	309	0.194175	11.65049
15 Time(sec)	38	38	39	38	38	38	3	50	230	0.26087	15.65217

Air

1,5Bar
Air:

Flowmeter(Scale) \ Liters	10	20	30	40	50	60	Actual total time min.	sec.	Total sec.	L/sec.	L/min.
5 Time(sec)	51	50	52	49	51	51	5	4	304	0.197368	11.84211
10 Time(sec)	29	29	29	29	29	29	2	54	174	0.344828	20.68966
15 Time(sec)	20	20	20	20	20	20	1	58	118	0.508475	30.50847
20 Time(sec)	15	15	15	15	15	15	1	30	90	0.666667	40

Hydrogen equation:
y = 1.204x - 2.5875
a = 1.204
b = -2.5875

Air equation:
y = 1.8859x + 2.1869
a = 1.8859
b = 2.1869

Vol%H2: 40
H2 flowmeter: 15
H2 liters/min: 15.4725

Vol%Air: 60
Air flowmeter: 15
Air liters/min: 23.20875

11.14685

Tube Vol. (liters): 300
Filling time (min.): 7.755696
sec. 42

Stoichiometric = 2.4
Ratio Air/H2: 2.4
Vol%H2calc. 29.41176

Underline/Red input

Hydrogen — liters/min vs Scale flowmeter; y = 1.204x - 2.5875; R² = 0.9983

Air — liters/min vs Scale flowmeter; y = 1.8859x + 2.1869; R² = 0.9996