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Abstract:

A brief literature study was carried out to learn more about detonations, deflagrations, shock waves and critical tube diameters.

A comprehensive experimental test rig was assembled based on an earlier test rig. The rig was fitted with stainless steel plugs that had very precisely machined tube diameter to minimize the deviation on this variable. The candidate carried out the machining and experimental rig assembly.

More than 50 soap bubble experiments has been performed on various acetylene-oxygen mixtures using four pressure transducers and a high-speed camera. The experimental data has been analyzed to determine if a detonation occurred. Using these data the critical tube diameter as a function of stoichiometric ratio was determined. The results have been compared to earlier experimental data from John Lee [2]. The CJ-detonation velocity has also been calculated and compared with simulation results from the software SUPERSTATE. MATLAB and Excel was used to analyze the data.

The Random Choice Method has been used to simulate spherical detonations. It provides a 3D overview of the detonation. This makes is easy to compare it to the pictures from the high-speed camera. By comparing the experimental data and simulation results one can see clear similarities such as the pressure, position and time properties of the detonation, rarefaction wave and the shock wave.

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Preface

This thesis is written by a second year process technology master student at Telemark University College during the spring semester of 2013.

The aim of this thesis is to investigate transmissions of detonation waves in small scale and to study flame propagation in homogeneous gas clouds.

This reports main purpose is to introduce the reader to critical tube diameters of an oxygen and acetylene mixture, the detonation velocity of lean to rich fuel-oxygen mixtures. As a part of this thesis an experimental rig has been built by the candidate that includes a high-speed camera and pressure transducers. The experiments involves filling a soap bubble with a volume of about $2.9 \cdot 10^{-4}$ m^3 with gas mixture and then ignite the mixture.

This report includes an overview of literature, theory, results, discussion, conclusion and more details about how the experimental setup has been made.

A big thanks to Professor Dag Bjerketvedt, Associate Professor Knut Vågsæther and doctoral student Andre Vagner Gaathaug for excellent guidance during the duration of this project.

Porsgrunn, June 2013

Abdulkadir Bat

Abdulkadir Bat

Nomenclature

p	Pressure
T	Temperatures
V	Volume of bubble
R	Universal gas constant
ρ	Density
c	Speed of sound
t	Time
ϕ	Stoichiometric ratio
M	Mach-number
n	Number of moles
v	Velocity
r	Radius of sphere

1 Introduction

This thesis presents an overview of critical tube diameter for fuel-oxygen mixture where only acetylene was used as fuel. It is of importance to first define detonations and deflagrations and give the characteristics separating these two types of combustion waves. This report focus on acetylene and oxygen mixtures, where a soap bubble with a volume of about $2.9 \cdot 10^{-4}\ \mathrm{m}^3$ full of acetylene and oxygen mixture is created. The mixture varies ranging from ϕ = 0.6 to 2.5, which corresponds to acetylene concentrations from 19 % to 50 %. Tube diameters of 2 to 5 mm was used in this small-scale experiment. The thesis includes designing an experimental test rig, literature study, velocity and pressure measurements of detonations and deflagrations as well as thin films that were filmed with a high-speed camera. The Random Choice Method (RCM) is presented, but only a few examples will be given due to lack of time.

1.1 Background

Rich fuel gas clouds can form during gaseous fuel leak accidents that can be a dangerous hazard. Telemark University College has a strong focus on gas explosions and hydrogen safety. This thesis is a part of the International Energy Agency (IEA) task 31 project on hydrogen safety. Hopefully by studying it closely we can reduce the risk of accidents.

1.2 Literature

The critical tube diameter for gas mixtures is defined as the limit that separates deflagrations and detonations for a specific stoichiometric ratio. Experiments on critical tube diameter detonations with several different fuels mixed with oxygen have been carried out earlier. Fuels such as: methane, propane, hydrogen and acetylene have been used in earlier attempts. Lee [2], Bjerketvedt [1], Joseph E. Shepherd [5] and Zeldovich-von Neumann-Döring (ZND) [4] are some of those known to have made several theories or experiments regarding detonations and critical tube diameter with different fuels.

Lafitte (1925) [2] was one of the first that conducted experiments on critical tube diameter using a spherical vessel with planar detonation. He used a 7mm diameter tube into the center of the vessel. A mixture of CS_2+$3O_2$ (Carbon disulfide) was used but he failed to obtain a direct initiation. Zeldovich [2] used different tube diameters for a given mixture and found that a critical tube diameter exists for direct initiations.

1.1.1 Detonation

A detonation can be described as a shock wave sustained by energy released by combustion immediately followed by a flame and defined as a combustion wave propagating at supersonic velocity relative to unburned gas. Reactants transform into products because of the combustion wave. In a detonation, the volume will decrease because the products will be compressed. The velocity of a detonation is larger than the speed of sound, in the unburned gas. For a fuel-oxygen mixture such as an acetylene-oxygen mixture the detonation velocity can be up to 3000 $\frac{\mathrm{m}}{\mathrm{s}}$, the pressure can exceed 30 bar and the temperature can be as high as 4500 K. A detonation can be initiated when a deflagration accelerates due to obstacles and confinement or that a high explosive charge is directly initiated. [1]

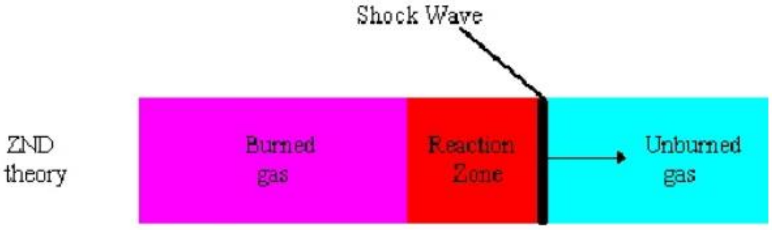

Figure 1-1 ZND Theory: detonation wave described as a shock wave [1]

1.1.2 Deflagration

Deflagrations burn at a velocity less speed than the speed of sound in the unburned gas and are defined as a combustion wave propagating with subsonic velocity relative to the unburned gas. The flame speed rages from 1 $\frac{\mathrm{m}}{\mathrm{s}}$ up to 1000$\frac{\mathrm{m}}{\mathrm{s}}$. In a deflagration where the combustion waves transform reactants into products, the products expand and the volume increases. The shock wave in a strong deflagration may propagate ahead of the deflagration. The explosion pressure of a deflagration can be between a few mbar to several bar. [1]

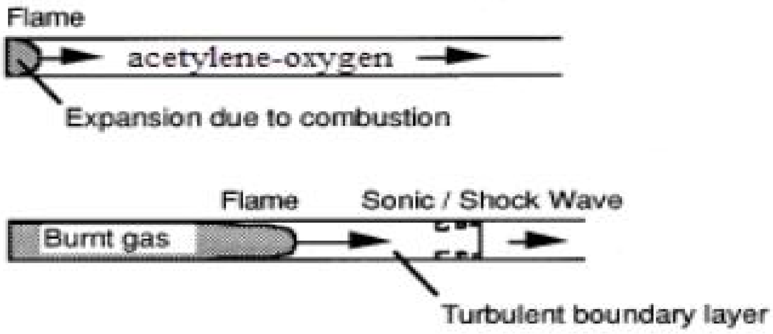

Figure 1-2 Deflagration, combustion wave propagating at subsonic velocity [1]

1.1.3 Shock wave

In a gas, a shock wave that propagates at supersonic velocity relative to the gas immediately ahead of the shock where the gas ahead is not disturbed by the shock can be defined as a compression wave with large amplitude. Particle velocity drastically changes as well as pressure and density, across a shock wave. It is always an extremely rapid rise in temperature, pressure and density of the flow. The propagation velocity depends of the pressure ratio across the wave. With distance, the energy of a shock wave dissipates relatively fast. [1]

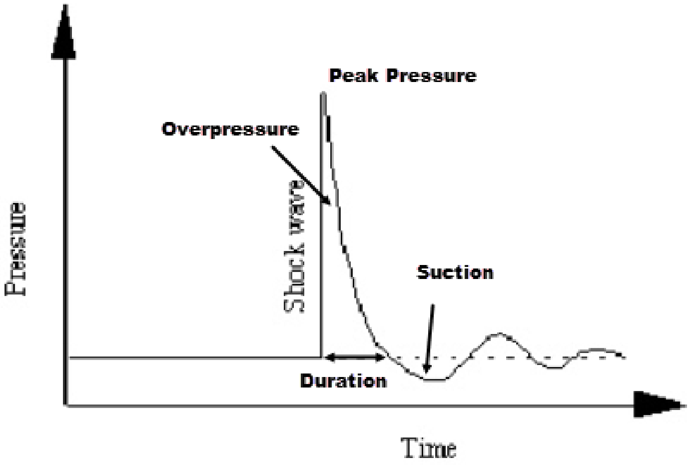

Figure 1-3 Shock wave followed by a rarefaction wave

1.1.4 Critical tube diameter

The critical tube diameter is the diameter, at which a planar detonation successfully evolves into a spherical detonation without failure out from the tube, this also occurs for tubes greater than the critical tube diameter. Below the critical tube diameter detonations fail to transform into a spherical detonation when it is exiting from the tube. Failed detonations are called deflagrations. The critical tube diameter is also dependent on stoichiometry.

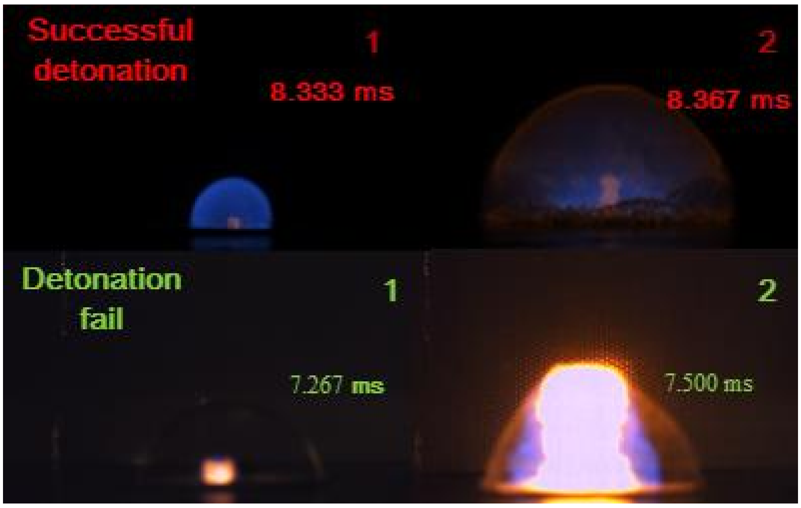

Figure 1-4 Detonation and deflagration critical tube diameter 4 mm

The successfully detonation as seen in Figure 1-4 has a stoichiometric ratio of $\phi = 0.8$. It is possible to see that it only takes 0.034 ms for the detonation to go outside of the bubble. A detonation with $\phi = 0.8$ has an overpressure around 20 bar and a CJ-detonation[1] velocity at nearly 2,350 $\frac{\mathrm{m}}{\mathrm{s}}$ that makes 30,000 frames per second (fps) too slow to catch details, it only gives one useful picture.

Figure 1-4 also shows a failed detonation, called deflagration, with $\phi = 0.7$, the velocity is about 500 $\frac{\mathrm{m}}{\mathrm{s}}$, the pressure is about 20 times less than for a successful detonation. It is also possible to see that a deflagration gives a vertical burning jet that cannot be found for the detonation case where a spherical detonation comes out of the critical tube.

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[1] CJ - Chapman–Jouguet

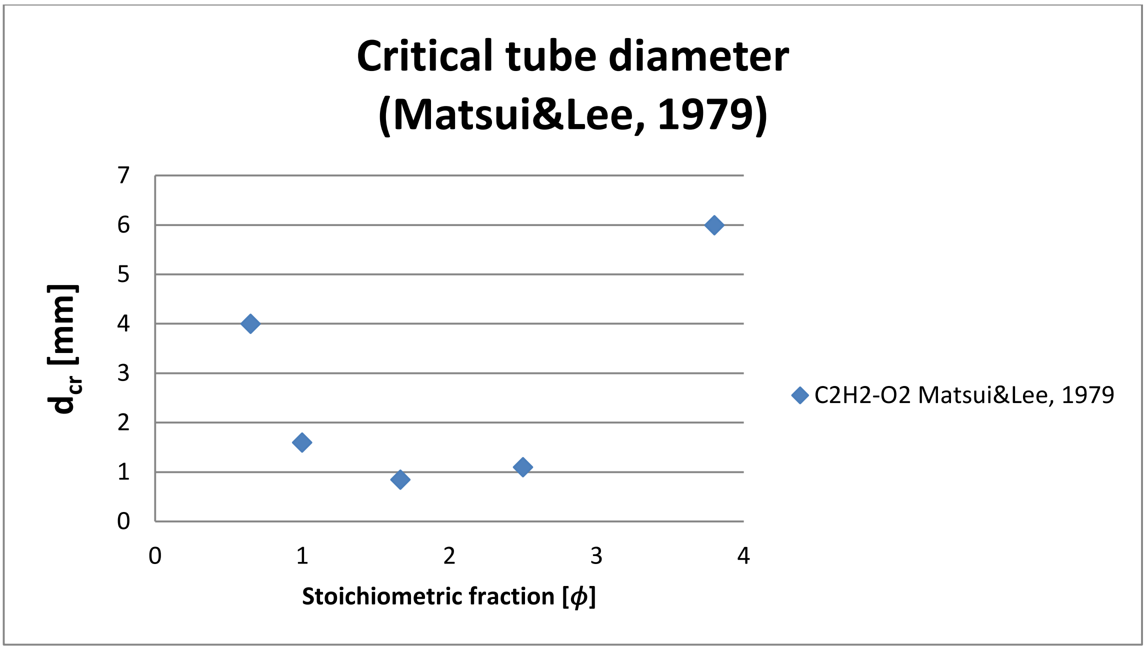


Figure 1-5 Critical tube diameter as a function of stoichiometry (Matsui & Lee, 1979)

Figure 1-5 shows the results from an experiment conducted by Matsui and Lee in 1979. This experiment determined the critical tube diameter for various stoichiometric ratios of acetylene and oxygen, which is almost the same experiment as will be presented in this thesis. [1] [2]

2 Experiment

Acetylene and oxygen combustion has been done on a critically tube diameter. The stoichiometric ratio has been varied and the limit value has been determined. The difference between a detonation and deflagration has been investigated.

Figure 2-1 Experimental soap bubble with C_2H_2-O_2 mixture

A soap bubble that is essentially a half sphere with radius 10 mm has been made for each experiment. The volume of this bubble is about $2.9 \cdot 10^{-4}$ m^3. It is filled with acetylene and oxygen gas and a tube of size between 2 and 5 mm in inner diameter. The combustion is initiated using a spark plug. This results in either a detonation or deflagration in the critical tube diameter depending on the mixing ratio. All experiments have been filmed with a high-speed camera nearly all films where filmed with 500,000 frames per second and a size of 256 x 16. The pressure has been measured using pressure transducers connected to amplifiers, in order to capture the smallest details of the pressure variations.

2.1 Calibration

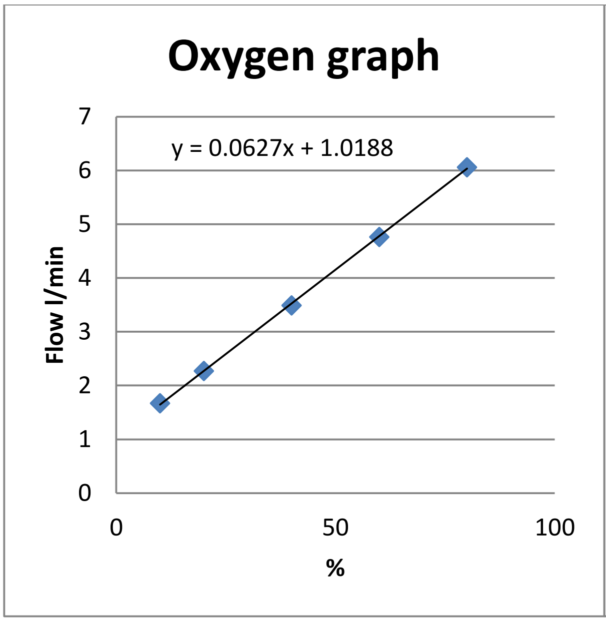
Error in the mixture between the two gases has to be as low as possible. Calibration of the gas flow meter, Vögtlin TYP V 100, was done using a wet-test gas flow meter called Ritter TG10 / 1. This was a time consuming operation. The gas flow meter was set at 10-100 %. A stopwatch was used to measure time. All calibrations was conducted 2-5 times and averaged. The least squares method was used to find a linear function that best matches the measured values.

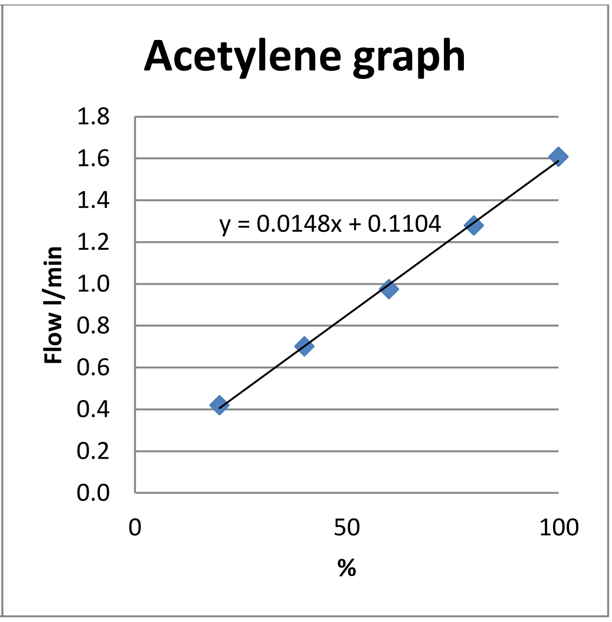
Table 2-2-1 Oxygen measurements

%	Time [sec]	volume [l]	Flow [l/min]
10	359	10	1.6713
20	264	10	2.2727
40	172	10	3.4884
60	126	10	4.7619
80	99	10	6.0606

Table 2-2-2 Acetylene measurements

%	Time [sec]	Volume [l]	Flow [l/min]
20	1428	10	0.4202
40	856	10	0.7009
60	615	10	0.9756
80	469	10	1.2793
100	373	10	1.6086





2.2 Error

To reduce error, multiple calibrations have been done. The ratio of acetylene and oxygen has been checked and the deviation is about 0.8 %. This discrepancy can be tolerated, 0 % error in this type of experiment is not possible. Deviation in the inner tube diameter can in the worst case be up to 0.65 %. But since the jump from changing tube diameters can lead to an difference of 50 % of empty space (from two mm inner tube diameter to three mm inner tube diameter), the only error being taken into account is the error in the gas mixture which is 0.8 % on the exact diameter.

2.3 Equipment setup

This experimental setup is quite extensive and it was hard to get a proper setup. Careful placement of the high-speed cameras was used to get proper pictures. The pressure transducers had to be placed at very specific points in the test rig. The igniter, gas flow meters, gas cylinders and valve switch had to be easily accessible to make it possible to do the experiments with one man only. It is important to follow procedure in order to avoid incorrect usage and hazards.

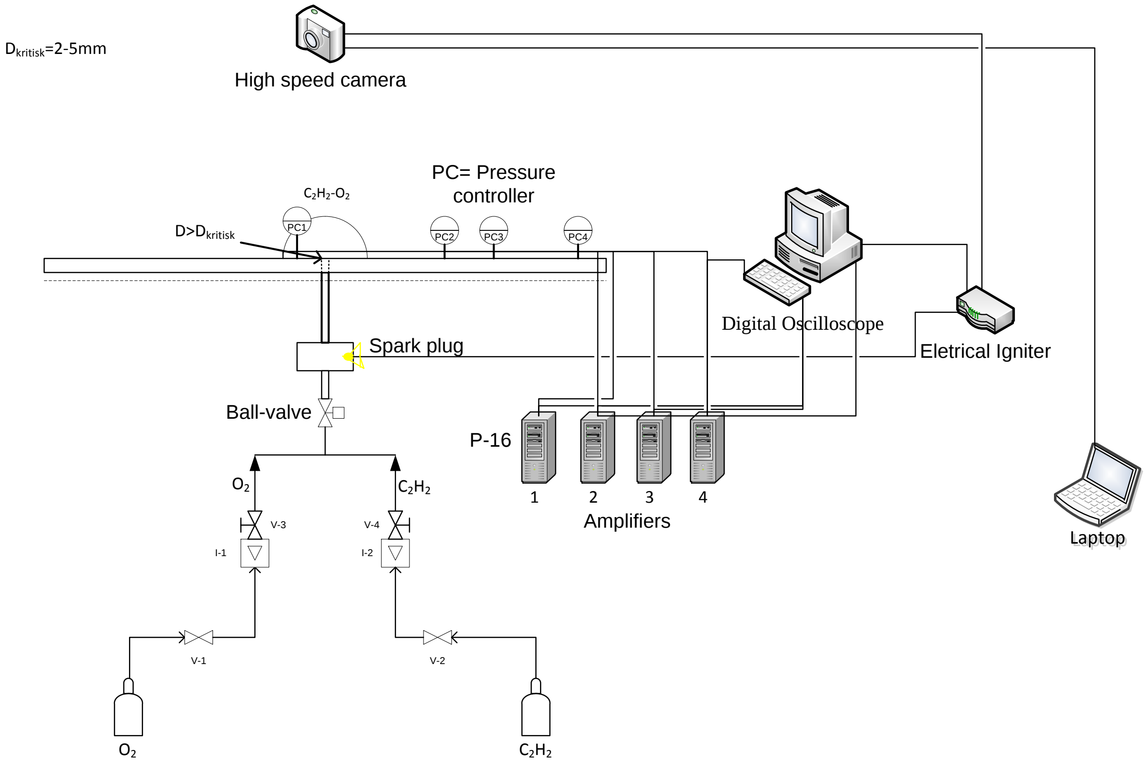


Figure 2-2 Experimental setup drawing

1) Soap bubble
   The soap bubble mixture has to be prepared one day in advance to increase its surface tension. The mixture is made by using 50 ml of distilled water, 5 ml of Zalo, 0.5 g of glucose and 1 ml of glue. Mix it well, if necessary, add some more water before use.

2) High-speed camera
   The high-speed camera is set at 500,000 frames per second and the maximum available picture size at this frame rate of 256x16 pixels (vertical x horizontal), connected to a pulse generator at channel C and a laptop with the necessary software. Calibrate the high-speed camera after brightness and frame rate is set. Put the camera with the correct height and

distance away which is about 1.5 m from the detonation. Check if the height and the distance are proper and test if it works.

3) Amplifiers
   Setup the amplifiers Type 603B and connect them to the digital oscilloscope and the sample table shown in Figure 2-2.
   i) Amplifier-1 set in 1 V = 10 bar connect to channel-2 at the digital oscilloscope, placed inside the bubble, 2.5 cm from the outlet of the tube
   ii) Amplifier-2 set in 1 V = 10 bar connect to channel-3 at the digital oscilloscope, placed 10 cm from the center of the tube
   iii) Amplifier-3 set in 1 V = 5 bar connect to channel-4 at the digital oscilloscope, placed 20 cm from the center of the tube
   iv) Amplifier-4 set in 1 V = 1 bar connect to channel-5 at the digital oscilloscope, placed 40 cm from the center of the tube

4) Exhaust fan/compressor
   Turn on the exhaust fan and the main compressor. Connect the switch valve to the compressor and the ball-valve. See if the switch-valve works by watching the ball-valve turn by pressing the switch-valve on.

5) Pulse-generator (igniter)
   i) Channel-A at the Pulse-Generator must be connected to channel-1 at the digital oscilloscope.
   ii) Channel-B must be connected to the coil. The coil is able to give all the necessary energy the spark plug needs for a proper ignition.
   iii) Channel-C at the pulse-generator must be connected high-speed camera
   iv) Setup pulse-generator Wid to 0.05 that means that when the bottom is pushed it will ignite for 0.05 seconds, set Dly to =0.0000 that mean there are no delay

6) Setup the digital oscilloscope
   i) Set sweep rate to 2 million samples per second
   ii) Set main to 50 milliseconds
   iii) Set V/Div Volt per dividend to avoid inaccurate measurements.
      (1) Channel-2 to 1 V/Div
      (2) Channel-3 to 1 V/Div
      (3) Channel-4 to 100 mV/Div
      (4) Channel-5 to 100 mV/Div

7) Gas flow meter

   Set the correct gas-flow with the flow meter, after calibrating the flow meter using gas-meter. The gas cylinder can be connected to the flow-meter en turn on, the gas-flow can be found out by using the Excel file (Kalibrering-Rotameter) by adding the right oxygen %.

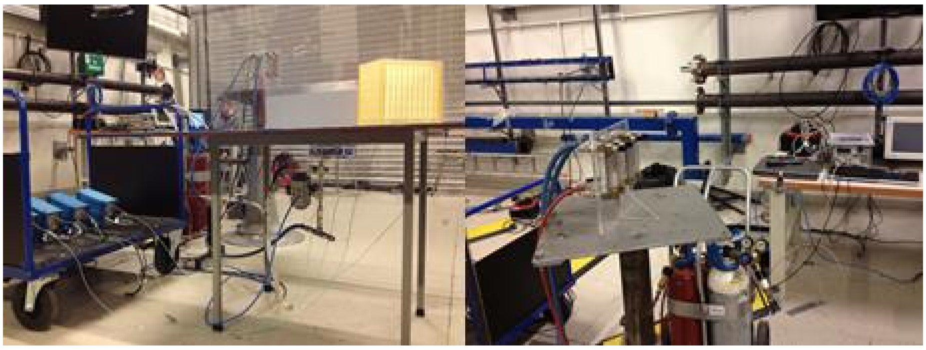


Figure 2-3 Experimental setup

2.4 Bubble size and amount of mole calculation

The bubble size is mostly assumed to be a half sphere; normally the bubble is more like a spherical cap.

In order to find the number of moles inside the bubble, some assumptions has to be made, and some formulas are needed.

Assumptions

- The bubble volume is assumed to be a half sphere. This assumption is made since the bubble form is very close or nearly equal to a half sphere.
- The ideal gas law gives a very small error in this case due to low pressure.
- The pressure is assumed to be equal to the atmospheric pressure.
- The temperature is assumed to be equal to the room temperature of nearly $20℃$

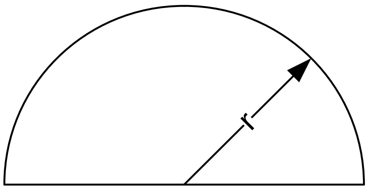


Figure 2-4 Bubble drawing with radius

Ideal gas law:

$$pV = nRT \tag{1}$$

Solving eq. (1) ideal gas law with respect to n (number of moles)

$$n = \frac{pV}{RT} \tag{2}$$

p, V and T in eq. (2) must be specified in order to calculate the number of moles

R is universal gas constant with a value of $8.314\,\frac{\mathrm{J}}{\mathrm{molK}}$.

The volume of a half sphere is given by:

$$V = \frac{2}{3}\pi r^3 \tag{3}$$

The bubble has a constant radius of 5 cm = 0.05 m.

The bubble volume is calculated to be:

$$V = \frac{2\pi r^3}{3} = \frac{2 \cdot \pi \cdot 0.05^3}{3} = 2.6 \cdot 10^{-4}\ \mathrm{m}^3$$

The bubble volume can be calculated more accurately using a spherical cap equation when the height of the bubble differs from 5 cm.

$$V_{spherical\ cap} = \frac{\pi h^2}{6}(3a^2 + h^2) \tag{4}$$

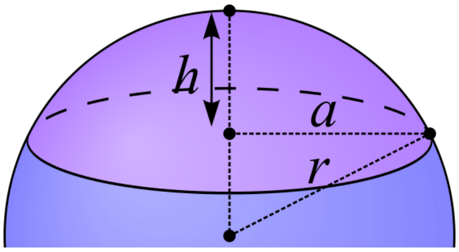


Figure 2-5 Spherical cap

Figure 2-6 Frame 9 experiment test 24

Solving spherical cap eq. 7 where *a* is the same as the radius of the ring where the radius is 5 cm.

$$V_{spherical\ cap} = \frac{\pi \cdot 0.053^2}{6}(3 \cdot 0.05^2 + 0.053^2) = 2.9 \cdot 10^{-4}\ \mathrm{m}^3$$

The pressure is equal to the atmospheric pressure, $p = 101.3\ \mathrm{kPa}$.

The temperature is equal to the room temperature, $T = 20℃ \approx 273.15 + 20 = 293\ \mathrm{K}$.

The amount of moles for test nr 24 is calculated to be:

$$n = \frac{101325\ \mathrm{Pa} \cdot 2.9 \cdot 10^{-4}\ \mathrm{m}^3}{8.314\ ^{\mathrm{J}}/_{\mathrm{K}\cdot\mathrm{mol}} \cdot 293\ \mathrm{K}} = 0.012\ \mathrm{mol}$$

2.5 The stoichiometry solution

To do the stoichiometry balance of oxygen and acetylene, it is assumed that the all bubbles have a volume equal to that of test nr 24.

The chemical formula for acetylene is:

$$C_2H_2$$

And for oxygen:

$$O_2$$

The first equation can be written as:

$$C_\alpha H_\beta + \left(\alpha + \frac{\beta}{4}\right) O_2 \rightarrow \alpha CO_2 + \frac{\beta}{2} H_2O \tag{5}$$

For complete combustion we have the following reactions:

$$C_2H_2 + \left(2 + \frac{2}{4}\right) O_2 \rightarrow 2CO_2 + \frac{2}{2} H_2O$$

$$C_2H_2 + \frac{5}{2} O_2 \rightarrow 2CO_2 + H_2O$$

From the reaction solution above, it is possible to see that the ratio between oxygen and acetylene is 2.5.

To find the number of moles of C_2H_2 and O_2 the solution found in the last chapter is utilized. The sum of the number of moles of C_2H_2 and O_2 must be equal to the amount found earlier.

$$n_{C_2H_2} + n_{O_2} = 0.012 \text{ mol}$$

Replacing $n_{O_2}$with $\frac{5}{2}\, n_{C_2H_2}$ in solution above and solving with respect to $n_{C_2H_2}$:

$$n_{C_2H_2} + \frac{5}{2}\, n_{C_2H_2} = 0.012 \text{ mol}$$

$$\frac{7}{2}\, n_{C_2H_2} = 0.012 \text{ mol}$$

$$n_{C_2H_2} = \frac{0.012 \text{ mol} \cdot 2}{7} = 3.43 \cdot 10^{-3} \text{ mol}$$

The number of moles of O_2 is given by:

$$n_{O_2} = \frac{5}{2} \cdot 3.43 \cdot 10^{-3}\ \text{mol} = 8.58 \cdot 10^{-3}\ \text{mol}$$

The mole percentage of $n_{C_2H_2}$ is:

$$\frac{3.43 \cdot 10^{-3}}{0.012} \cdot 100\% = 28.6\%$$

The mole percentage of O_2 is:

$$\frac{8.58 \cdot 10^{-3}}{0.012} \cdot 100\% = 71.4\%$$

For rich and lean mixture the acetylene concentration equation is known to be:

$$C = \frac{1}{1 + \frac{5}{2\phi}}$$

Table 2-3 Concentration of acetylene in percent

ϕ	0.6	0.65	0.675	0.7	0.75	0.775	0.8	0.85	0.875
C_2H_2 %	19.4	20.6	21.3	21.9	23	23.7	24.2	25.4	26

ϕ	0.9	0.925	0.95	0.975	1	1.1	1.15	1.2	1.3
C_2H_2 %	26.5	27	27.5	28	28.6	30.1	31.5	32.4	34.2

ϕ	1.4	1.5	1.6667	2.5
C_2H_2 %	35.9	37.5	40	50

3 Results

In this section the most relevant data is presented for the different stoichiometric ratios (ϕ) and different tube diameters. The results are divided into; detonations, critical tube diameter, detonation velocity, deflagrations and RCM[2].

The focus of the results is mainly toward detonation, deflagration and detonation velocity, and RCM comparison. Note that the test starts from test nr.13, test nr. 1-12 were inaccurate and the reason that they have not been taken for closer review.

Some of the tests that successfully detonated will be compared with RCM results.

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[2] RCM – Random Choice Method

3.1 Detonation results

Table 3-1 lists the tests where a successful detonation took place with both distinctively different tube diameters and stoichiometric ratios. Pressure, velocities, RCM results and pictures will give a better overview of the experiments. Detonation peak pressure varies from 16.8 bar to 26.2 bar, depending on the size of the bubble and the stoichiometric ratio inside the bubble that vary from a lean mixture ϕ = 0.7 to a rich mixture ϕ = 2.5 and tube diameter from 2-5 mm.

Table 3-1 Detonation table, critical stoichiometric ratio [ϕ] is marked with red

Test nr.	Pmax [bar] ch. 2	Pmax [bar] ch. 3	Pmax [bar] ch. 4	Pmax [bar] ch. 5	Equivalence ratio [ϕ]	Tube diameter [mm]
13	17.56	3.16	1.12	0.33	0.8	5
14	19.15	2.76	1.06	0.31	0.7	5
23	20.38	3.18	1.12	0.34	0.7	5
24	26.24	3.74	1.54	0.43	2.5	5
25	19.85	3.54	1.26	0.40	1	5
27	22.47	3.47	1.26	0.38	0.775	4
29	17.40	2.89	1.15	0.34	0.75	4
32	17.41	3.65	1.30	0.39	1	4
33	21.85	4.45	1.58	0.42	1.67	4
34	25.37	5.11	1.83	1.83	2.5	4
40	19.62	3.51	1.27	0.38	1	3
43	19.90	3.75	1.31	0.38	0.975	3
44	24.32	5.30	1.82	0.48	2.5	3
46	20.10	4.45	1.66	0.46	1.6667	2
47	19.06	4.51	1.66	0.47	1.5	2
48	19.41	4.95	1.82	0.49	1.4	2
49	16.76	4.37	1.48	0.43	1.3	2
52	19.49	3.88	1.41	0.43	1.2	2

3.2 Critical tube diameter results

One of the main goals of this thesis is to find the critical tube diameter. The critical tube diameter experiments have been investigated closer. There are several high-speed camera films that are converted to TIFF [3]format and made into slices that make it easier to detect a detonation.

Test 14

Starting with test 14 since that is the critical stoichiometric ratio for tube diameter with size 5 mm. The stoichiometric ratio is ϕ = 0.7.

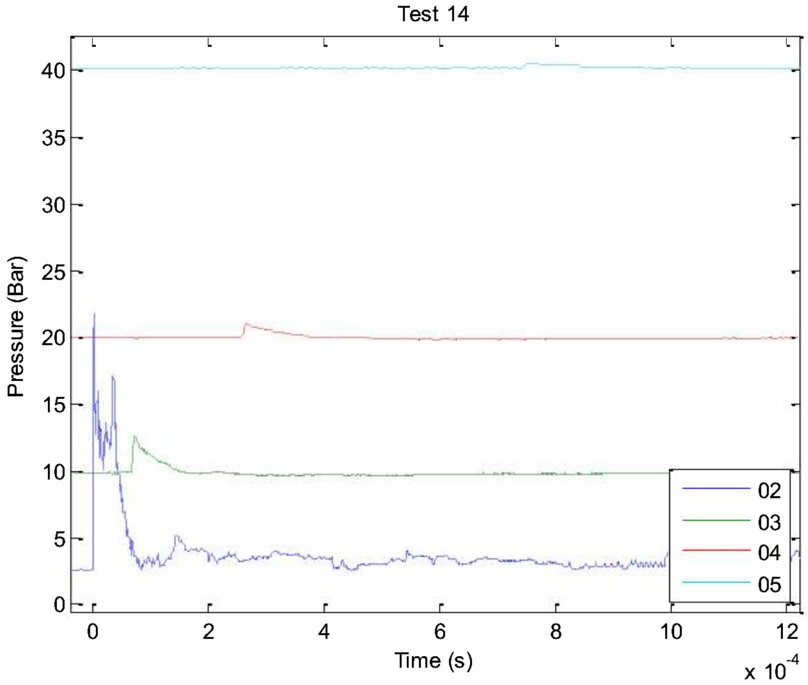

Figure 3-1 Detonation pressure results test 14

The overpressure result from test 14 shown in Figure 3-1 varies from 19.2 bar to 0.31 bar. From the pressure result it can be concluded that this experiment had a successful detonation.

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[3] TIFF – Tagged Image File Format

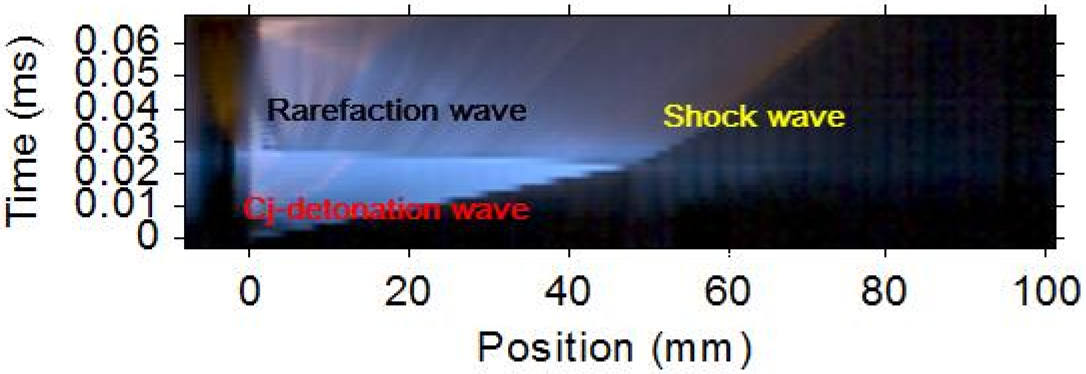

Figure 3-2 Detonation test 14

Figure 3-2 shows 36 combined frames from the film from test 14 taken at 500,000 fps. From the start, it is possible to see that there is a detonation due to velocity where it only takes 0.02 ms to reach the end. The light blue color is caused by the high temperature from the detonation. In the film it is also possible to see that the detonation comes out spherical with the critical tube diameter. From position 0 at time 0 to position 50 mm to time 0.02 ms the detonation is the reason for the slightly darker blue color. The shock wave continues after position 50 mm with velocity dropping while the rarefaction immediately follows the detonation.

Test 29

Test 29 has a critical tube diameter of 4 mm and a stoichiometric mixture of $\phi = 0.75$.

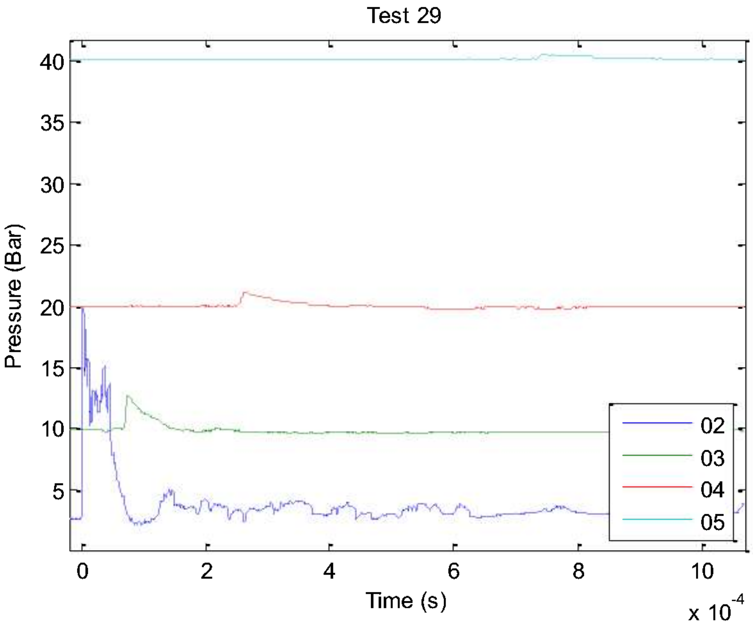

Figure 3-3 Detonation pressure results from test 29

It is possible to see in Figure 3-3 that the peak pressure is caused by a detonation. The overpressure result varies from 17.4 to 0.34 bar. The peak pressure which is 1.8 bar less than the peak pressure in test 14 may be caused by a too low sampling frequency of the pressure transducer. The pressures in channel 3, 4 and 5 shows greater pressure in test 29 than in test 14.The exact size of the bubble is not known, but it is thought to have nearly the same size as the one in test 14. There is more energy present in bubble test 29 than the bubble in test 14 due to a higher concentration of acetylene. The critical tube diameter has no effect on the pressure during a detonation; it is the bubble size and the stoichiometric ratio that has the main effects on pressure, velocity and temperature.

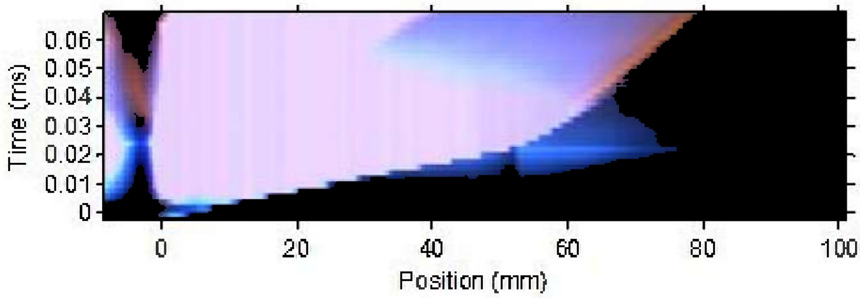

Figure 3-4 Detonation test 29

Figure 3-4 is a high-speed camera film that is converted to a TIFF picture. The bright color is caused by the fact that the camera was not calibrated correctly. It means that it is difficult to see the detail in the bubble, but it is good enough to judge that this is a detonation.

Test 43

Test 43 with a critical tube diameter of 3 mm and a stoichiometric mixture $\phi = 0.975$.

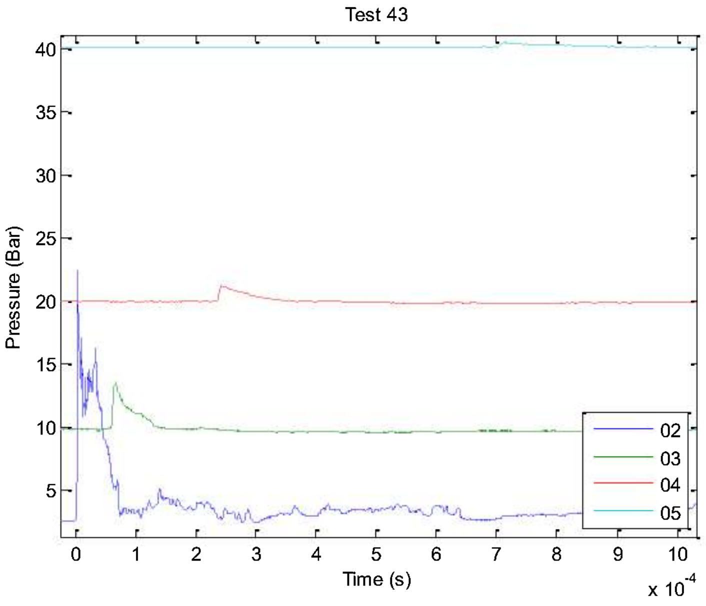

Figure 3-5 Detonation pressure result test 43

Figure 3-5 shows an overview of the result of the detonation from experiment test 43. Detonation pressure varies from 19.9 to 0.38 bar. The pressure result is greater than the test 14 and 29 the reason for that is probably the stoichiometric mixture where Φ is larger in test 43 that means that there is more energy in the bubble due the amount of acetylene.

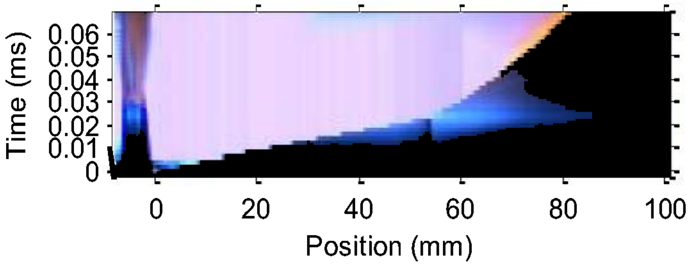

Figure 3-6 Detonation test 43

From Figure 3-6 it can be concluded that a detonation took place due to the velocity and the bright light. The bright light makes it difficult to see the blast, shock and rarefaction wave in details.

Test 52

Test 52 with a critical tube diameter of 2 mm and a stoichiometric mixture Φ = 1.2

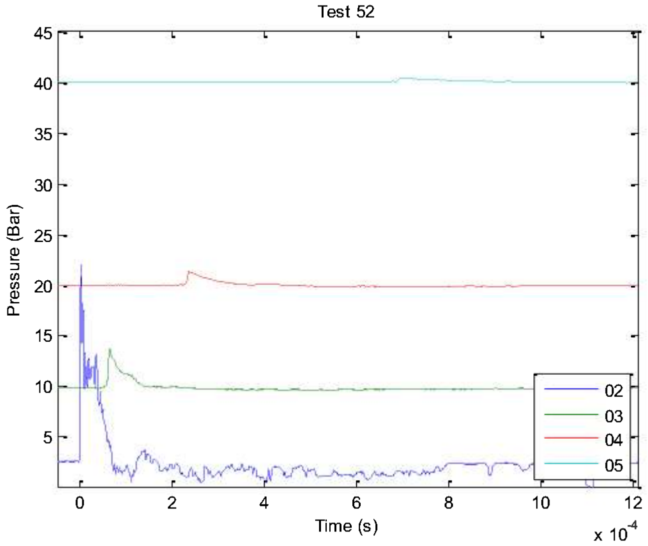

Figure 3-7 Detonation pressure result test 52

Figure 3-7 shows an overview of the pressure result that varies from 19.5 to 0.43 bar. The peak pressure in test 52 is less than the peak pressure in test 43, however the rest of the pressures are greater in test 52. The stoichiometric mixture concludes that there is more energy in test 52 due the amount of acetylene. The smaller peak pressure could be caused by the low sampling rate of the pressure transducer.

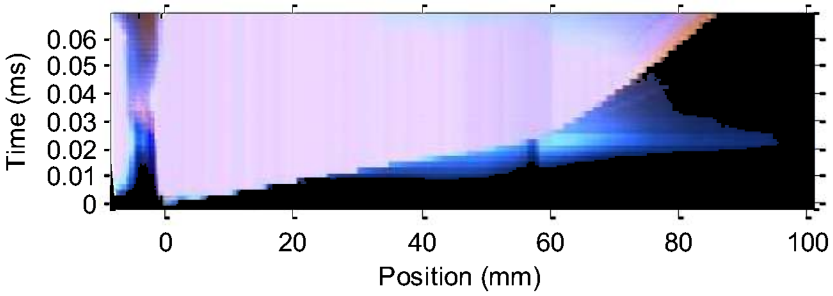

Figure 3-8 Detonation test 52

Figure 3-8 confirms a detonation from the bright light and the velocity due the blast wave, shock wave and rarefaction wave.

Results of the critical tube diameter

As a result of those experiments that was performed and confirmed, it is concluded that the critical tube diameter for 2, 3, 4 and 5 mm is known with a function of stoichiometric shown in Figure 3-9.

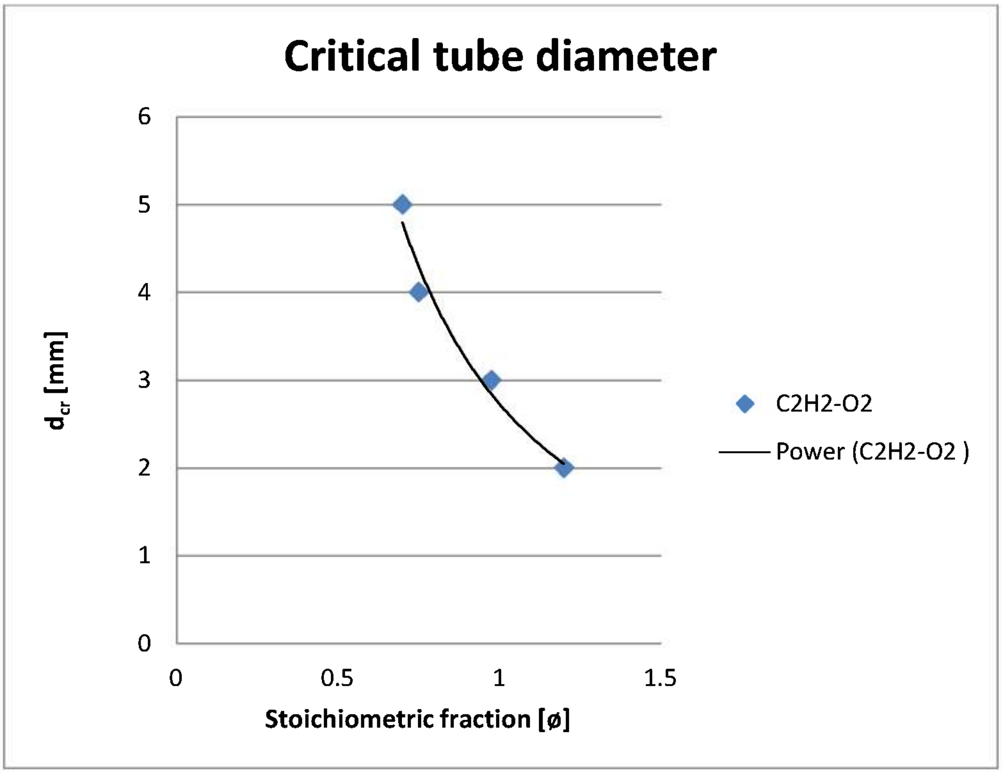

Figure 3-9 Critical tube diameter

Figure 3-9 shows only the experiments done on the four different tube diameters that successfully detonated.

Table 3-2 Critical tube diameter result

Test nr.	Pmax [bar] ch. 2	Pmax [bar] ch. 3	Pmax [bar] ch. 4	Pmax [bar] ch. 5	Stoichiometric ratio [ϕ]	Tube diameter [mm]
14	19.15	2.76	1.06	0.31	0.7	5
29	17.40	2.89	1.15	0.34	0.75	4
43	19.91	3.75	1.31	0.38	0.975	3
52	19.49	3.88	1.41	0.43	1.2	2

Table 3-2 shows an overview of the pressure results that belongs to the critical tube diameters. The peak pressure that may confuse is a result of the low sampling rate of the pressure transducer. However if the pressure in channel 3, 4 and 5 is taken to a further investigation it is possible to notice that the stoichiometric ratio has an important part of the pressure result due the amount of energy from acetylene.

3.3 Results compared with RCM

The software MATLAB is used to simulate spherical detonations model. The spherical model is mostly similar to the experiments results, from RCM simulation it is possible to get more detailed information about how the shockwave propagates.

The stoichiometric ratios from lean to rich conditions will be compered in RCM. One stoichiometric simulation ϕ=1, one lean mixture ϕ =0.8 and one rich mixture simulation were the ϕ =1.667 will be compared to the experiments that has been done and simulated.

The help of Professor Dag Bjerketvedt made it possible to compare detonation results for some of the experiments with RCM. The mathematical results and the test results generally shows small deviations. It is important to notice that the RCM does not take the tube diameter into account. The results of the RCM are independent of the diameter of the tube.

Test 25

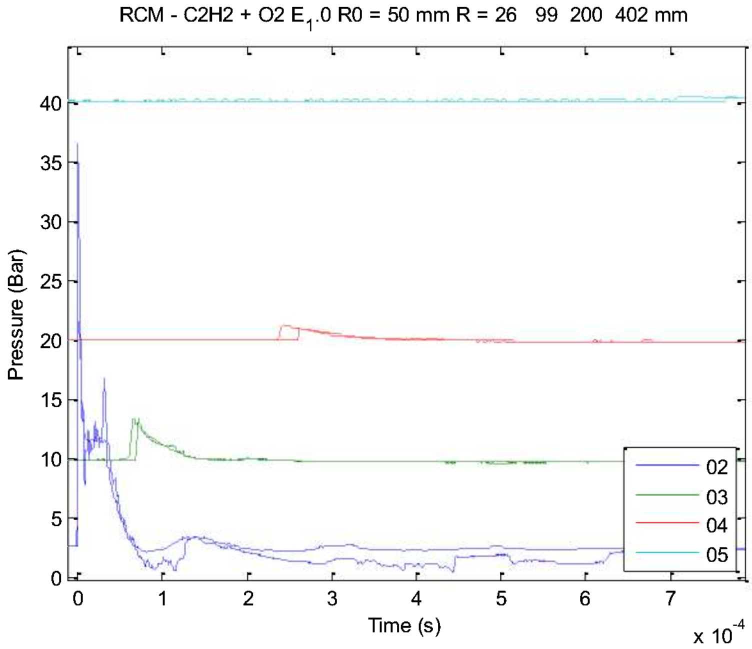

Figure 3-10 Detonation pressure result of test 25 compared with RCM result

Test parameters; stoichiometric ratio $\phi = 1$ and critical tube diameter of 5 mm. Figure 3-10 shows an overview of the RCM results (straighter lines compared to measured data) compared to the results of the pressure transducer. The peak pressure deviation is probably caused by the low sampling rate of the pressure transducer. The measurements fit well to the predictions of the RCM, except that the RCM is somewhat slower according to the figure. The RCM result will be the same for all the stoichiometric ratios with different tube diameters that successfully detonated, as long as the size of the bubble is the same.

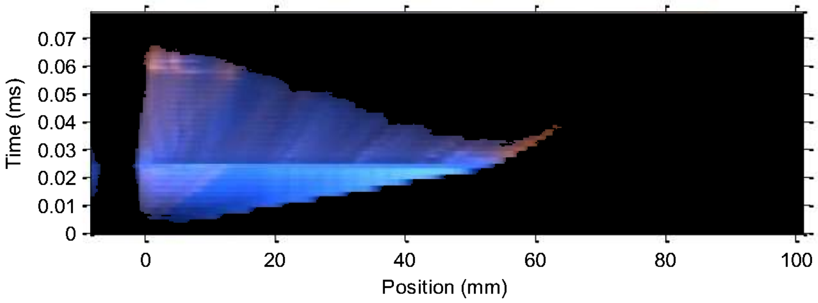

Figure 3-11 Detonation test 25

Figure 3-11 shows a successfully detonation. The detonation blast wave starts at the bottom of the figure; the rarefaction wave is possible to see after 0.02 ms.

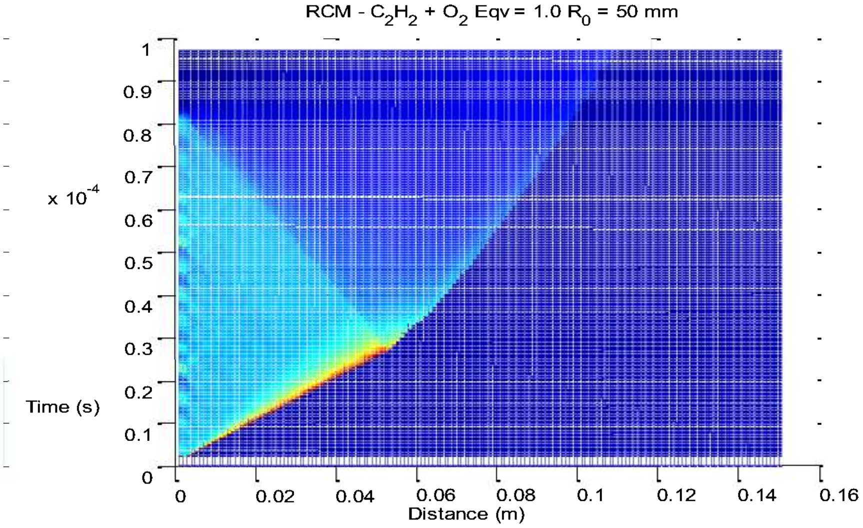

Figure 3-12 RCM result of test 25

Figure 3-12 is a result of RCM calculation with respect to distance and time. The detonation starts from the bottom at time $t = 2 \cdot 10^{-6}\ s$ at position 0 m and continues to $t = 2.8 \cdot 10^{-5}\ s$ to a position of 0.05 m. The shock wave and rarefaction wave is possible to see at position 0.05 m. The velocity of the shock wave gradually decreases. The RCM result seen in Figure 3-12 matches the detonations picture shown in Figure 3-11.

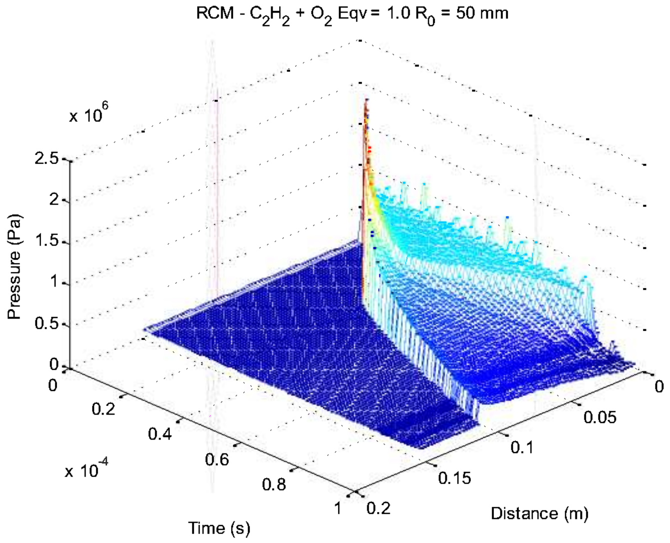

Figure 3-13 Test 25 RCM 3-D Dimension

Figure 3-13 shows a better overview of the detonation result from the RCM 3-D solution. Time, pressure and distance are measured. The detonation starts at time 0 at the peak pressure and is immediately followed by the rarefaction wave while the shock wave continues after position 50 mm with velocity and pressure dropping gradually.

Test 13

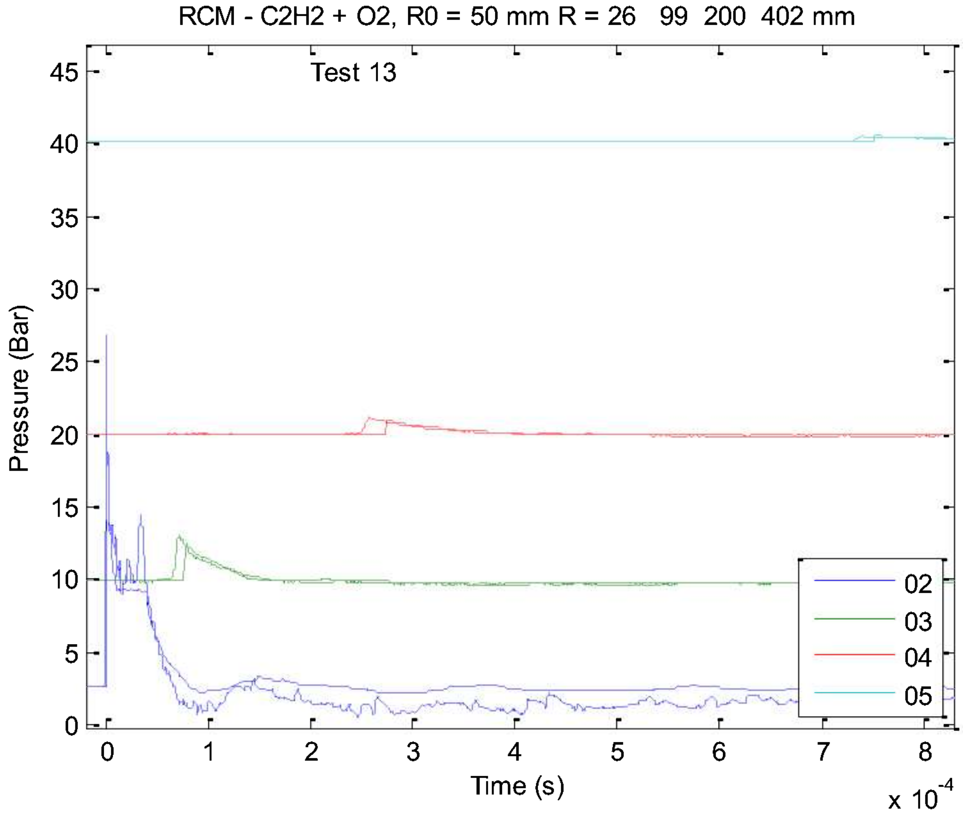

Figure 3-14 Detonation pressure result test 13 compared with RCM result

Test parameters; lean mixture $\phi = 0.8$ and critical tube diameter of 5 mm. Lean mixtures are expected to have less energy. The pressure results are compared to the RCM. The deviation at the peak pressure can again be concluded as a result of low sampling frequency of the pressure transducer. The rest of the results match the measurements quite accurately.

Test 33

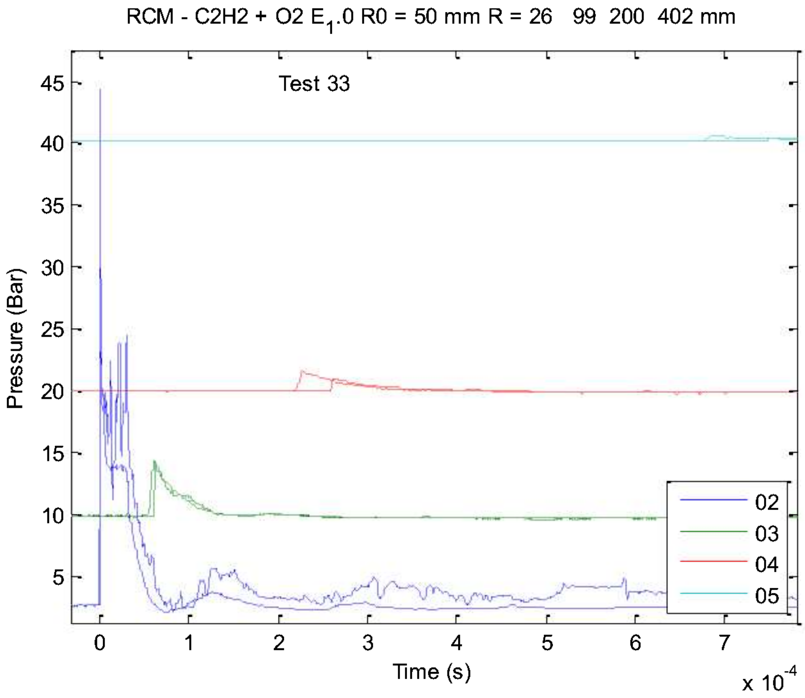

Figure 3-15 CO-stoichiometric experiment test 33 compared to RCM

CO-stoichiometric ratio ϕ = 1.6667 and critical tube diameter of 4 mm. The pressure results are compared to the RCM. In a rich mixture, it is expected to yield a high velocity, temperature and pressure due the amount of energy released by combustion. The deviation of the peak pressure is probably a result of low sampling frequency of the pressure transducer. The rest of the results match the measurements quite accurately.

3.4 Detonation velocity calculation

The velocity of the tests that successfully detonated is estimated using a ruler that is within the picture frame. The frame rate is known (500,000 fps), this gives us a time reference. The detonation velocity can be calculated by measuring how many pixels it moves in a few frames, scaling with pixel/mm and dividing by the amount of time that has passed. The position result is then calculated using Excel. The velocity of a rich, lean and stoichiometric is calculated. The detonation velocity depends on the stoichiometric mixture and is expected to increase when the stoichiometric ratio increases, as long as a successful detonation appears. The detonation velocity is independent of the tube diameter.

Test 23

Test parameters; lean mixture $\phi = 0.7$ and a critical tube diameter of 5 mm. Starting with the lean mixture from test 23, it is expected that the detonation velocity of test 23 will be the lowest since the detonation velocity increases when the stoichiometric ratio increases.

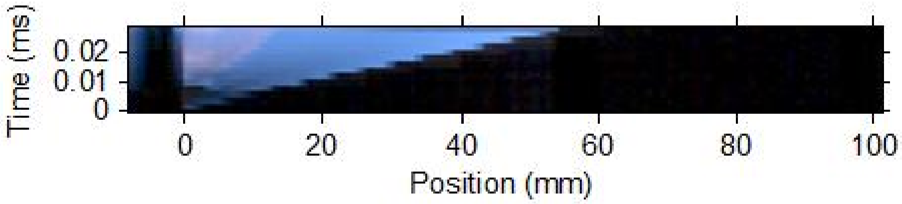

Figure 3-16 Detonation test 23

Figure 3-16 shows an overview of the detonation frames set up frame by frame horizontally at each other with position and time.

Table 3-3 Detonation velocity caclulation experiment test 23

y-direction [pxl]	Position [mm]	Time[s]	Detonation velocity [m/s]	Scale mm/pxl	Bottom pxl position
239	109.32	0.011274	0	0.43	239
228	113.98	0.011276	2331		
219	117.80	0.011278	1907		
210	121.61	0.011280	1907		
202	125.00	0.011282	1695		
193	128.81	0.011284	1907		
183	133.05	0.011286	2119		
174	136.86	0.011288	1907		
164	141.10	0.011290	2119		
154	145.34	0.011292	2119		

Table 3-3 is made by Excel software where all data of position, time, y-direction and bottom position helps to find the accurate detonation velocity. The detonation velocity is approximately 2001 $\frac{\mathrm{m}}{\mathrm{s}}$ for test 23 with a lean mixture.

Test 24

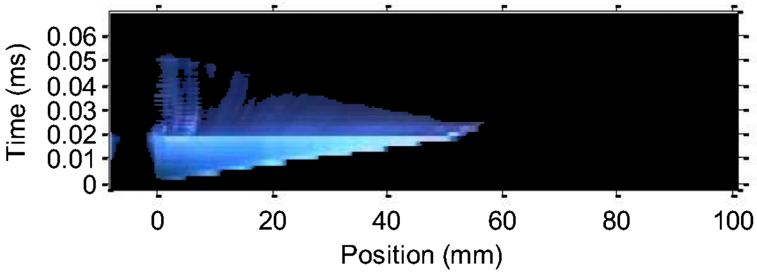

Figure 3-17 test 24

Test parameters, rich mixture $\phi = 2.5$ and a critical tube diameter of 5 mm. The picture series shown in Figure 3-17 shows an overview of the position in mm with respect to time in ms, which can make it possible to estimate the detonation velocity. However the error can be large by using this method.

Table 3-4 Detonation velocity calculation test nr 24

y-direction [pxl]	Position [mm]	Time[s]	Detonation velocity [m/s]	Scale mm/pxl	Bottom pxl position
236	110.59	0.001688	0	0.43	236
222	116.53	0.001690	2966		
209	122.03	0.001692	2754		
196	127.54	0.001694	2754		
183	133.05	0.001696	2754		
170	138.56	0.001698	2754		
156	144.49	0.001700	2966		

Table 3-4 shows an overview of position, time and detonation velocity calculated in Excel. For test 24 the detonation velocity is approximately $2824\frac{\mathrm{m}}{\mathrm{s}}$, the rich mixture velocity is expected to be greater than the velocities of a stoichiometric and lean mixture.

Test 25

Table 3-5 Detonation velocity caclulation experiment test 25

y-direction [pxl]	Position [mm]	Time[s]	Detonation velocity [m/s]	Scale mm/pxl	Bottom pxl position
239	109.32	0.009972	0	0.43	239
228	113.98	0.009974	2331		
217	118.64	0.009976	2331		
206	123.31	0.009978	2331		
195	127.97	0.009980	2331		
184	132.63	0.009982	2331		
173	137.29	0.009984	2331		

Test parameters; stoichiometric mixture $\phi = 1$ and a critical tube diameter of 5 mm. Table 3-5 shows an overview of the detonation velocity result of test 25. Test 25 is a stoichiometric mixture with Φ = 1, the velocity is approximately $2331\frac{\mathrm{m}}{\mathrm{s}}$.

3.5 Deflagrations

A failed detonation is known as deflagration, the cause of a failed detonation can be the size of the tube diameter as well as the stoichiometric ratio. All combustion waves that exited the tube that did not have a spherical geometry are defined as deflagrations. In this thesis a deflagration can be decided by the pressure result and the high-speed film. Deflagration can be recognized by the low pressure, velocity and yellow colored flame due the low temperatures. To be able to find the critical tube diameter, experiments have been done where detonation limit is close to the deflagrations. Some of the tests even detonated in earlier tests, but then failed after another try. Many of the tests that failed to detonate when exiting the tube managed to detonate outside the tube.

Table 3-6 Deflagration pressure results

Test nr.	Pmax [bar] ch. 2	Pmax [bar] ch. 3	Pmax [bar] ch. 4	Pmax [bar] ch. 5	Equivalence ratio [ϕ]	Tube Diameter [mm]
16	8.38	0.44	0.30	0.15	0.6	5
18	6.96	0.52	0.31	0.16	0.65	5
20	7.72	0.50	0.33	0.17	0.675	5
22	5.73	0.56	0.28	0.14	0.7	5
26	8.79	3.26	1.13	0.39	0.7	4
28	7.52	3.68	0.88	0.32	0.75	4
35	6.44	3.61	1.08	0.32	0.8	3
36	3.92	6.26	1.53	0.38	0.85	3
37	4.79	9.53	1.59	0.38	0.875	3
38	4.39	3.31	1.48	0.37	0.9	3
39	14.87	2.87	1.41	0.45	0.925	3
42	7.24	3.82	1.18	0.41	0.95	3
45	7.61	8.23	2.01	0.44	1	2
50	6.55	8.71	2.22	0.47	1.1	2
53	5.95	4.47	1.81	0.43	1.15	2

Table 3-6 shows an overview of nearly all the deflagration pressure results that appeared in the tests. Most of these deflagrations have a higher pressure than expected, caused by the detonation appearing after exiting the tube.

Test 39

Experiment test 39 was done with a lean mixture where ϕ = 0.925 and a tube diameter of 3 mm.

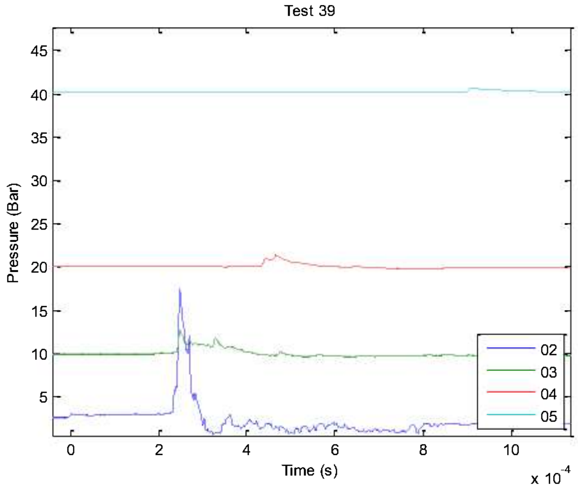

Figure 3-18 Deflagration pressure results test 39

Figure 3-18 shows an overview of the pressure results appearing due the deflagration. The results are close to a detonation results and are greater than what was expected for a deflagration. The high pressures are caused by a detonation that appeared 0.26 ms in the figure to the left and 0.21 ms in the figure to the right after the combustion exiting the tube shown in Figure 3-19.

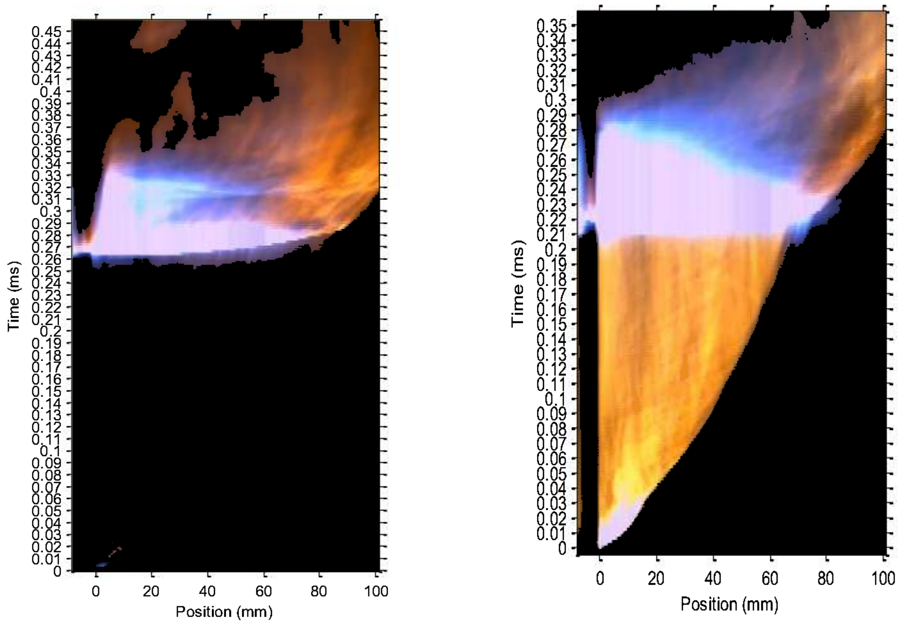

Figure 3-19 Test nr 39 and 50 detonations fails and starts again (deflagration)

4 Discussion

The experiments show that the critical tube diameter value is slightly larger than what was observed by Lee [2]. It is not known how the earlier experiment was exactly performed.

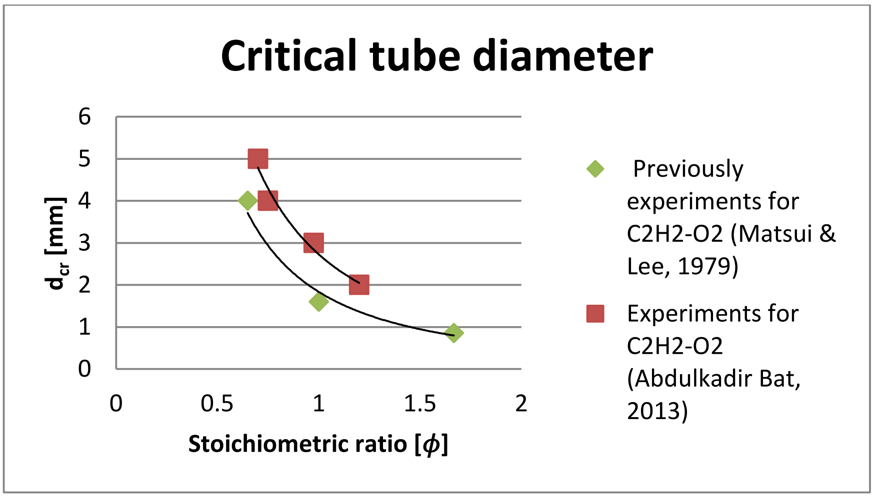

Figure 4-1 Critical tube diameter

Figure 4-1 show an overview of the results found during the experiments compared with the earlier experiments done by Lee [2]. There is a small deviation that may be caused by different experimental equipment. The calibration and the size of the tube errors had a greater effect on the results than expected. Some of the deflagration experiments that detonated after exiting the tube could be mistaken as a detonation due the pressure results. The way that detonation and deflagrations where determined was by studying the pressure results and reviewing the high-speed recording to see if a spherical combustion wave was exiting the tube. Figure 3-18 can be taken as an example of the detonation that may appear after exiting the tube.

The limit for a successful detonation for a specific critical tube diameter lies between two stoichiometric ratios. This leaves a bit of uncertainty of the exact value. The stoichiometry ratio for the critical tube is shown in table below.

Table 4-7: Detonation limits for specific critical tube diameters

Detonation	Deflagration	Critical tube diameter [mm]
ϕ=0.7	ϕ=0.675	5
ϕ=0.75	ϕ=0.75	4
ϕ=0.975	ϕ=0.95	3
ϕ=1.2	ϕ=1.15	2

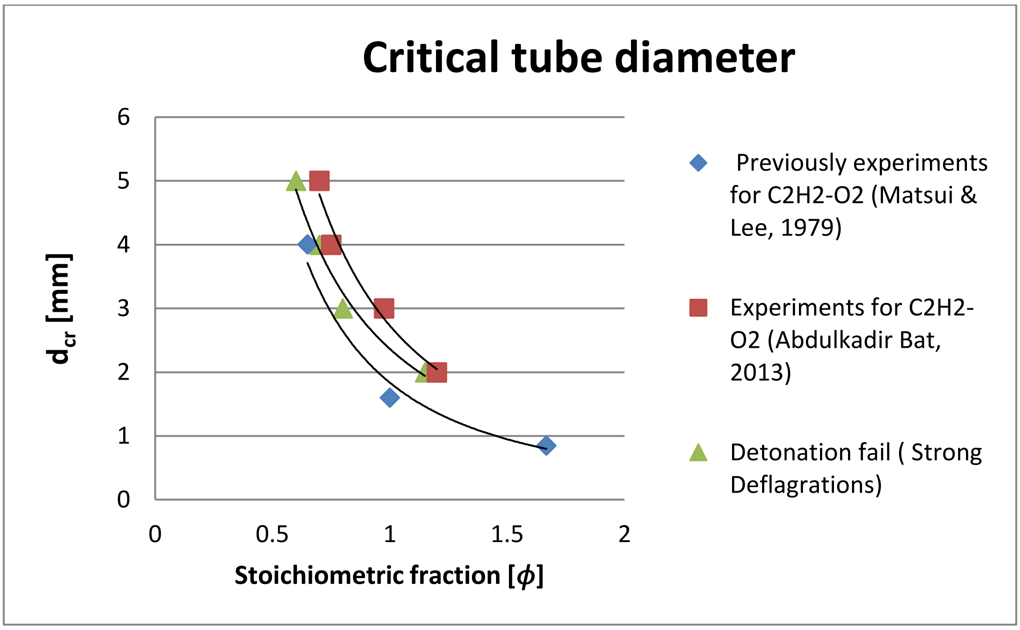

Figure 4-2 Critical tube diameter including failed detonations

Figure 4-2 shows an overview of the strong deflagrations that managed to detonate after exiting the tube. Some of the deflagration tests had high-pressure readings that could easily be misinterpreted as a successful detonation. It is likely that some failed detonations may have been included in the results from earlier experiments; it is much easier to differentiate these two types of detonations using modern high-speed cameras. Such failed detonations are shown in Figure 3-18 have a high pressure caused by the detonation appearing after exiting the tube are defined as deflagrations after the film was carefully watched. When the failed detonations are included in the results the curves of this experiment gets much closer to the results that Lee [2] got in 1979.

Deflagrations (failed detonations)

Some of the deflagrations that detonated after exiting the tube gave a pressure result at channel 3 where the pressure transducer is installed outside the bubble to be greater than the pressure at channel 2 that is inside the bubble, the results are shown in Table 3-6. It is probably caused by the detonation that appeared was closer to the pressure transducer at channel 3. The position where the detonation appears after the deflagration exits the tube is not known, so there is no possibility of using the Multi Energy Method.

RCM

The RCM results match the measurements quite accurately. There is a small error that gives a time delay for the RCM. The error that appears at the peak pressure is a consequence of the low sampling frequency of the pressure transducer. The RCM gives a great 3-D overview of the detonation where it is possible to see how the detonation, rarefaction wave and the shock wave propagate.

Detonation velocity

The detonation velocity is calculated by measuring the high-speed films. The result can be assumed to have a small error. The earlier calculations done by Dag Bjerketvedt in the SUPERSTATE software is compared to the calculations based the high-speed film.

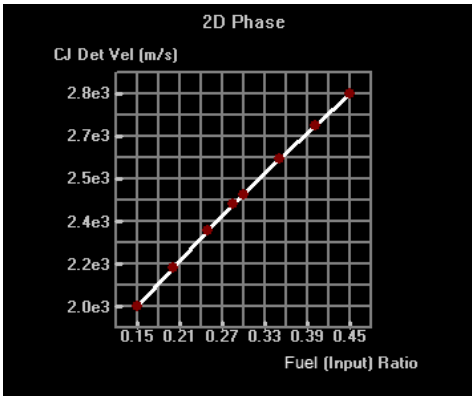

Figure 4-3 SUPERSTATE CJ-detonation velocity

Figure 4-3 Show the CJ-detonation velocity calculated by the SUPERSTATE software. **Error! Reference source not found.**

Table 4-8: Overview of the different CJ-detonation velocities and error.

Stoichiometric ratio	ϕ = 0.7	ϕ = 1	ϕ = 2.5
SUPERSTATE detonation velocity[$\frac{m}{s}$]	2200	2450	2850
High-speed film detonation velocity[$\frac{m}{s}$]	2001	2331	2824
Deviation [%]	9.9	5.1	1

The error that appears from the lean mixture where ϕ = 0.7 is much larger than the error that appears for the rich mixture where ϕ = 2.5. The trend is that the deviation gets small when ϕ is increased.

5 Conclusion

About 50 small-scale experiments have been performed, but not all are described in this thesis. All experiments were based on an acetylene and oxygen mixture. The experiments were done in different stoichiometric ratios (ϕ) from lean to rich conditions.

- A literature review have been done on earlier experiments, detonations, deflagrations, shock waves and on the critical tube diameter.

- An experimental test rig has been built, with different tube diameters for detonation tests. The experiments were carried out successfully.

- A high-speed camera has been used to film bubble explosions. The film makes it easier to determine if the combustion was a detonation or a deflagration. The film also allows us to calculate the CJ-detonation velocity quite accurately.

- The critical tube diameter with respect to stoichiometric ratio has been found for 2, 3, 4 and 5 mm tube size, and compared with the earlier results done by Lee [2] in 1979.

- The CJ-detonation velocity has been calculated for a lean mixture where $\phi = 0.7$, a stoichiometric mixture where $\phi = 1$ and a rich mixture where $\phi = 2.5$ by measuring the high-speed film. The CJ-detonation velocity results were compared with the results from the SUPERSTATE software.

- Explosion of acetylene related data from experiments were compared with MATLAB software (Random choice method); RCM has been used to simulate the model which is close to the experiment that has been done. The experimental results shows a good correlation with the simulation results from RCM. The simulation shows a constant pressure increasing process; the experimental data shows that the pressure has an acceleration period. Both of them have a similar positive pressure value and duration time.

6 References

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Appendix 1: Test overview

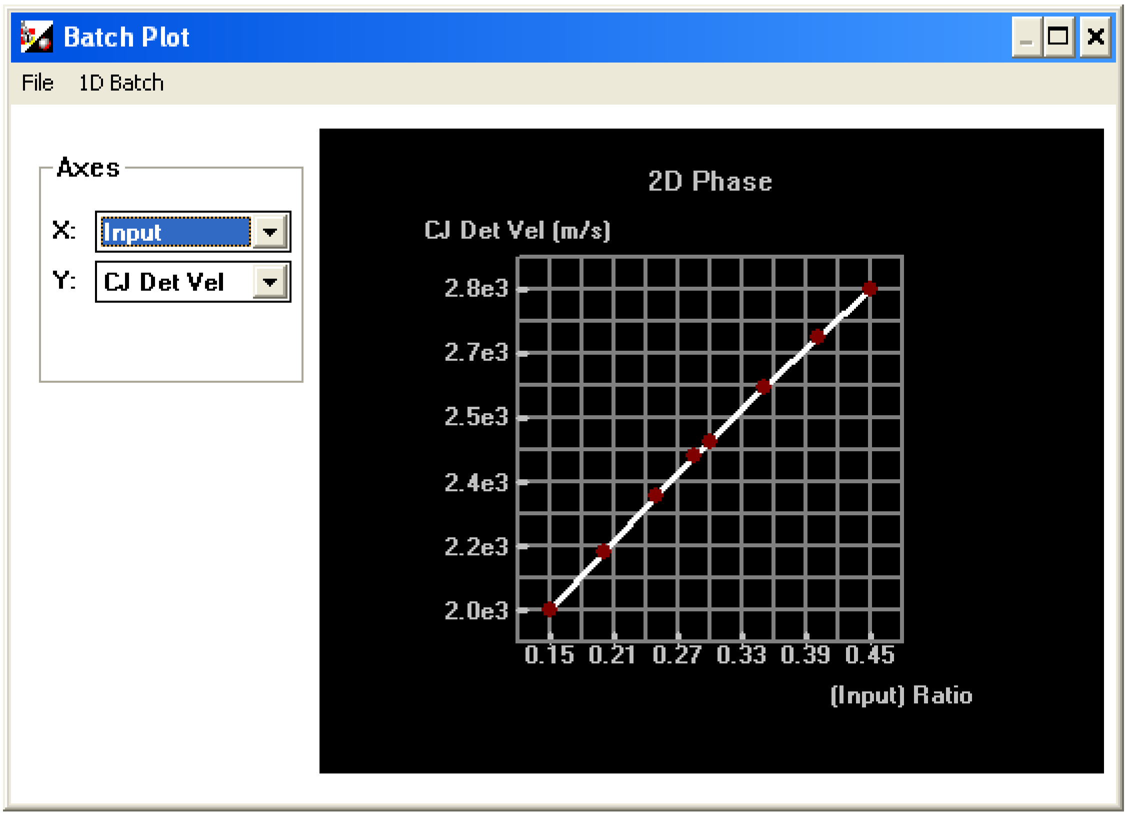
Date	Test nr.	ϕ	Det? [1/0]	Comments	VideoFile	Pressure records file
08.03.2013	13	0.8	1		13_AKB_P101_T00013	13_AKB_P101_T00013
08.03.2013	14	0.7	1		13_AKB_P101_T00014	13_AKB_P101_T00014
08.03.2013	15	0.7	1	Repeat test 2	13_AKB_P101_T00015	13_AKB_P101_T00015
08.03.2013	16	0.6	0		13_AKB_P101_T00016	13_AKB_P101_T00016
08.03.2013	17	0.6	0	Repeat test 4	13_AKB_P101_T00017	13_AKB_P101_T00017
08.03.2013	18	0.65	0		13_AKB_P101_T00018	13_AKB_P101_T00018
08.03.2013	19	0.65	0	Repeat test 6	13_AKB_P101_T00019	13_AKB_P101_T00019
08.03.2013	20	0.675	0		13_AKB_P101_T00020	13_AKB_P101_T00020
08.03.2013	21	0.675	0	Repeat test 8	13_AKB_P101_T00021	13_AKB_P101_T00021
08.03.2013	22	0.7	0	Repeat test 2 and 3	13_AKB_P101_T00022	13_AKB_P101_T00022
08.03.2013	23	0.7	1	Repeat test 2, 3 and 10	13_AKB_P101_T00023	13_AKB_P101_T00023
11.03.2013	24	2.5	1		13_AKB_P101_T00024	13_AKB_P101_T00024
11.03.2013	25	1	1		13_AKB_P101_T00025	13_AKB_P101_T00025
20.03.2013	26	0.7	0		13_AKB_P101_T00026	13_AKB_P101_T00026
20.02.2013	27	0.775	1		13_AKB_P101_T00027	13_AKB_P101_T00027
20.02.2013	28	0.75	0		13_AKB_P101_T00028	13_AKB_P101_T00028
20.02.2013	29	0.75	1	Repeat test 16	13_AKB_P101_T00029	13_AKB_P101_T00029
20.02.2013	30	0.75	0	Repeat test 16 og 17	13_AKB_P101_T00030	13_AKB_P101_T00030
20.02.2013	31	0.75	0	Repeat test 16, 17 and 18	13_AKB_P101_T00031	13_AKB_P101_T00031
20.02.2013	32	1	1		13_AKB_P101_T00032	13_AKB_P101_T00032
20.02.2013	33	1.666	1		13_AKB_P101_T00033	13_AKB_P101_T00033
20.02.2013	34	2.5	1		13_AKB_P101_T00034	13_AKB_P101_T00034
22.03.2013	35	0.8	0		13_AKB_P101_T00035	13_AKB_P101_T00035
02.04.2013	36	0.85	0		13_AKB_P101_T00036	13_AKB_P101_T00036
02.04.2013	37	0.875	0		13_AKB_P101_T00037	13_AKB_P101_T00037
02.04.2013	38	0.9	0		13_AKB_P101_T00038	13_AKB_P101_T00038
12.04.2013	39	0.925	0		13_AKB_P101_T00039	13_AKB_P101_T00039
12.04.2013	40	1	1		13_AKB_P101_T00040	13_AKB_P101_T00040
12.04.2013	41	0.925	0	Repeat test 27	13_AKB_P101_T00041	13_AKB_P101_T00041
12.04.2013	42	0.95	0		13_AKB_P101_T00042	13_AKB_P101_T00042
12.04.2013	43	0.975	1		13_AKB_P101_T00043	13_AKB_P101_T00043
12.04.2013	44	2.5	1		13_AKB_P101_T00044	13_AKB_P101_T00044
16.04.2013	45	1	0		13_AKB_P101_T00045	13_AKB_P101_T00045
16.04.2013	46	1.666	1		13_AKB_P101_T00046	13_AKB_P101_T00046
16.04.2013	47	1.5	1		13_AKB_P101_T00047	13_AKB_P101_T00047
16.04.2013	48	1.4	1		13_AKB_P101_T00048	13_AKB_P101_T00048
16.04.2013	49	1.3	1		13_AKB_P101_T00049	13_AKB_P101_T00049
16.04.2013	50	1.1	0		13_AKB_P101_T00050	13_AKB_P101_T00050
18.04.2013	51	1.2	1	Very high pressure	13_AKB_P101_T00051	13_AKB_P101_T00051
18.04.2013	52	1.2	1	Repeat test 39	13_AKB_P101_T00052	13_AKB_P101_T00052
18.04.2013	53	1.15	0		13_AKB_P101_T00053	13_AKB_P101_T00053

Settings:

Resolution 256x16 pixels
Fps: 500,000

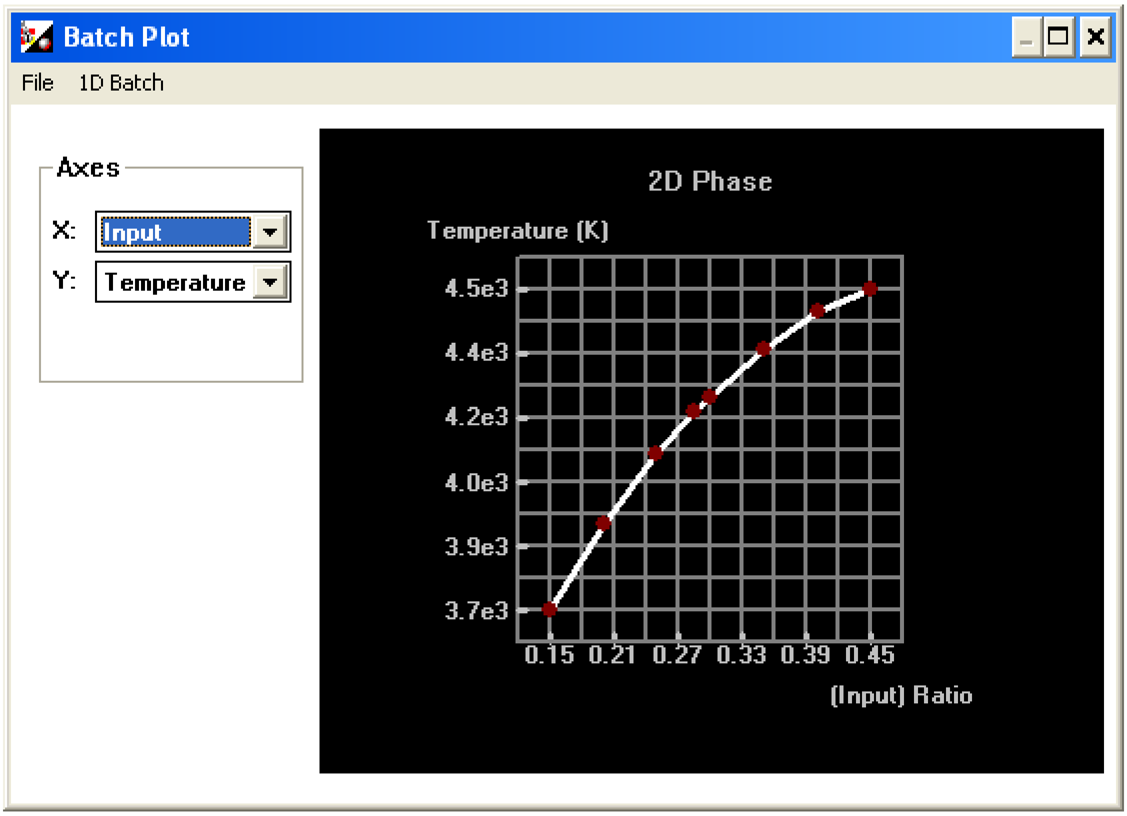
Amplifier 1	**Amplifier2**	**Amplifier 3**	**Amplifier 4**	**Pos amp 1[mm]**	**Pos amp 2[mm]**	**Pos amp 3[mm]**	**Pos amp 4[mm]**
10 Bar/V	10 Bar/V	5 Bar/V	1 Bar/V	25	100	200	400

Appendix 2: SUPERSTATE



X: Input

Y: CJ Det Vel



X: Input

Y: Temperature

Appendix 3: Procedure check

Procedure for acetylene-oxygen detonation experiment

1. Check necessary hearing protection, glass walls and safety glasses
2. Lock the doors manually and turn on the alarm light. Write name and number outside
3. Note down the experiment (number, date, %fuel, %Oxygen)
4. Turn on the Digital Oscilloscope and check that the amplifiers are connected properly
5. Check if the main-compressor is on by checking the pressure at the manometer
6. Check if the Pulse Generator (igniter) is on and that it works
7. Check that the flow-meters are off
8. Turn on the gas cylinders (Oxygen/Acetylene)
9. Turn on the switch-valve and adjust the flow-meters to the proper pressure for both gases
10. Make the bubble with the right stoichiometry mixture of both gases
11. Make sure that the high-speed camera is on and properly connected
12. Turn on the alarm for the research building using a remote control
13. Turn off the switch valve, flow meters for both gases and the acetylene cylinder
14. Detonation
15. Turn off the alarm and read the pressure from the Digital Oscilloscope

Appendix 4: MATLAB Codes

MATLAB code for pressure results

```
clear ;
% HiT gas esplosion  data files : 08_DBj_P001_T 0009/CH1_01h.TXT
%                                 123456789012345678901234567890

test          = input('Test number: ');
if isempty(test)

    'No test number given'
end

ch=input('channels ex. [2 3 4 5 6 7] ');
if isempty(ch)
    ch = [3 4 5 6] ;
end
%
% 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 = '10_AVG_P301_T 00001/CH1_06h.TXT';
filename = '13_AKB_P101_T 00001/CH1_06h.TXT';

%            12345678901234567890123456789
% ch = [4 5 6,7,8] ; % Channel # Nicolet Sigma 90


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))]; %
%
%   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 Samples
%       1000000
%   13  DATA START
%       -0.007161
%       -0.005078
%       -0.004036
%       -0.008203
%       .


for i = 1:length(ch);

    %filename(2) = num2str(ch(i)-3);
    filename(23) = num2str(ch(i));
    filename(26) = num2str(ch(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
% [scale,fuel,Conc,comment,SensorPos,SensorType]=scaleextr(test,ch);
scale = [10 10 5 1];

        windowSize = 1; %1e-6/ST;

        V0=mean(V(1:15,:));
        for k=1:length(V(1,:))
            VF(:,k)=filter(ones(1,windowSize)/windowSize,1,V(:,k));
%             PRes(:,k)=(V(:,k)-V0(k)).* scale(k);
            PRes(:,k)=(VF(:,k)-V0(k)).* scale(k);
        end
```

```
    % [PKF1]=lowpass_filter(V(:,1)).*scale(1);
%   [PKF2]=lowpass_filter(V(:,2)).*scale(2);
 %  [PKF3]=lowpass_filter(V(:,3)).*scale(3);
  %   [PKF4]=lowpass_filter(V(:,4)).*scale(4);
   % [PKF5]=lowpass_filter(V(:,5)).*scale(5);

    % PRes(1,:)=PKF1;
     %PRes(2,:)=PKF2;
   %  PRes(3,:)=PKF3;
%     PRes(4,:)=PKF4;
%    PRes(5,:)=PKF5;

R = [26 99 200 402] % Distance mm
C1 = 0.1;

ind = find(PRes(:,1)>0.3, 1, 'first');
Time1 = T(ind);

Pmax(1)=0;

for i =1:size (R,2)
 PRes2(:,i) = PRes(:,i) + C1*R(i);
 Pm = max(PRes(:,i));
 indp = find(PRes(:,i)== Pm, 1, 'first');
 Pmax(i) = PRes(indp,i)
end

plot (T-Time1,PRes2);

axis([-0.0001,0.005, 0,50])
xlabel('Time (s)')
ylabel('Pressure (Bar)')
% title([' Nicolet Sigma 90 ', filename(4:7),' ',filename(8:11),'
',filename(13:17),' Trigger Time: ',TT,'  Fuel ',fuel]);
% title([' Nicolet Sigma 90 ';'Fuel ';fuel;' Conc ';num2str(Conc)]);
%axis([0 50e-3 -100 1000])

title(['Test ',num2str(test)])

% leg=[num2str(M),[' ',' ',' ',' ',' ',' ']',SensorType,[' ',' ',' ',' ','
',' ']',num2str(SensorPos'),['m','m','m','m','m','m']'];

legend(M,4)
% legend(leg)

% hold on
% sensorline=ones(length(T),5);
% for l=1:5
%     sensorline(:,l)=sensorline(:,l)*SensorPos(l);
% end
% plot (T,sensorline)
% plot(T,zeros(1,length(T)),'k');
% hold off
```

MATLAB code for RCM

```
clear ;
close ;
% HiT gas esplosion  data files : 08_DBj_P001_T 0009/CH1_01h.TXT
%                                 1234567890123456789012345678 90

test        = input('Test number: ');
if isempty(test)
    'No test number given'
end

ch=input('channels ex. [2 3 4 5 6 7] ');
if isempty(ch)
    % ch = [3 4 5 6] ;
    ch = [2 3 4 5]  ;
end
%
% 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 = '10_AVG_P301_T 00001/CH1_06h.TXT';
%filename = '12_AOX_P002_T 00001/CH1_06h.TXT';
filename = '13_AKB_P101_T 00040/CH1_06h.TXT';
%           12345678901234567890123456789
% ch = [4 5 6,7,8] ; % Channel # Nicolet Sigma 90


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))]; %
%
%   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 Samples
%       1000000
%   13  DATA START
%       -0.007161
%       -0.005078
%       -0.004036
%       -0.008203
%       .


for i = 1:length(ch);

    %filename(2) = num2str(ch(i)-3);
    filename(23) = num2str(ch(i));
    filename(26) = num2str(ch(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
% [scale,fuel,Conc,comment,SensorPos,SensorType]=scaleextr(test,ch);
scale = [10 10 5 1];

        windowSize = 1; %1e-6/ST;

        V0=mean(V(1:15,:));
        for k=1:length(V(1,:))
            VF(:,k)=filter(ones(1,windowSize)/windowSize,1,V(:,k));
%             PRes(:,k)=(V(:,k)-V0(k)).* scale(k);
            PRes(:,k)=(VF(:,k)-V0(k)).* scale(k);
        end


    % [PKF1]=lowpass_filter(V(:,1)).*scale(1);
%   [PKF2]=lowpass_filter(V(:,2)).*scale(2);
 %  [PKF3]=lowpass_filter(V(:,3)).*scale(3);
```

```
  %   [PKF4]=lowpass_filter(V(:,4)).*scale(4);
   % [PKF5]=lowpass_filter(V(:,5)).*scale(5);

    % PRes(1,:)=PKF1;
     %PRes(2,:)=PKF2;
   %  PRes(3,:)=PKF3;
%     PRes(4,:)=PKF4;
%    PRes(5,:)=PKF5;

R2 = [26 99 200 402]; % Distance mm
C1 = 0.1;

ind = find(PRes(:,1)>15, 1, 'first');
Time1 = T(ind);

Pmax(1)=0;

for i =1:size (R2,2)
 PRes2(:,i) = PRes(:,i) + C1*R2(i);
 Pm = max(PRes(:,i));
 indp = find(PRes(:,i)== Pm, 1, 'first');
 Pmax(i) = PRes(indp,i);
end

figure (1)

plot (T-Time1,PRes2);

axis([-0.0001,0.001, 0,50])
xlabel('Time (s)')
ylabel('Pressure (Bar)')
% title([' Nicolet Sigma 90 ', filename(4:7),' ',filename(8:11),'
',filename(13:17),' Trigger Time: ',TT,'  Fuel ',fuel]);
% title([' Nicolet Sigma 90 ';'Fuel ';fuel;' Conc ';num2str(Conc)]);
%axis([0 50e-3 -100 1000])

text(2e-4,45,['Test ',num2str(test)])

% leg=[num2str(M),[' ',' ',' ',' ',' ',' ']',SensorType,[' ',' ',' ',' ',' ',' ']',num2str(SensorPos'),['m','m','m','m','m','m']'];

legend(M,4)
% legend(leg)

 hold on

 % RCM data _________________________

 load ('rcmdat08')  %SETT INN RIKTIG FILE

 ndistance = [26 99 200 402];
 nydistance = [26 99+5 200+5 402];

ind = find(P(:,nydistance(1))>1.3e5, 1, 'first');
Time2 = TIME(ind);
C2 =0.1;

windowSize = 1; %
```

```
        for k=1:length(ndistance)


PF(:,k)=filter(ones(1,windowSize)/windowSize,1,P(:,nydistance(k)));
%
        end

%  for i =1:size (ndistance,2)
%  Pn(:,i) = -1+(1e-5*P(:,(nydistance(i)))) + C2*ndistance(i);
% end

for i =1:size (ndistance,2)
 Pn(:,i) = -1+(1e-5*PF(:,i)) + C2*ndistance(i);
end

%--------------------------------------------------------------

figure (1)
plot ((TIME-Time2),Pn)  % P(t) ved ndistance

% xlabel('Time (ms)')
% ylabel('Pressure (Pa)')
 title(['RCM - C2H2 + O2, R0 = 50 mm ','R = ', num2str(ndistance),' mm'])
% %axis([0.0  1.0 0e5 40e5])
% %text(3.3e-3,680,'Reflected')
% %text(3.3e-3,365,'Constant volume combustion')
% legend('Side-on')

%hold off





% sensorline=ones(length(T),5);
% for l=1:5
%     sensorline(:,l)=sensorline(:,l)*SensorPos(l);
% end
% plot (T,sensorline)
% plot(T,zeros(1,length(T)),'k');
% hold off

figure (2)
q = 2;
X = dx.*(1:length(P(1,:)));
mesh(X(1:q:150),TIME(1:q:200),P(1:q:200,1:q:150))
 title(['RCM - C_2H_2 + O_2 Eqv = 1.0 R_0 = 50 mm '])
 xlabel('Distance (m)')
 ylabel('Time (s)')
 zlabel('Pressure (Pa)')

%  figure (3)
%
% mesh(X(1:150),TIME(1:200),R(1:200,1:150))
%  title(['RCM - C_2H_2 + O_2 Eqv = 1.0 R_0 = 50 mm '])
%  xlabel('Distance (m)')
%  ylabel('Time (s)')
%  zlabel('Desity (kg/m_3)')
%
%  figure (4)
```

```
%
% mesh(X(1:150),TIME(1:200),U(1:200,1:150))
%  title(['RCM - C_2H_2 + O_2 Eqv = 1.0 R_0 = 50 mm '])
%  xlabel('Distance (m)')
%  ylabel('Time (s)')
%  zlabel('Velocity (m/s)')
```

MATLAB code for frames upset

```
%   leser inn bilder

clear all
close all
fclose all

ant_frames=36;
dt = 1/500000;
null_x = 256-236;
scale = 0.427 ;%mm/pxl


x1er = 0:20:100;
x2er = x1er./scale;
x2er=x2er+null_x;


tid1=0:ant_frames/5;
tid=tid1*5*dt;




% T = 1:10:71;
T=tid1*10;


filename='tiff/frame_000001.tif';
C=[];

for i=1:ant_frames

    if i<10
        filename(17)=num2str(i);
    elseif i<100
        filename(16:17)=num2str(i);
    else
        filename(15:17)=num2str(i);
    end

    A=imread(filename);


   B(1:16,1:256,1)=fliplr((A(:,:,1)'));
   B(1:16,1:256,2)=fliplr((A(:,:,2)'));
   B(1:16,1:256,3)=fliplr((A(:,:,3)'));

%     figure(1)
%     imshow(B)
%     h=getframe;
```

```
    C=[B(8:9,:,:);C];

end

for j=1:length(T)
   TT{j}=num2str(tid(end-j+1)*1000);
end

figure(1)
imshow(C)
axis on
set(gca,'Visible','on','XTick',x2er,'XTickLabel',{'0','20','40','60','80','
100'},'YTick',T,'YTickLabel',TT )
xlabel('Position (mm)')
ylabel('Time (ms)')
```

Appendix 5: MULTI ENERGY METHOD

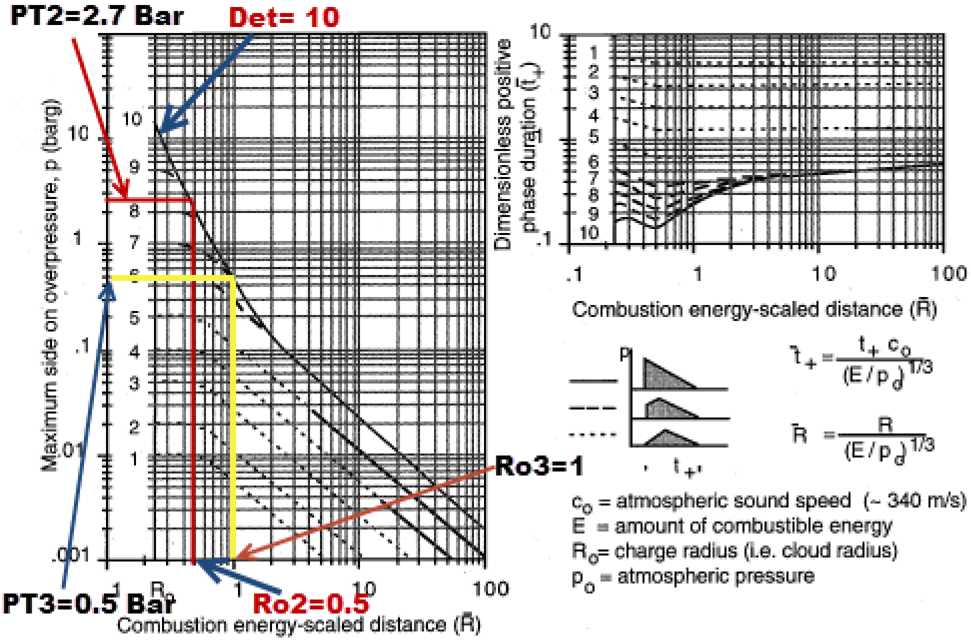


Figure 6-1 Hemispherical Fuel-Air charge blast for multi-energy

Combustion energy-scaled distance ($\bar{R}$)

Where the different letters stand for:

- E for amount of combustible energy [J]
- R for distance from the pressure amplifiers [m]
- P_0 atmospheric pressure [Pa]

  Example a detonation appeared the pressure results of:

  Pressure transducer 2 gave an overpressure of 2.6 bar from a distance of 0.1m while pressure transducer 3 gave an overpressure of 0.5 bar from a distance of 0.2m.

  Reading of results from Figure 6-1

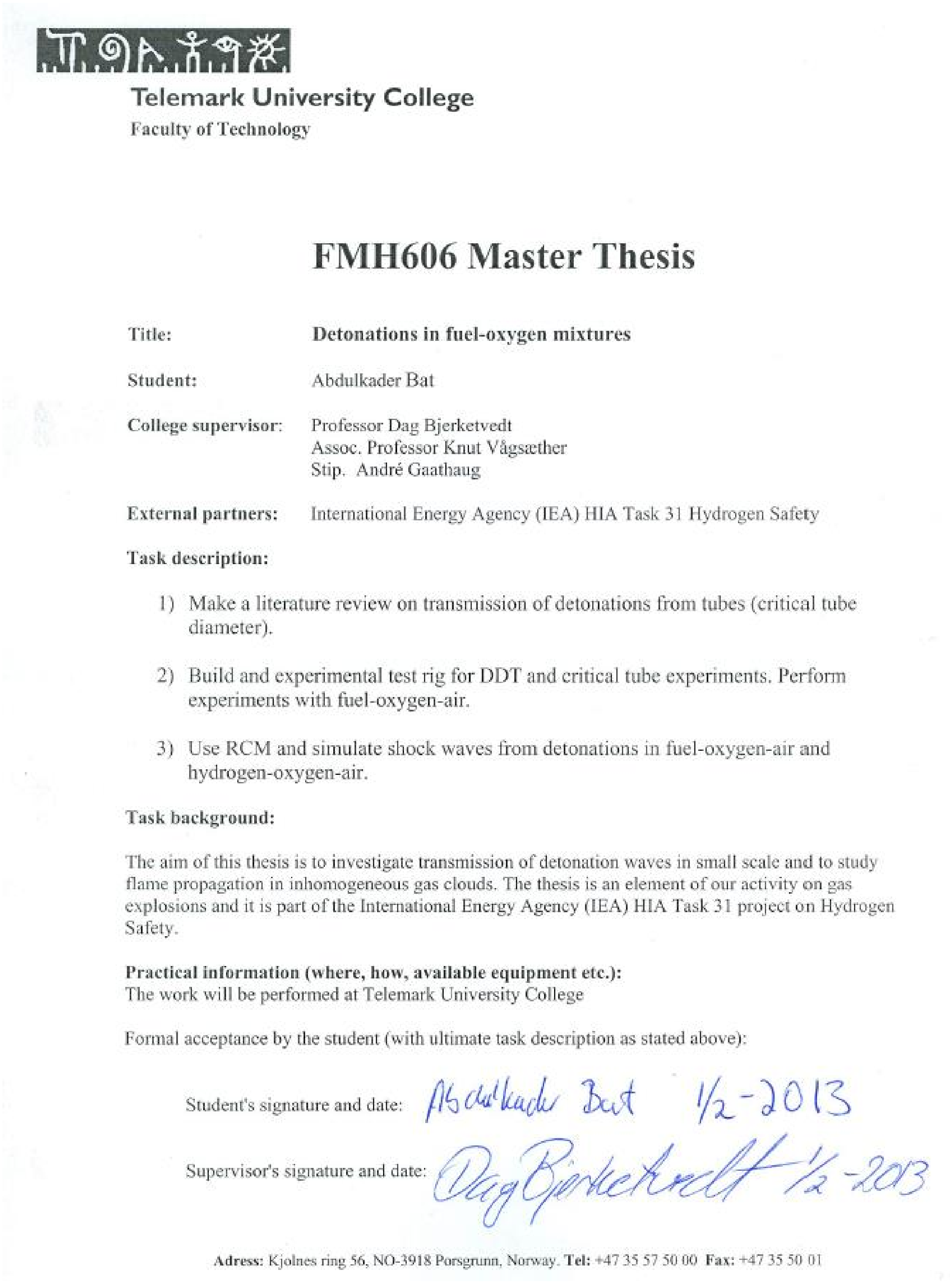
Energy relists from detonation using $E = \frac{R^3}{\bar{R}^3} \cdot P_0$ and pressure transmitter with distance of 0.1m: R=0.1, R_{02}=0.5 and P_0=101325

$$E = \frac{0.1^3}{0.5^3} \cdot 101325 = 810.6\,J$$

Pressure transmitter with distance of 0.2m: R=0.2, R_{02}=1 and P_0=101325

$$E = \frac{0.2^3}{1^3} \cdot 101325 = 810.6\,J$$

Appendix 6: Task description



Telemark University College
Faculty of Technology

FMH606 Master Thesis

Title: **Detonations in fuel-oxygen mixtures**

Student: Abdulkader Bat

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

External partners: International Energy Agency (IEA) HIA Task 31 Hydrogen Safety

Task description:

1) Make a literature review on transmission of detonations from tubes (critical tube diameter).
2) Build and experimental test rig for DDT and critical tube experiments. Perform experiments with fuel-oxygen-air.
3) Use RCM and simulate shock waves from detonations in fuel-oxygen-air and hydrogen-oxygen-air.

Task background:

The aim of this thesis is to investigate transmission of detonation waves in small scale and to study flame propagation in inhomogeneous gas clouds. The thesis is an element of our activity on gas explosions and it is part of the International Energy Agency (IEA) HIA Task 31 project on Hydrogen Safety.

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: Abdulkader Bat 1/2-2013

Supervisor's signature and date: Dag Bjerketvedt 1/2-2013

Adress: Kjolnes ring 56, NO-3918 Porsgrunn, Norway. **Tel:** +47 35 57 50 00 **Fax:** +47 35 50 01