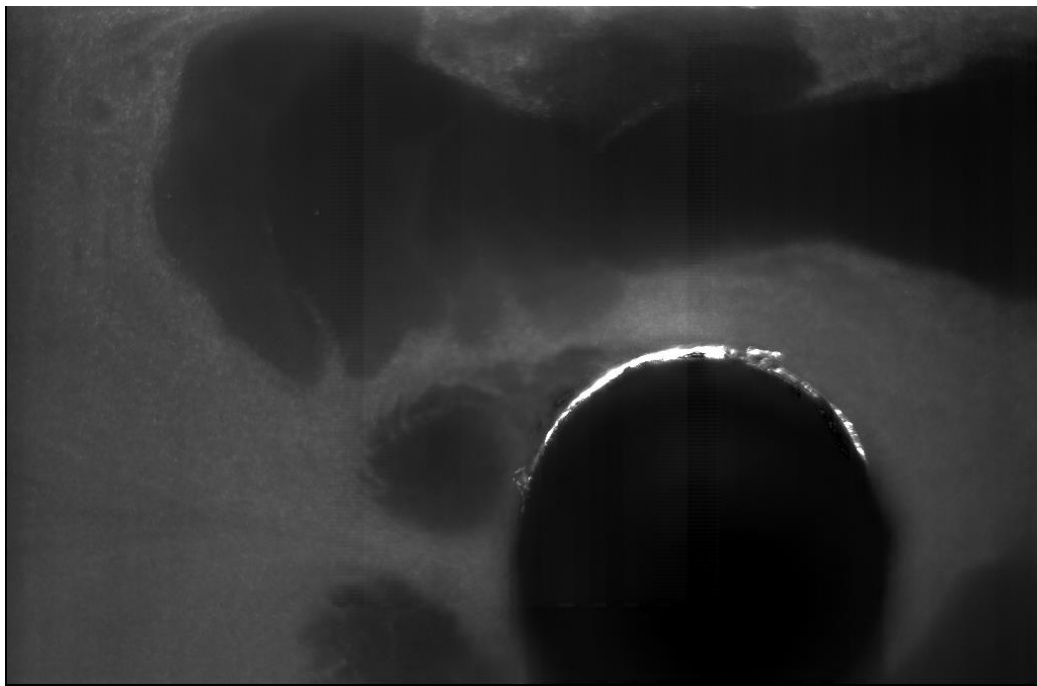


FMH606 Master's Thesis 2018

Process Technology

# **Change in flame front area over time with premixed combustion across an obstacle**



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**Summary:**

This thesis is a joint project of USN, and CMR Gexcon to explore the changes in flame front area over time with premixed combustion across an obstacle. The objective of this thesis is to make a literature review on relevant topics, as well as perform experiments with flame tomography in the lab at USN. Through these experiments, this thesis will assess the change in flame front area over time across an obstacle and explore whether there is any relation between the different concentrations in H<sub>2</sub>-Air mixture. The method used to achieve this is performing experiments with flame tomography and recording it with a high-speed camera. The experiments are then evaluated through a MATLAB code developed during this thesis to track the flame front area, and through this code provide three different results. First being the area of the flame front, second being the change in area scaled to the cross-section area of the combustion chamber. The 3<sup>rd</sup> result being the change in area scaled to the cross section of the combustion area as well as the laminar burning velocity, and relative density between burnt, and unburnt mixture at the given H<sub>2</sub>-Air mixture. And all these are plotted dependent on the position of the flame front relative to the position of the flame front. Through these experiments it has been found that regardless of the concentration of the H<sub>2</sub>-Air mixture, the area of the flame front increases at a consistent rate dependent on the flame front position. The change to flame front area scaled to the cross-section area of the combustion chamber also stays consistent dependent on the flame front position regardless of H<sub>2</sub>-Air mixture. When additionally scaled to the laminar burning velocity, and relative density between burnt, and unburnt mixture, the results are no longer consistent, with there being a decreasing value in change per meter with an increase in concentration.

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# Preface

This thesis would not have been possible to complete without the invaluable help of André Vagner Gaathaug in developing the code that is used to track the flame front, which is the core of this thesis. I would therefor like to thank him especially for making this possible.

Porsgrunn, 19.06.2018

Christian Eide Stueland

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# Nomenclature

$A$  [ $\text{m}^2$ ] = Area

$A_{\text{eff}}$  [ $\text{m}^2$ ] =  $A_u$  = Effective area/flame front area

$A_{\text{cross-section}}$  [ $\text{m}^2$ ] = Cross-section area, in particular for the combustion chamber

$Ka$  = Karlowitz number

$Re$  = Reynolds number

$S_L$  [ $\text{m/s}$ ] =  $S$  = Laminar burning velocity

$u'_n$  [ $\text{m/s}$ ] = velocity at which the eddies rotate with

$u_u$  [ $\text{m/s}$ ] = velocity of the unburnt mixture

$u_b$  [ $\text{m/s}$ ] = velocity of the burnt mixture

$\dot{V}$  [ $\text{m}^3/\text{s}$ ] = Volume flow

$\ell$  [ $\text{m}$ ] = length of the largest eddie

$\ell_F$  [ $\text{m}$ ] = Flame thickness

$\sigma$  = Relative density between burnt, and unburnt mixture

$\Phi$  = fuel to air equivalence ratio

$\rho_b$  [ $\text{kg}/\text{m}^3$ ] = Density of the burn mixture

$\rho_{ub}$  [ $\text{kg}/\text{m}^3$ ] = Density of the unburnt mixture

# 1 Introduction

There has been extensive research into the behavior of the flame during premixed combustion over an obstacle. A big part of this research has been into the effect of the shape of the obstacle, as well as concentration of the combustions, on the flame speed, flame tomography, flame acceleration, and peak pressure.

There is however little, to no research into the actual change in area that occurs during the propagation. The change in area is what facilitates the increase in acceleration, and thereby explains a lot of the changes that occurs when you introduce an obstacle into the chamber. By defining the change in area over time, it is therefore easier to make a realistic simulation of the conditions inside the combustion chamber.

The objective of this thesis is therefor:

- Study the changes in area over time at different concentrations of hydrogen during premixed combustion over an obstacle
- Make a literature study of similar experiments and area as a factor in combustion
- Assess whether there is a correlation between area changes at different concentrations

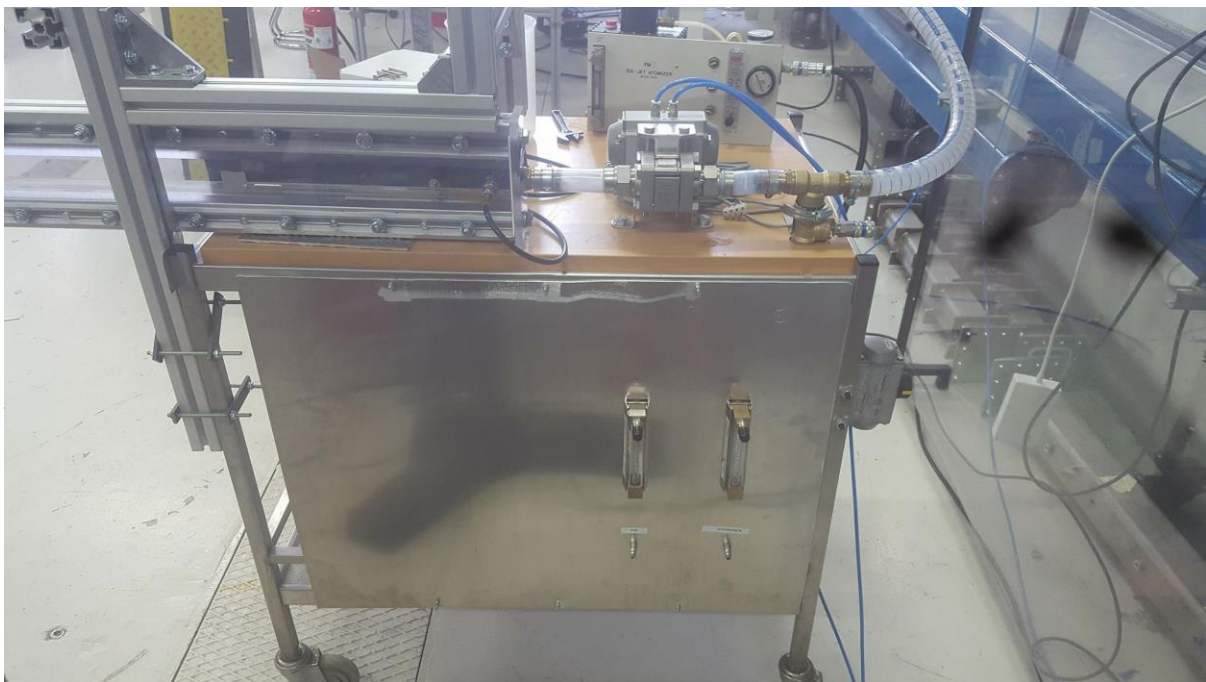


Figure 1-1 Picture of the experimental rig used in this thesis

To do these experiments the experimental rig in figure 1-1 is used. The combustion chamber used has the dimensions 700 mm long, 48 mm wide, 48 mm cm high. The ignition occurs when the inlet to the chamber is closed, and the flow is approaching quiescent conditions. The ignition is placed 25 mm into the chamber, while the obstacle is placed 100 mm into the chamber.

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## 1 Introduction

The combustion is a premixed combustion of a hydrogen/air mixture, which has varying concentrations, ranging from a  $\phi$  of 0.25, to 0.3915.

The flame front is made clear by laser, in a thin sheet. This laser goes along the chamber and lights up small water particles mixed into the air prior to the mixing of hydrogen into the air. The thin sheet of laser gives you information on that specific location in the chamber, but it is assumed that the chamber is uniform in every sheet in the z-direction of the chamber.

This report covers a brief literature study of the topic and method used for the experiments. It expounds on the data obtained in the experiments and discusses the results.



## 2 Literature Study

This chapter elaborates on similar experiments as the ones done in this thesis, as well as some theory on the impact of area on velocity, and what the area increases can consist of.

### 2.1 Similar experiments

There have been a few experiments in a similar setting as the one in this thesis, however the goal of the experiments has been different.

#### 2.1.1 Vågsæther, Gaathaug, Bjerketvedt

At the international conference on hydrogen safety in 2017 Vågsæther, Gaathaug, and Bjerketvedt showed the paper, “PIV-MEASUREMENTS OF REACTANT FLOW IN HYDROGEN-AIR EXPLOSIONS”. For this paper they did experiments on the same experimental rig used in this thesis, but with a different combustion chamber.

In the paper they explored the velocity field of hydrogen-air mixtures at 14, and 17 vol% H<sub>2</sub> with one experiment each. And in this process, they also tracked the flame front area change, in the form of change per meter, and change per second. They were however scaled differently from how it is done in this thesis, which will be further explained in chapter 4.2.

[1]

#### 2.1.2 High speed Visualization

Hargrave, G. K. Williams, T. C. and Jarvis S. Studied the impact of the shape of the obstacle on the flame structure, flame speed and peak pressure in their article, High-speed visualization of flame propagation in explosions. The 3 shapes were cylinder, square, and rectangle. The square and rectangle had the same blockage, but different lengths.

In these experiments, it was found to be the case that the flame front accelerates as it passes an obstacle, decelerates once it passes the obstacle and starts burning into the wake of the obstacle, where a pocket of gas is unburnt. Once the flame passed the obstacle, and has decelerated, it starts accelerating again burning up the remainder of the mixture in the chamber

The article explains that the pressure in the chamber spikes at two different occasions, regardless of the shape of the obstacle. Once when the diaphragm burst, and the second when the mixture in the wake of the obstacle is burnt.

The shapes impacted the velocity, and acceleration of the flame front. The highest velocity as it passed the obstacle was achieved by the square obstacle, while the highest acceleration was achieved with the rectangular obstacle. The rectangular obstacle also had the highest overpressure. This is assumed to be because the rectangular shape creates the largest trapped volume.

[2]

### 2.1.3 Boeck, Lapointe, Malguizo-Gavilanes, Ciccarelli

L.R. Boeck, S. Lapointe, J. Malguizo-Gavilanes, G. Ciccarelli found in their article “Flame propagation across and obstacle: OH-PLIF and 2-D simulations with detailed chemistry”, that their experiment with fence type obstacles in their square chamber also induced a higher velocity as the flame front passed through the obstacle. It was also observed that the flame accelerated, then decelerated once past the obstacle, and then accelerated again.

Using OH-PLIF technology, they compared the topography of the flame with simulations, and found that the wrinkling in the simulations were too strong. This might have been due to neglect of the 3<sup>rd</sup> dimension of the chamber.

[3]

### 2.1.4 Na'inna, A.M., H.N. Phylaktou, and G.E. Andrews

In the article “the acceleration of flames in tube explosions with two obstacles as a function of the obstacle separation distance”, the topic explored was at which distance between two obstacles, would the explosions in the experiments be most severe. The combustible used was methane. Used in the experiment was a pipe, with two obstacles installed, with changeable distance.

Through this thesis it was found that the most severe explosions occurred at 1.75 meters, where the flame speed reached 500 m/s and there was a overpressure of 3 bar. With 2.75 meters between them, these values were halved.

[4]

## 2.2 The effect of Area on flame speed

The purpose of this thesis is to explore the changes to the flame front area over time, when a flame passes over an obstacle. The flame front is the area in front of the flame as it propagates. The changes in the flame front is an important aspect of the flame propagation, and the reason for this is that the flame is assumed to propagate uniformly across its area, at a certain rate. If the flame has a larger area to propagate over, the flame will consume fuel faster, creating a larger amount of energy, heat, and will get a larger increase in velocity over time.

### 2.2.1 Conservance of mass

The size of the flame front area is important to know because of its effects on the velocity of the flame. This effect can be proven if simplified to the conservance of mass, seen in formula 2.1, and formula 2.2. From formula 2.2 it can be seen that if the area of the flame front ( $A_u$ ) significantly increases, compared to the area far enough behind the flame front to be equal to the cross section of the chamber ( $A_b$ ) then the speed at which the burnt mixture moves at ( $u_b$ ) is increased.

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$$\rho_u * u_u * A_u = \rho_b * u_b * A_b \quad (2.1)$$

$$u_b = \frac{\rho_u * u_u * A_u}{\rho_b * A_b} \quad (2.2)$$

### 2.2.1.1 Steady state

In this thesis, the area of the flame front is found through experiments and gets scaled to the cross section of the area. Further scaling is done with the conservance of mass in mind. Formula 2.4 shows the value of

Figure 2.1 shows the further simplified steady state combustion, where the flame front doesn't move, the unburnt mixture flows into the flame front at an  $S$  velocity, and  $u_b$  is a function of the velocity of the unburnt mixture, and the difference in density for the burnt, and unburnt mixture.

$$\rho_b * u_b = S * \rho_u \quad (2.3)$$

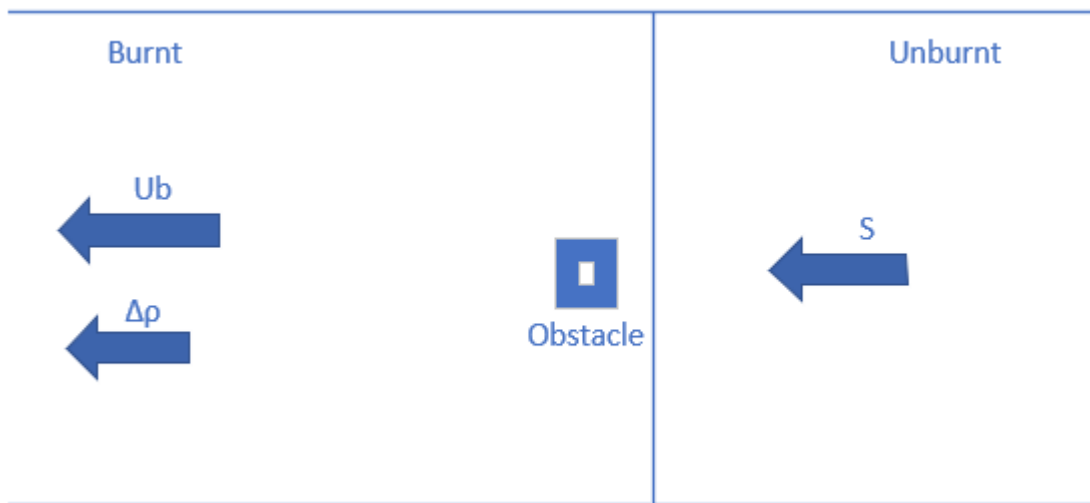


Figure 2-1 Steady state combustion in a chamber, where the flame front represented by the line doesn't move. The velocity of the unburnt mixture ( $U_b$ ) is then defined by formula 2.4 as seen below.

$$u_b = S * \frac{\rho_u}{\rho_b} = S * \sigma \quad (2.4)$$

### 2.2.1.2 Actual conditions

In the present thesis however, the flame is not set in 1 position. The chamber is closed off on the ignition side, before it is ignited, and the flame moves outwards towards the opening of the chamber into fresh air. This means the exhaust stays in its position, while the flame moves towards the unburnt mixture. As the mixture is burnt, the exhausts density reduced compared to the unburnt mixture, due to the change in temperature. As the ignition point is closed, the increased volume in the exhaust needs to displace something, which means the flame front, and unburnt mixture is pushed out of the chamber. This makes the velocity of the unburnt mixture 0. To show this in vectors, every part of interest is compensated for the change in velocity for the unburnt mixture, by adding a  $u_b$  vector to the burnt mixture, the flame front, and the unburnt mixture. That gives us the resulting vectors for the chamber in figure 2-2.

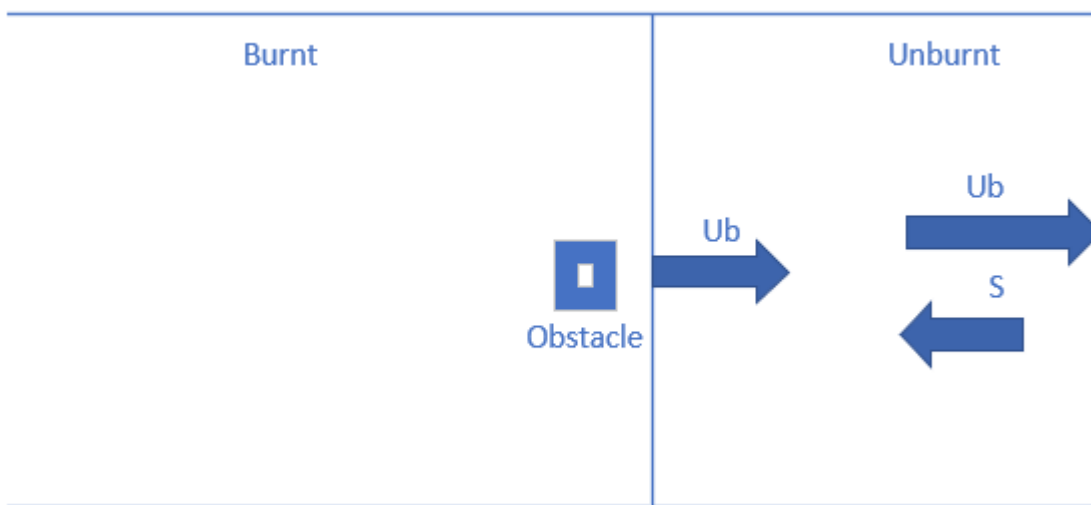


Figure 2-2 Combustion when the flame front is moving, and the burnt mixture is locked in position due to a closed off wall. The velocity of the unburnt mixture is then added to all points, giving the situation seen in this figure.

The velocity of the unburnt mixture is then expressed by formula 2.5.

$$u_u = u_b - S = S * \sigma - S = S(\sigma - 1) \quad (2.5)$$

### 2.2.2 Flame wrinkling

Some of the ways to increase the area for the flame front is flame wrinkling, or how it's done during the experiments in this thesis, through installing an object that blocks the flow, creating a larger area for the flame to propagate into once past the object and burns into the wake of the obstacle. It can also be expected in the latter case for there to be large eddies to further expand the flame front area.

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Flame wrinkling is the name for when the flame front distorts, and changes shape. The change of shape makes it so that the front gets creases in it, or more aptly described – wrinkles. Figure 2-3 illustrates what flame wrinkles look like. The flame wrinkles increase the effective area ( $A_{\text{eff}}$ ) of the flame front, allowing the flame to propagate across a larger area increasing the acceleration of the flame.

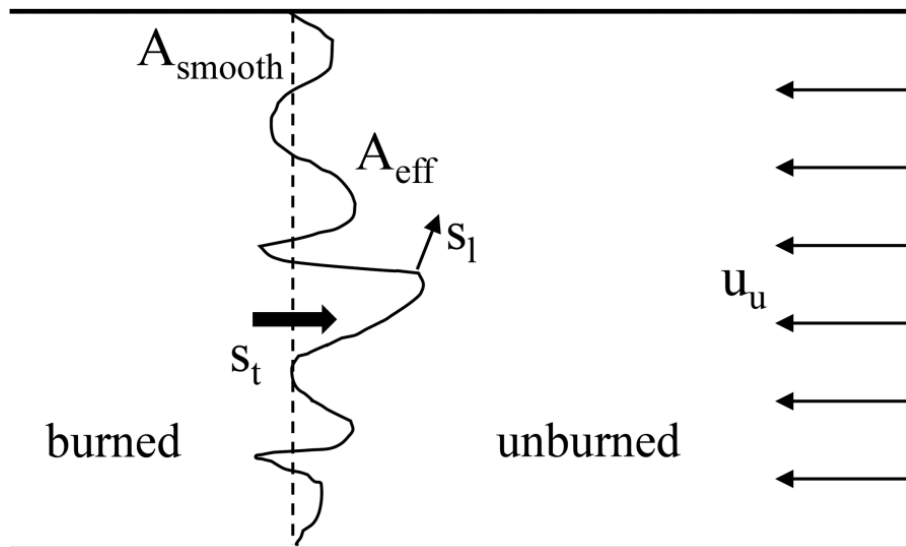


Figure 2-3 Illustration of what a wrinkled flame front would look like, where  $A_{\text{eff}}$  is the wrinkled flame front area [5]

Flame wrinkles occur when there are chaotic changes in the velocity and pressure in a flow, creating disturbances in the flame front, distorting it into creases. The main cause of flame wrinkling is turbulent conditions during the combustion. Turbulent conditions is achieved when the Reynolds number becomes turbulent, either by the size of the largest eddies being significantly larger than the flame thickness, or the velocity of the eddies being higher than the laminar flame speed. To enter the wrinkled domain of turbulent combustion however, the velocity of the eddies can not be higher than the flame speed. For there to be wrinkles, the size of the largest eddie will need to be significantly larger than the flame thickness.

In the experiments in this thesis, it is assumed that in the wake of the obstacle, the size of the largest eddies will be larger than the flame thickness, although the flame thickness is not something that will be measured. So although the velocity of the eddies are assumed to be too slow for them to cause turbulence on their own, it is assumed that the size of the eddies after the flame will be large enough for the system to approach turbulent conditions temporarily after the obstacle. This might cause some wrinkling, which would increase the area, and thusly increase the acceleration of the system.

[6, 7]

## 2.3 The effect of turbulence on Area

It is a well-known fact that turbulence affects the flame front area. [2] Borghi tried to explain this with a graph, named after him as the Borghi diagram, as shown in figure 2-4. The Borghi diagram shows the relationship between the ratio of the velocity of the rotation of eddies, over the laminar flame speed on the y axis, while it shows the largest turbulence size (The size of the largest eddies), over the flame thickness on the x-axis. Both of these ratios can be considered as a factor in the turbulent Reynolds number. Thereby if the value of each axis is higher, the turbulent Reynolds number is higher. This in turn means that increasing either of these values, would increase the instabilities in the flame front, which would in turn make some changes to it. Either by distorting the flame front so it stretches, or causing enough turbulence to cause wrinkles, or even a corrugated flamelets.

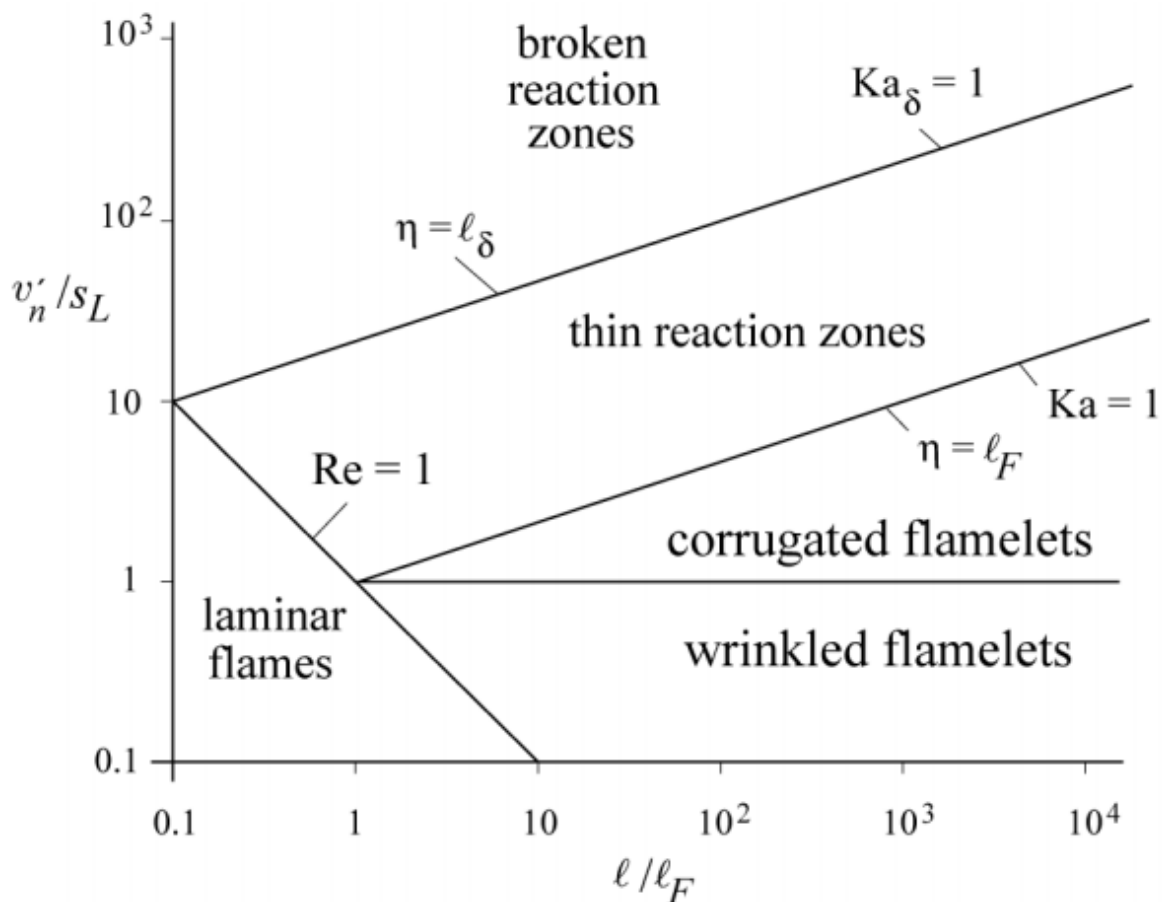


Figure 2-4 Borghi diagram, describing the regimes in turbulent combustion, where  $u'_n$  is the velocity at which the eddies turn,  $S_L$  is the laminar burning velocity.  $l$  is the size of the largest eddie, and  $l_F$  is the thickness of the flame front [8]

Through 2 turbulent Karlovitz numbers and Reynolds number, the diagram is defined into regimes for the turbulent combustion. The first line, which is when  $Ka = 1$ , defines the change from a corrugated flamelets condition to a thin reaction zone. Corrugated flamelets meaning sparks are thrown ahead of the flame front and start burning in front of it.

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## 2 Literature Study

If  $Ka_{\text{delta}}$  is above 1, then you have broken reaction zones, meaning that the chamber is burning everywhere at the same time.

If  $u'/S_L$  is higher than 1, then flamelets start to appear. Below it, but with Reynolds number higher than 1, you get a wrinkled system due to the turbulences being slower, than the flame speed, but the size of the largest eddies being thicker than the flame thickness.

The size, and amount of wrinkles are also affected by the  $u'_n/S_L$ . [9]

In the experiments done during this thesis, although the conditions are expected to initially be laminar, the obstacle is assumed to distort the flame front, and cause large eddies that stretch longer than the flame thickness by quite an amount. This makes it possible for the combustion to enter turbulent conditions, and the wrinkled regime.

It is however not expected for the velocity of the eddies after the obstacle to be larger than the laminar burning velocity. It is therefore not expected for the combustion to enter the corrugated flamelet regime.

[7-13]

# 3 Experiments

This chapter will explain the experimental setup, and what methods are used to reach the goals of this thesis.

## 3.1 Experimental setup

### 3.1.1 Combustion chamber

The combustion chamber is 700 mm long, has a width, and height of 48 mm. The obstacle is placed 100 mm into the chamber, while the ignition is placed 25 mm in. The chamber is made from polycarbonate walls, and aluminium beams.

### 3.1.2 Control board

The control board has the switch controlling the direction of the flow on the rig. The flow has two valves controlling the direction, with 1 of them being into the combustion chamber, and the other going into bypass. By flipping the switch seen on the control board on figure ... the direction of the flow is changed. The switch controls a 5/2 pneumatic valve that sends the pneumatic air to the 2 valves controlling the flow. Each outlet for the 5/2 valve is split into 2 directions, going to the 2 valves on the rig. Each of the 2 outlets close 1 valve and opens the other. The switch is labeled on, and off, to signify whether the flow into the chamber is on or off. The pneumatic pressure to control the valves is supplied by the pneumatic air system in the lab, and is regulated to 5 bar pressure, to make sure the valves open, and close as intended.



Figure 3-1 Control board. Controls the flow of hydrogen, and whether the flow goes into the combustion chamber, or the bypass into the ventilation

#### 3.1.2.1 Hydrogen Rotameter

The control board also has the rotameter used to measure the hydrogen flow in the rig. The rotameter has numbered values and is calibrated to fit the given pressure of the hydrogen going into the system.



### 3.1.3 Coriolis flowmeter

The flow of the air is measured by a Coriolis flowmeter. The flowmeter measures the mass flow of air by grams per second. The air measured is supplied by a local compressor.

### 3.1.4 Seeder

A seeder is used to disperse water into the air going into the chamber. These droplets dispersed into the flow is then what reflects the light caused by the laser, and is what causes there to be a front in the video caught by the camera, as the areas where the combustion has occurred, the water has been evaporated, while in the areas where the flame hasn't moved in yet, the droplets are still there. [14]

### 3.1.5 Laser

The laser used throughout this thesis is a class 4 firefly laser made by oxford lasers. The laser can be adjusted in several ways. First and foremost is laser thickness which decide the thickness of the laser sheet that illuminates the droplets that is recorded by the camera. A thicker laser that focuses on area illumination would pick up more water particles and makes it more difficult to differentiate between particles. It does however give a clearer picture of the flame front. A thin laser sheet would make it easier to track the movement of single water particle. Other factors that can be adjusted with the laser is the time between bursts (which is remotely controlled by the computer, by setting a wanted frame rate for the camera). The amount of pulses in each burst, and the duration of the burst. It is also possible to set a delay, to time when you want the laser to start pulsing in frame.

These things make it a versatile laser, that can be adjusted for many purposes.

While operating the laser it is important to never expose skin to the laser, and always wear laser proof goggles to prevent injury to the eyes.



### 3.1.6 Camera

The camera used in this experiment is the PHOTRON FASTCAM SA-Z. It is a highspeed camera that can record videos at a very high shutter rate. It uses the software Photron Fastcam Viewer to modify the camera settings, and record the video.

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### 3.1.7 Trigger

The trigger used consists of 3 parts. The trigger itself, a power supply to power it, and a button that enables to power to reach the trigger. The power supply delivers 5 volts. It connects through cables to both the camera, and the ignition. Once camera is prepped to record, and the trigger button is hit, 5 volts is sent to the ignition and the camera, which triggers the recording, and ignites the mixture in the chamber.

## 3.2 Preparation

To do experiments, some preparatory work is necessary. This includes calibrating the flow meters for the hydrogen, as well as adjusting the laser and camera to make sure every part of the picture is properly lighted, so that MATLAB can pick up the flame front from the frames.

### 3.2.1 Calibration

The flowmeter that adjusts the flow of hydrogen into the system is a rotameter. This rotameter has set numbers, and each of these numbers need to be calibrated to the flow of hydrogen at the set pressure. To do this, a drum type flow meter is used. The drum type flow meter rotates a clock, and the one seen in the picture below, is a 10-liter drum. For every 10 liters of gas that passes through the drum, the clock rotates once. To calibrate using this, you take the time for how long it takes for the clock to rotate 10 times. This signifies that 100 liters passed through the rotameter, and that can be divided by the time used to find the volume flow of the hydrogen through the rotameter. Table 3-1 shows the volume flow through the rotameter at the given pressure.



Figure 3-2 Drum-type flowmeter used to calibrate the rotameter used in the experiments

Table 3-1 Flow rate through rotameter at 2.3 bar absolute pressure.

Rotameter #	Time	Flow[l/s]
8	34 minutes, 30 seconds	0,048
9	29 minutes, 5 seconds	0,057
10	25 minutes, 20,6 seconds	0,066
11	22 minutes, 28,5 seconds	0,0741
12	20 minutes, 24 seconds	0,0816

The flow through the drum type flow meter is at 2.3 bar absolute pressure. The value of air is measured with a Coriolis mass flow meter, and then changed to volume flow through the density at 1 bar. This gives a disparity in the value between the value in the air, and hydrogen flow. To compensate for this, the hydrogen is adjusted as seen in formula.

$$\dot{V}_{H_2, 1 \text{ bar}} = \frac{\dot{V}_{H_2, 2.3 \text{ bar}}}{\rho_{H_2, 1 \text{ bar}}} \rho_{H_2, 2.3 \text{ bar}} \quad (3.1)$$

Assuming 0°C in the chamber, the density values for hydrogen is found by interpolating the values found in the excel sheet for hydrogen densities at hydrogen tools. [15]

### 3.2.2 Adjusting picture

The camera and laser need to be adjusted. Initially, the frame desired in this project was of the entire height of the chamber, to capture the entire flame propagation. Capturing the whole chamber however turned out to not be possible due to the shade cast by the obstacle. The shade caused the code to be unable to follow the flame front, which can be seen in figure 3-3, as well as the laser being unable to light up the whole frame. Several adjustments had to be made to the frame, amongst others zooming in to prevent the edges from being too dark for the code to be able to read it, as well as changing the resolution to capture only the top half of the chamber instead of the entire thing due to the shade.

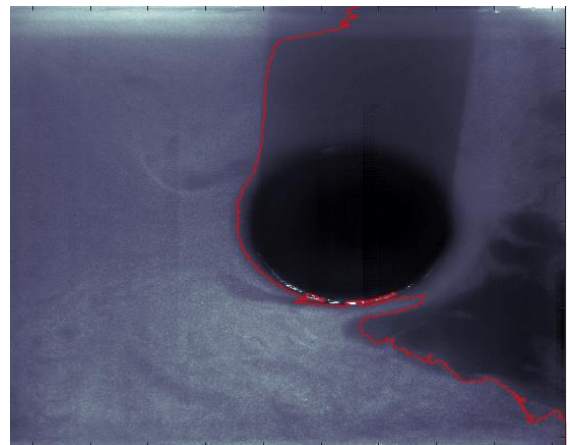


Figure 3-3 Code being unable to follow the flame front due to the shade cast by the obstacle

#### 3.2.2.1 Camera

As mentioned earlier, initially the frame covered the entire height of the combustion chamber. Adjustments were made through trial and error, finding that the code used in the

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thesis could not track through the shade of the obstacle. The camera settings were then adjusted so that the frame only covered the top of the obstacle, and what's above it, and zoomed in significantly, while adjusting the frame from 1024x1024 pixels to 1024x720 pixels to get as much of the length of the chamber as possible, while only getting the top of the chamber.

### 3.2.2.2 Laser

The laser settings used in the experiments had to be adjusted to make sure that the pulses of the laser always happened at the same time in the frames of the video to make sure all the frames were similarly lighted.

The parameters that were adjustable were

- Frame rate (which was given from the camera)
  - Gives the time each frame lasts.
- Duration
  - Gives the duration of the pulse. Longer duration means brighter images but is limited at a max value based on the frame rate to prevent laser from always being on.
- Amount of pulses
  - Decides the amount of pulses in each burst of pulses
- Separation
  - Time between each burst of pulses
- Delay
  - Initial delay before pulses start firing. Used to decide at which point in the frame the pulse occurs
- Thickness of laser

The settings for the laser were constant throughout the experiments performed in this thesis and were as follows

- Framerate at 10000 – Each frame being 10  $\mu$ s
- 1 pulse each burst
- Duration at 1  $\mu$ s
- Separation at 9  $\mu$ s
- Delay at 5  $\mu$ s
- Thickness of laser being slightly thick as there is no need to track individual particles

### 3.2.3 Air to hydrogen ratio calculations

There are some difficulties with calculating the ratio between air and hydrogen, as the equipment used to measure air and hydrogen gives two different types of measurements. Air gets measured in mass flow, while hydrogen gets measured in volume flow, which is impacted by the pressure.

Calculations are then needed to first calculate the needed volume flow of air at 1 bar, to then convert it into mass flow.

To be able to find the needed volume of air at 1 bar however, the volume flow for the

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### 3 Experiments

hydrogen at 1 bar needs to be figured out first, as the calibrated values of hydrogen for the rotameter were at 2.3 bars. This is done through formula 3.1.

The needed air volume flow is then found out through the wanted concentration, and flow of hydrogen through formula 3.2.

$$\dot{V}_{air, 1 bar} = \dot{V}_{H_2, 1 bar} * \left( \frac{1}{vol\%H_2} - 1 \right) \quad (3.2)$$

Once the volume flow of air at 1 bar is found, it is possible to convert this to mass flow of air through its density. The resulting mass flow is then what the flow through the Coriolis flow meter needs to be.

## 3.3 Experimental Procedure

The experiment has two phases. Preparatory work, and the execution of the experiments. The preparatory work consists of things done prior to each experiment to make sure it has the right parameters, and that it is safe to perform the experiment.

### 3.3.1 Preparation

To prepare for an experiment there are some vital points that need to be done/checked.

- Is the compressor for the pneumatic air system on?
- Connect the valve system to the air supply, and adjust it to 5 bars
- Are the valves turning?
- Turn on the ventilation system, and make sure it functions by hovering a hand over the inlet.
- Turn on air compressor and adjust to the wanted pressure. Which is 5 bars in this thesis
- Test that the ignition is working, and whether it triggers the camera
- Test the laser to make sure it functions, and make sure the settings are correct. (Make sure to wear laser proof goggles)
- Clear the system with hydrogen to prevent oxygen from being in the hoses.
- Adjust the air, and hydrogen to the previously calculated values for the given experiment

### 3.3.2 Execution

Execution of the experiment is rather simple. Most importantly, safety first. Make sure all necessary safety precautions are taken. At this point, all actions done should be behind a safety wall, while wearing laser proof goggles.

Open the hydrogen into the system, and make sure the concentration is as wanted through the rotameter, and Coriolis flow meter. Once certain, open the flow into the chamber, and start the recording on the camera. The camera is then ready to be triggered, to start filming. After waiting approximately 30 seconds, flip the switch for flow direction into bypass, and trigger the ignition. After triggering the ignition, instantly turn of the hydrogen supply to prevent the warm air in the ventilation system from igniting the hydrogen in the bypass hose. Decide the frames that is wanted from the film and download it from the camera.

## 3.4 Data extraction

The data extraction is done by a code written in MATLAB that prepares the image to make it more easily handled, creates a boundary around the largest

### 3.4.1 Image preparation

MATLAB is used to make a black/white version of the image. The process consists of a smoothing of the peaks of light in picture, by making every cell the same height of its highest value neighboring cell. Through this process peaks are smoothed out, and thresholds between the black/white is made clearer.

The optimal grey threshold is found through the `greythresh` command and is implemented as the value at which the cell is considered black, or white. A line is then made between cells that are on different sides of this value with the command `bwboundaries`.

### 3.4.2 Making the area boundary

The line produced by the command `bwboundaries` is then further limited from a min to a max point in the matrix, by manually selecting the starting point, and ending point in each frame. These manual points are put in matrixes for each unique experiment and called upon to make the boundary called `ContX`, and `ContY`.

These starting points are then used to find the length of the line that's different from the initial boundary around the largest body of white cells. Using Pythagoras theorem, the distance between each point in the matrix for the area is calculated and summarized as a value for the length of the line that surrounds the flame front of interest.

The length of the flame front is then scaled to the length of the chamber in millimeters, and with the assumption that the flame front is uniform in the z-direction, the area is calculated with the width of the chamber.

The change in area over time is then calculated by subtracting the previous area from the new area. This change in area is then plotted to compare different results, before it is further developed by making the change independent of the cross-section area of the channel, and the concentration of the mixture, by making it independent of the laminar velocity of certain concentrations.

The position of the flame front is found by finding the minimum value of the boundary `ContX`

### 3.4.3 Scaling of results

Once the results have been retrieved from the code, it comes in the form of change in area per frame. This makes it rather difficult to compare results as depending on the concentrations of the experiments, different velocities will be achieved, and there will be different amounts of frames. It is also not optimal, as the change in area is only specific to the cross-section area of the frame, and the concentration of the mixture.

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### 3 Experiments

First the change in area is calculated by the code is scaled to the cross section of the area by dividing it by the cross section of the area, making it change per second. This can be seen in formula 3.3. It can then be scaled back up to the size of the chamber used to get an approximation of the area change in the given chamber.

$$\frac{dA}{dt} \left[ \frac{m^2}{s} \right] \rightarrow \frac{dA}{dt} * \frac{1}{A_{Cross-section}} = \frac{d}{dt} [/s] \quad (3.3)$$

Afterwards, the change per second is scaled to the concentration of the mixture. This is done by scaling it by the velocity of the unburnt mixture, which was expressed in formula 2.5. This requires the laminar burning velocity ( $S_L$ ), and the relative densities ( $\sigma$ ) of the burnt, and unburnt mixtures, for the respective concentrations of hydrogen. This gives the following expression found in formula 3.4

$$\frac{d}{dt} [/s] = \frac{d}{dt} * \frac{1}{S(\sigma-1)} [/m] \quad (3.4)$$

This will give the expression change per meter. To do this however, the values provided by Mathias Henriksen in table 3-2 needs to be adjusted through linear interpolation to reflect the concentrations used in the experiments in this thesis. The values have been interpolated for each experiment in table 3-3.



### 3 Experiments

Table 3-2 Relative density ( $\sigma$ ) and laminar burning velocity values at given fuel-air equivalence ratio ( $\Phi$ ) provided by Mathias Henriksen, where the  $\sigma$  is the density of the burnt mixture, over the density of the unburnt mixture. ( $\rho_b/\rho_{ub}$ )

$\Phi$	$\sigma$	$S_L$ [m/s]
0,2499	0,297	0,0014
0,2589	0,2914	0,0019
0,2679	0,2856	0,0029
0,2768	0,2806	0,0042
0,2858	0,2759	0,0065
0,2947	0,2707	0,0108
0,3037	0,2671	0,0154
0,3127	0,2637	0,0211
0,3216	0,2597	0,0291
0,3306	0,2548	0,0408
0,3395	0,2508	0,0526
0,3485	0,2474	0,0638
0,3575	0,244	0,0766
0,3664	0,241	0,09
0,3754	0,238	0,1042
0,3843	0,2353	0,1184
0,3933	0,2321	0,1358
0,4023	0,2291	0,1538
0,4112	0,2262	0,1732
0,4202	0,2235	0,193

### 3 Experiments

Table 3-3 Interpolated values for density ratio ( $\sigma$ ), and laminar burning velocity ( $S_L$ ), based on the fuel-air equivalence ratio ( $\Phi$ ), used to scale the results to be per meter, where the  $\sigma$  is the density of the burnt mixture, over the density of the unburnt mixture. ( $\rho_b/\rho_{ub}$ )

Experiment #	$\Phi$	$\sigma$	$S_L$ [m/s]
2,3	0,2500	0,2969	0,0014
8	0,2989	0,2690	0,0129
11,12,14,15	0,3240	0,2584	0,0322
16,17,19,20	0,3570	0,2442	0,0759
21,22,23,24	0,3915	0,2327	0,1323
28	0,2590	0,2707	0,0109
30,31	0,2880	0,2671	0,0155

### 3.5 Choice of experiments

Throughout this thesis, a total of 31 experiments, ranging a concentration of 9.6%, to 14,4% hydrogen in the mixture. Not all these experiments yielded viable footage for the code used to extract data. In some cases, the code couldn't follow the flame front. Other times, the code found flame fronts where there were none. Dew forming around the obstacle and reflecting light from the laser also caused some issues. Some experiments were simply poorly lit, or the reflection on the obstacle was so bright that the rest of the frames got too dark in comparison, and the code couldn't pick up the flame front as a result. Throughout all these challenges, 17 experiments are viable to be used. These experiments can be seen in table 3-4.

### 3 Experiments

Table 3-4 Viable experiments, and their concentration of hydrogen and  $\Phi$

Experiment #	Concentration [vol%]	$\Phi$
2	9.68	0.25
3	9.68	0.25
8	11.36	0.2989
11	12.2	0.342
14	12.2	0.342
15	12.2	0.342
16	13.28	0.357
17	13.28	0.357
19	13.28	0.357
20	13.28	0.357
21	14.36	0.3915
22	14.36	0.3915
23	14.36	0.3915
24	14.36	0.3915
28	10%	0.259
30	11%	0.288
31	11%	0.288

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## 4 Results

This chapter contains figures depicting the change in area, the change per second, and the change per meter for all viable experiments done in this thesis, except two. Experiment 2, and 3, which were at 9.6% H<sub>2</sub> concentration. These experiments had extreme outlier values and were therefor removed from the results.

### 4.1 Flame front area dependent on position

Although there is a slight spread, it is possible to see that the flame front area increases in a linear manner, while slightly steeper at first, with a slight dip across the obstacle (which ends at 0 flame front position) and increases once again a bit after the obstacle. This approximately linear increase in area, should give a change in area that consistent throughout the experiment.

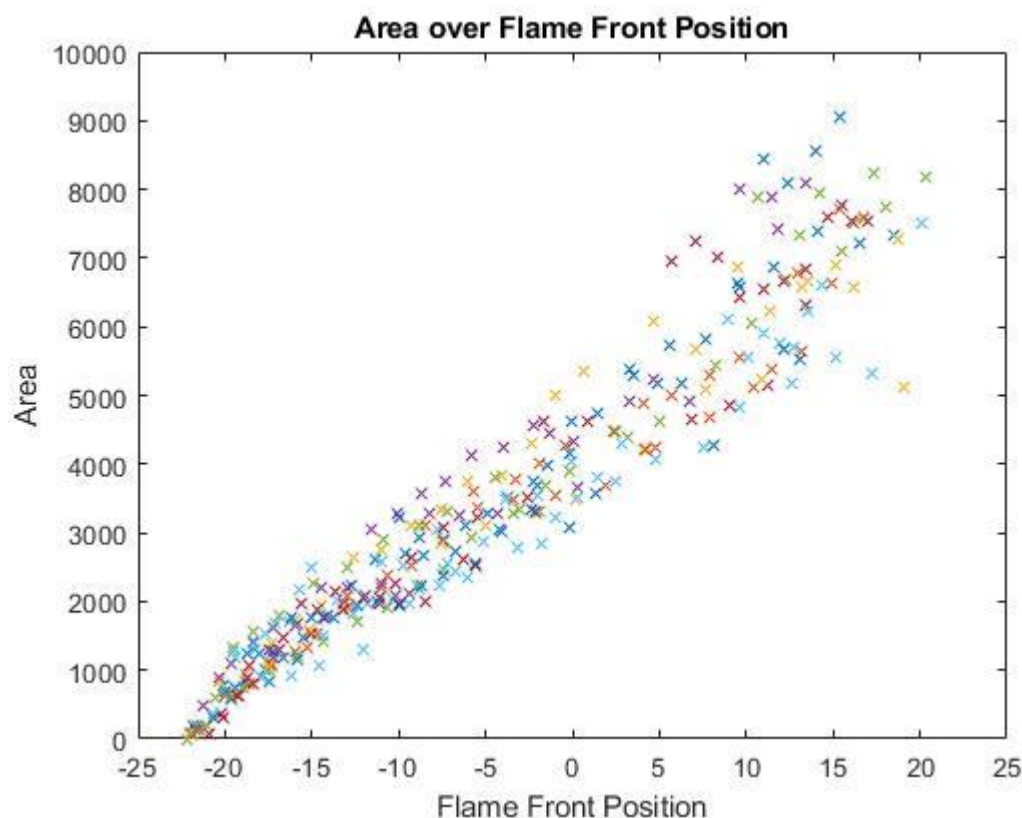


Figure 4-1 Area of the flame front, based on the position of the flame front.

## 4.2 Area Change

The actual change in area that occurs can be described in several ways. In this thesis, to make the change reflect the actual change in area, the area change is divided by the cross section of the chamber shown in the frame. This makes it possible to find the change in area for any chamber size, just by multiplying with the given chamber cross section area.

$$Change[/s] = \frac{Area_2 - Area_1}{Cross\ section\ area} \quad (4.1)$$

Another alternative is scaling the calculations according to the area in the prior frame giving the following formula 4.2. This was done in the conference paper written by Vågsæther, Gaathaug, and Bjerketvedt.[1] This gives a graph where despite the area change being similar there's an initial high value, which decreases due to the area change being unchanged, but the area size of the prior area growing larger. This would make it seem like the area change is higher initially, and starts falling off, despite the actual area change being consistent.

$$Change[/s] = \frac{Area_2 - Area_1}{Area_1} \quad (4.2)$$

### 4.2.1 Change per second

Change per second is calculated with formula 4.1 for each frame, giving the values shown in figure 4-2. The flame front position is found in chapter 3.4 and is further scaled to the size of the chamber. This means the position is in millimeters away from the end of the obstacle.

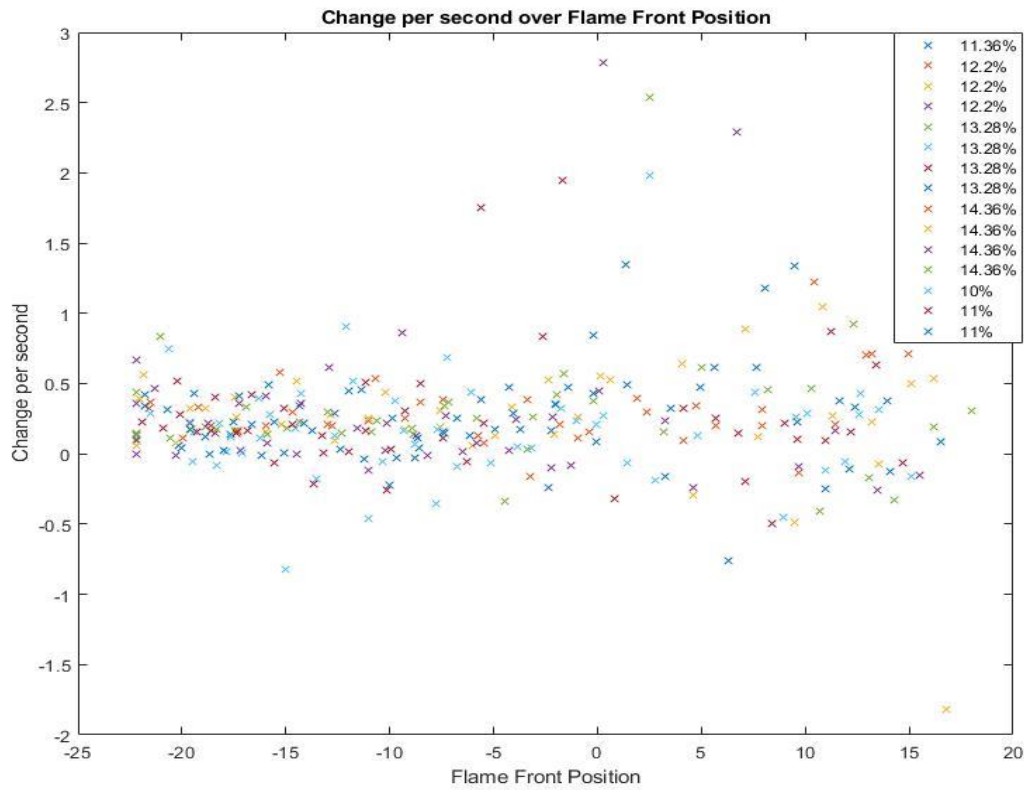


Figure 4-2 The change in area per second scaled to the size of the cross section, and dependent on the position of the flame front. The value 0 on flame front position signifies the end of the obstacle, while negative values is before, and above the obstacle.

#### 4.2.1.1 10% H<sub>2</sub> Concentration

The values gathered from the single 10vol% experiment shows ranging values between 0 and 1 s<sup>-1</sup> before the obstacle. After the obstacle, most of the values stay similar, although there were 1 peak value afterwards.

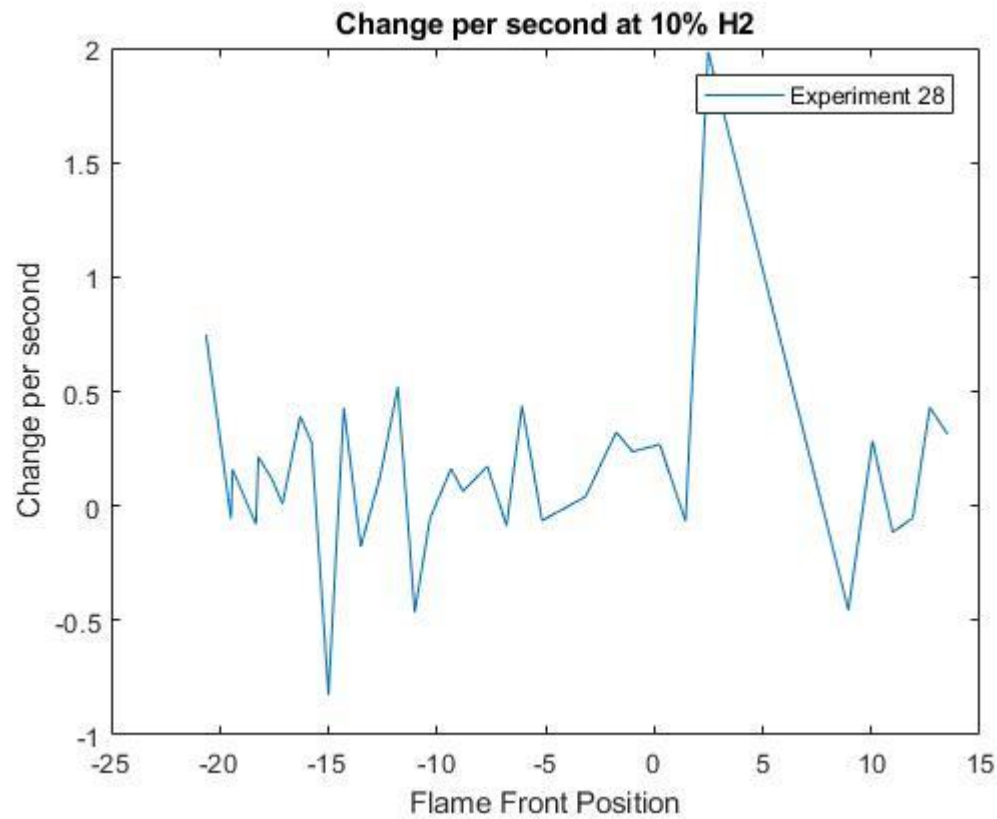


Figure 4-3 Change in area scaled to the cross-section area of the visible combustion chamber, dependent on the flame front position [mm] at 10vol% H<sub>2</sub>

#### 4.2.1.2 11% H<sub>2</sub> Concentration

In the two experiments done at 11 vol% H<sub>2</sub> the values for change per second fluctuates between 0-0.5 s<sup>-1</sup>, and starts spiking right before the flame front has passed the obstacle. Making it similar to the 10 vol% experiment.

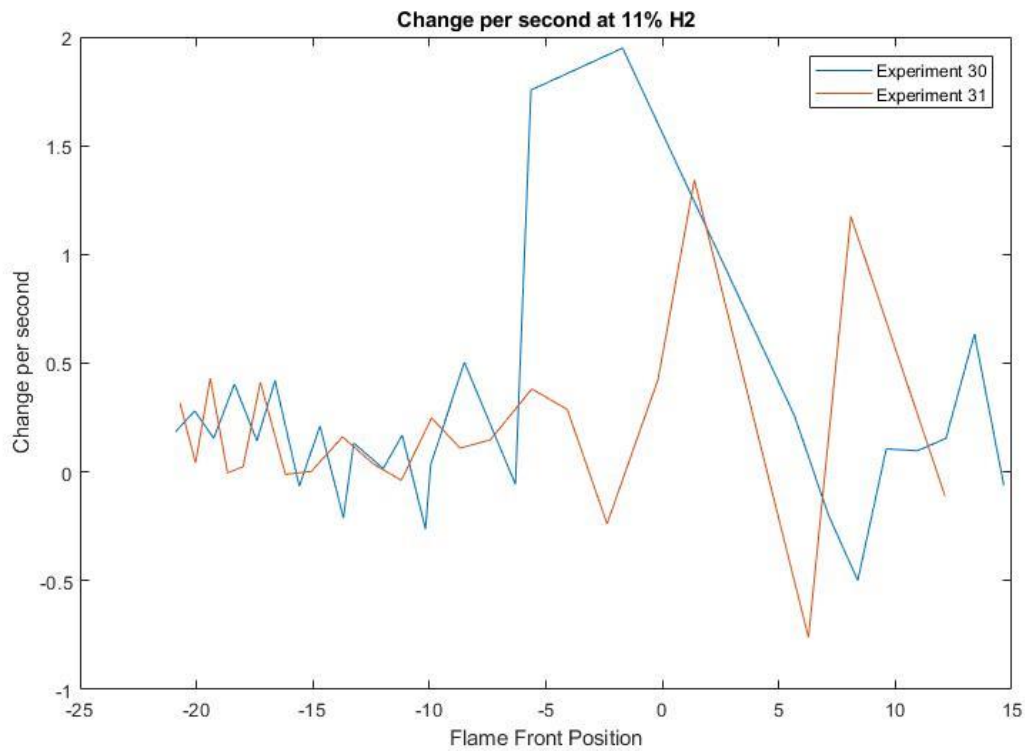


Figure 4-4 Change in area scaled to the cross-section area of the visible combustion chamber, dependent on the flame front position [mm] at 11 vol% H<sub>2</sub>



#### 4.2.1.3 11.36% H<sub>2</sub> Concentration

The experiment done at 11.36 vol% H<sub>2</sub> fluctuates between 0, and 0.5 s<sup>-1</sup> and starts spiking after the flame front has passed the obstacle.

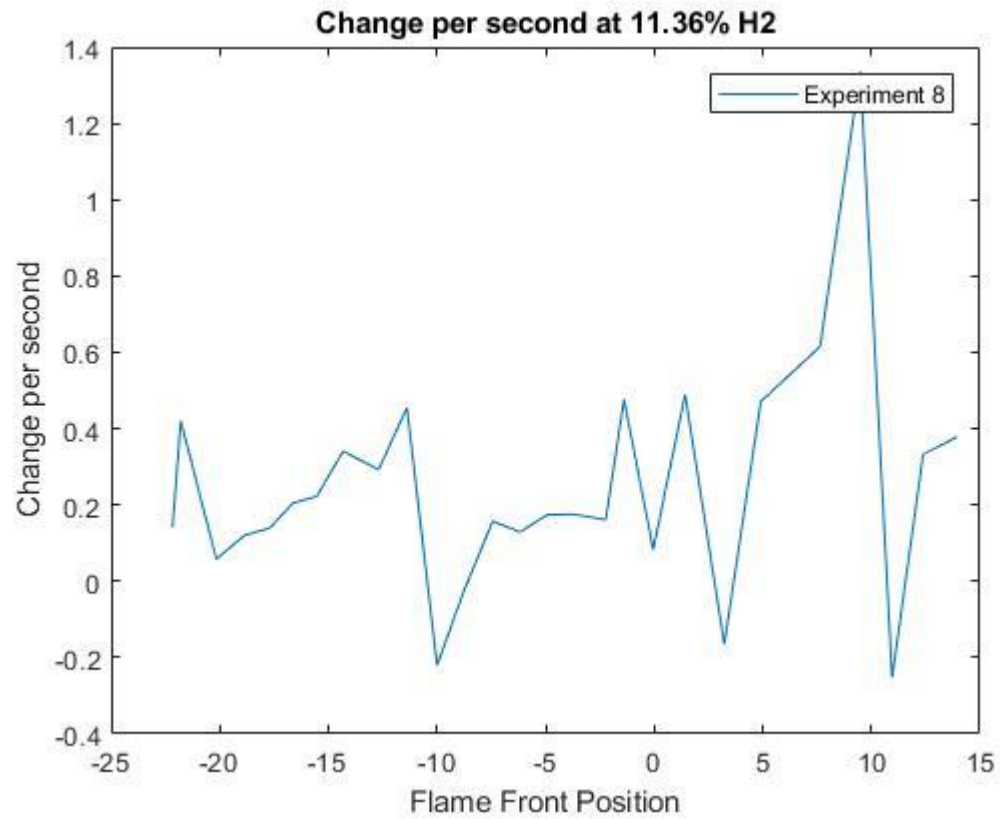


Figure 4-5 Change in area scaled to the cross-section area of the visible combustion chamber, dependent on the flame front position [mm] at 11.36vol% H<sub>2</sub>

#### 4.2.1.4 12.2% H<sub>2</sub> Concentration

The 3 experiments done at 12.2 vol% H<sub>2</sub> fluctuates between 0, and 0.6 s<sup>-1</sup>, and gets slightly higher values after the obstacle, as well as some spikes.

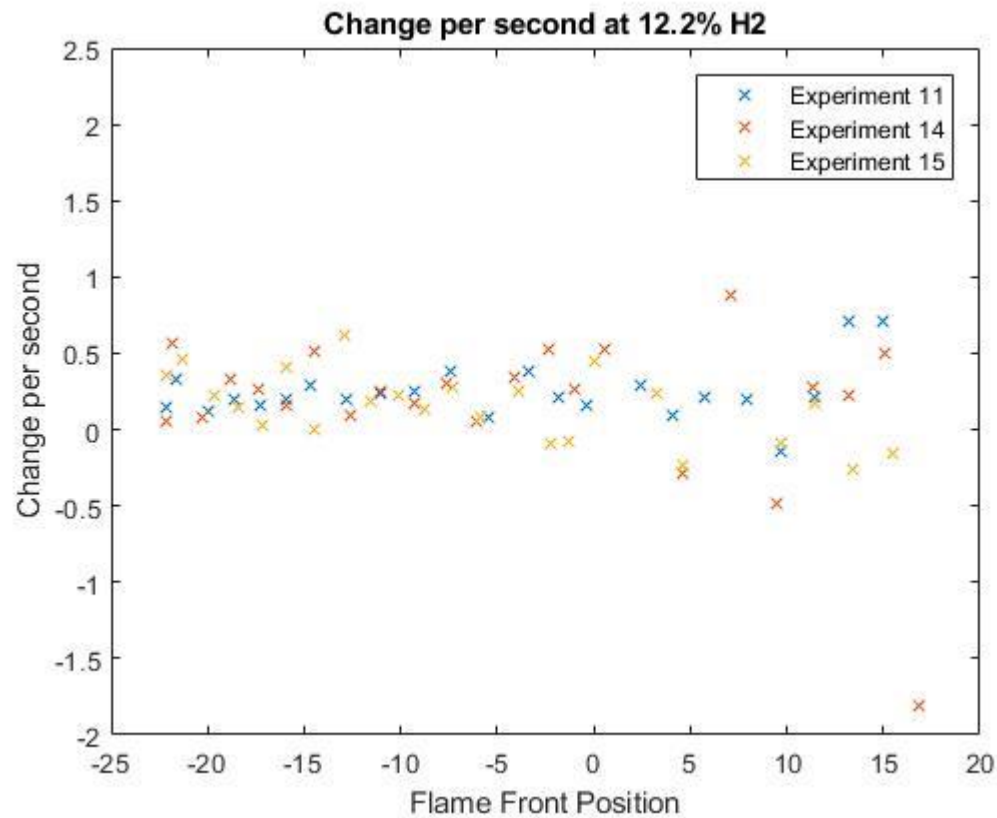


Figure 4-6 Change in area scaled to the cross-section area of the visible combustion chamber, dependent on the flame front position [mm] at 12.2vol% H<sub>2</sub>

#### 4.2.1.5 13.28% H<sub>2</sub> concentration

For the four experiments done at 13.28 vol% H<sub>2</sub> most of the values before the flame front has gotten past the obstacle has is between 0, and 0.5 s<sup>-1</sup>. After the obstacle, slightly higher values, as well as some spikes occur.

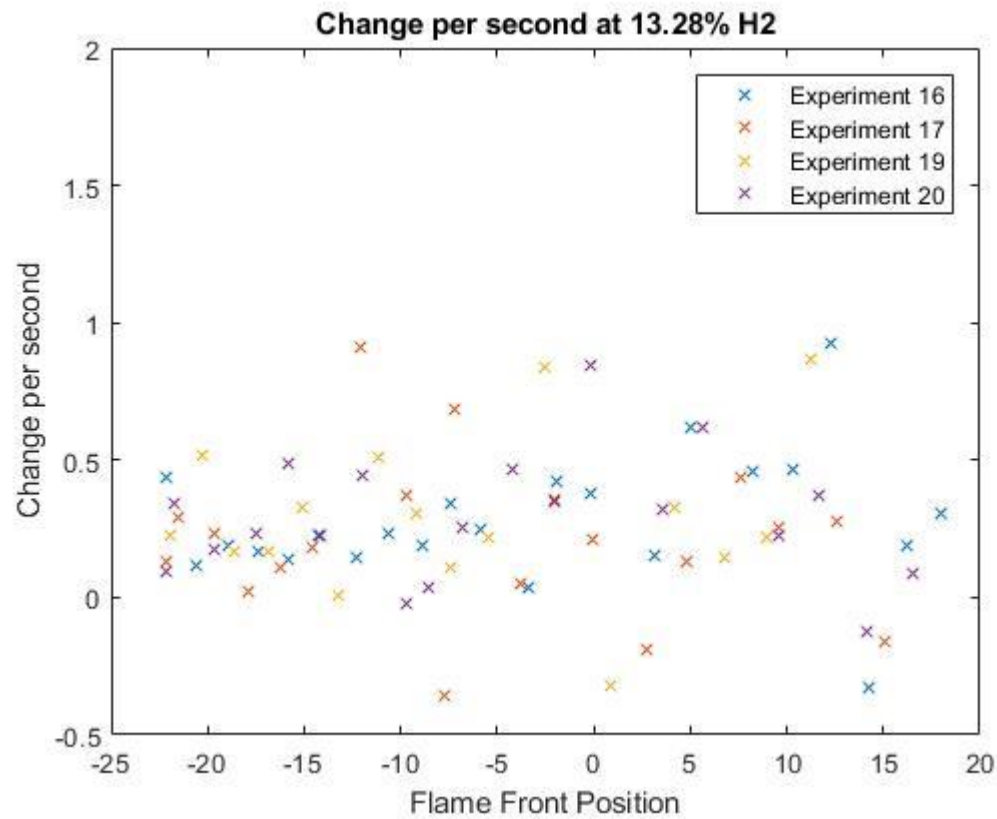


Figure 4-7 Change in area scaled to the cross-section area of the visible combustion chamber, dependent on the flame front position [mm] at 13.28vol% H<sub>2</sub>

#### 4.2.1.6 14.36% H<sub>2</sub> concentration

The four experiments at 14.36 vol% H<sub>2</sub> has most of the values before the obstacle are found to be between 0, to 0.6 s<sup>-1</sup>. Some values that are higher does however occur. After the obstacle, spikes occur, as well as there being slightly higher values in general.

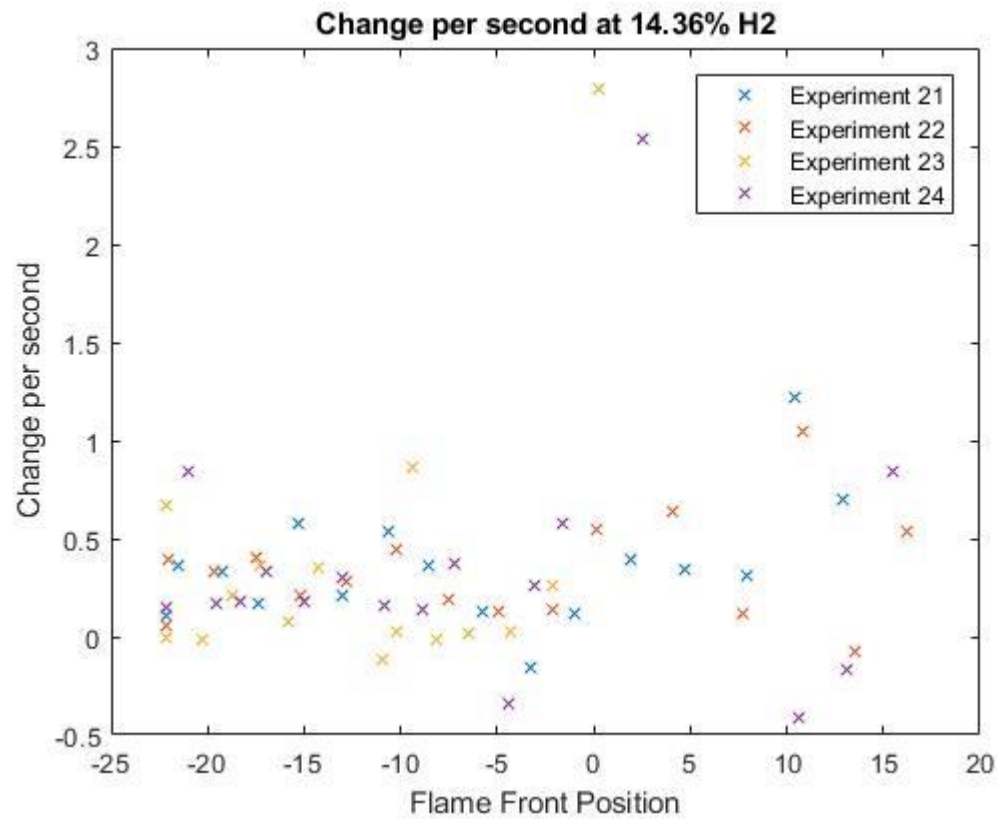


Figure 4-8 Change in area scaled to the cross-section area of the visible combustion chamber, dependent on the flame front position [mm] at 14.36vol% H<sub>2</sub>

### 4.2.2 Change per meter

The change per meter is achieved by scaling the change in area on the cross-section area of the visible part of the combustion chamber, and on the burning velocity of the unburned mixture,  $S$ , and the density difference between the burnt, and unburnt mixtures,  $\sigma$ , which are interpolated in chapter 3.4.

Formula 4.3 is used when scaling and is derived from the conservance of mass shown in chapter 2.2, and formula 3.4. The relative density ( $\sigma$ ) is inverted due to the provided values being lower than 1.

$$\text{Change [}/m] = \frac{\text{Change [}/s]}{(S_L * (\frac{1}{\sigma} - 1)) \left[\frac{m}{s}\right]} \quad (4.3)$$

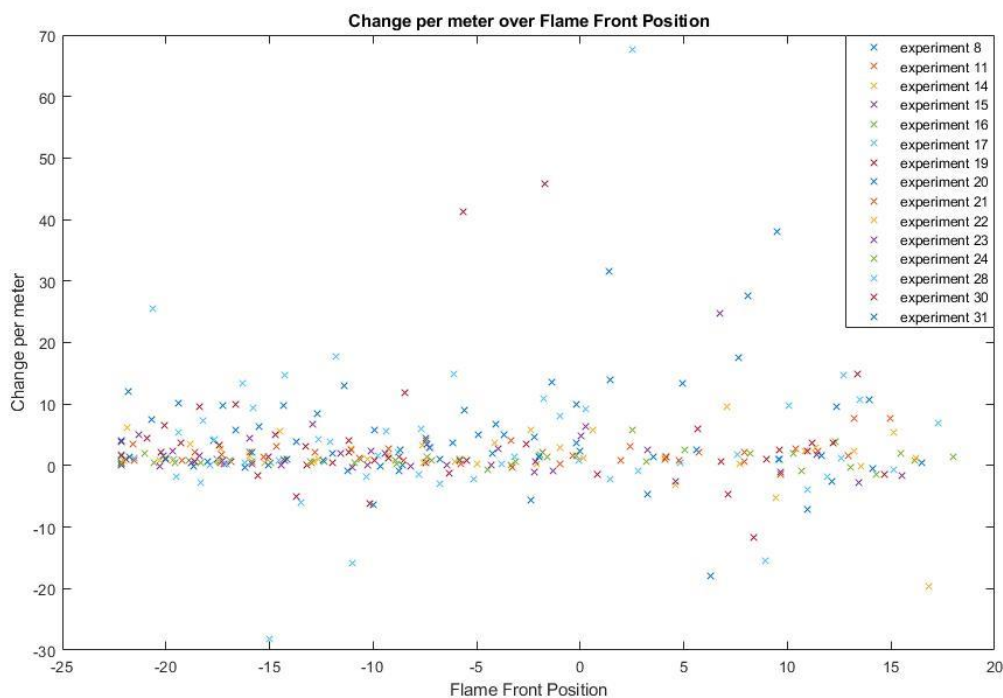


Figure 4-9 Change per meter dependent on the position of the flame front (in mm) relative to the end of the obstacle, which is set to 0.

#### 4.2.2.1 10% H<sub>2</sub> Concentration

The experiment done at 10 vol% H<sub>2</sub> ranges between 0 to 20 m<sup>-1</sup> before the obstacle, and after the obstacle the values spike once and go back to the same range.

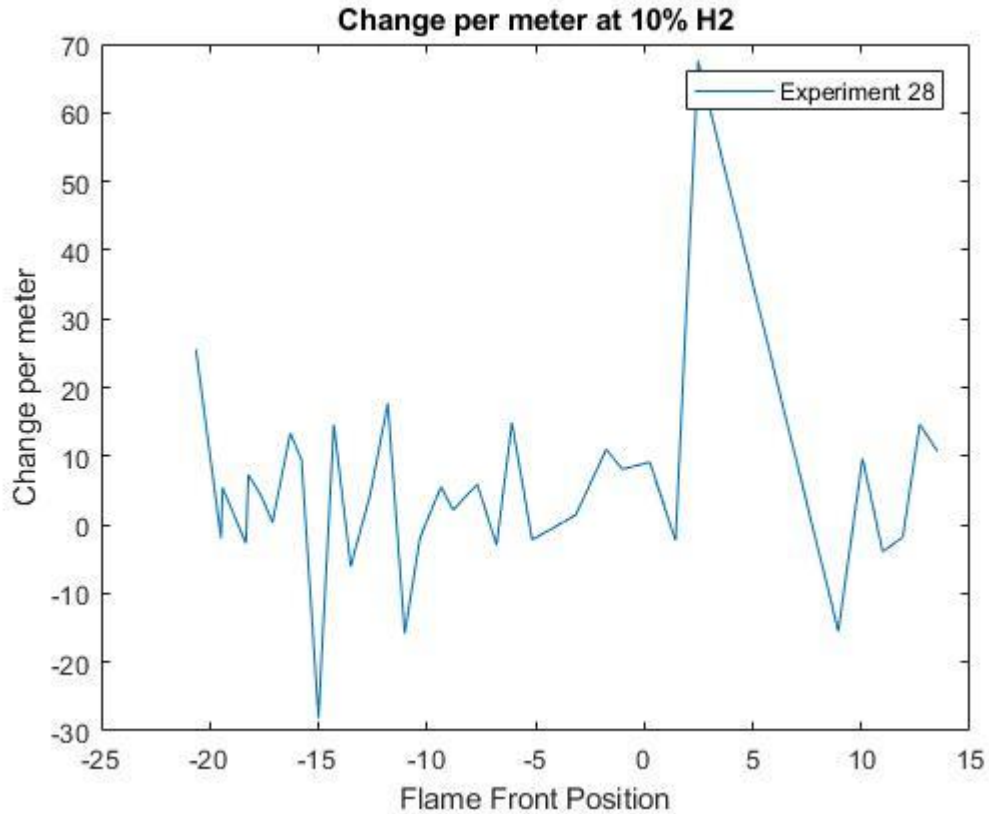


Figure 4-10 Change in area on the cross-section area of the visible part of the combustion chamber, and on the burning velocity of the unburned mixture,  $S$ , and the density difference between the burnt, and unburnt mixtures at 10vol% H<sub>2</sub>, dependent on the flame front position in mm

#### 4.2.2.2 11% H<sub>2</sub> Concentration

The two experiments done at 11 vol% H<sub>2</sub> has values before and during the obstacle that fluctuates between 0 and 10 m<sup>-1</sup>. Right before the end of the obstacle, and after, spikes in change per meter occurs.

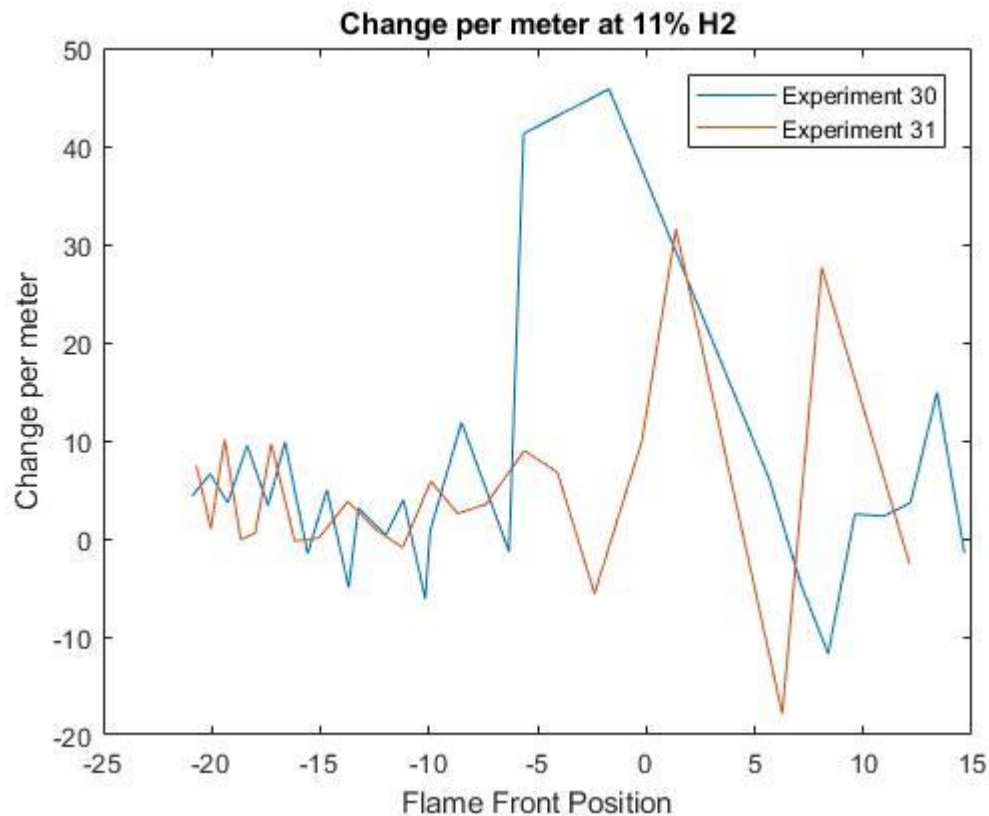


Figure 4-11 Change in area on the cross-section area of the visible part of the combustion chamber, and on the burning velocity of the unburned mixture,  $S$ , and the density difference between the burnt, and unburnt mixtures at 11 vol% H<sub>2</sub>, dependent on the flame front position in mm

#### 4.2.2.3 11.36% H<sub>2</sub> Concentration

The experiment done at 11.36 vol% H<sub>2</sub> has fluctuating values between 0 and 15 m<sup>-1</sup>, with a dip at -5 m<sup>-1</sup> before and during the obstacle. After the obstacle, the values raise, and some spikes in value occur.

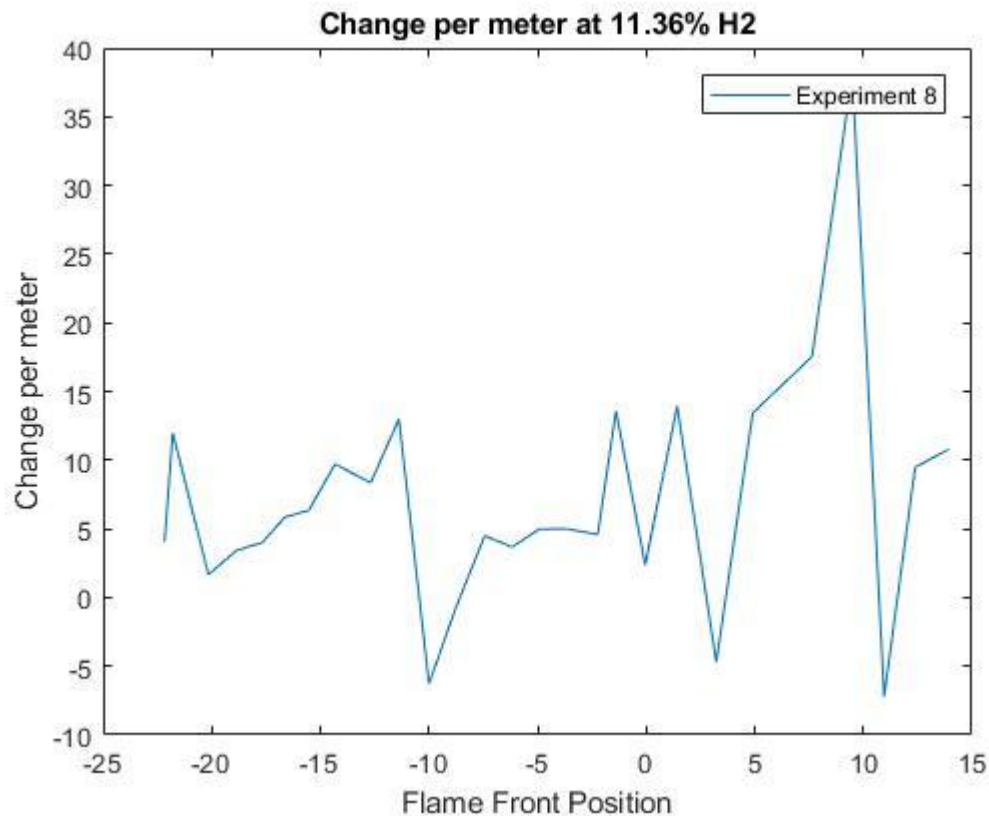


Figure 4-12 Change in area on the cross-section area of the visible part of the combustion chamber, and on the burning velocity of the unburned mixture,  $S$ , and the density difference between the burnt, and unburnt mixtures at 11.36vol% H<sub>2</sub>, dependent on the flame front position in mm



#### 4.2.2.4 12.2% H<sub>2</sub> Concentration

For the 3 experiments done at 12.2 vol% H<sub>2</sub> the change per meter fluctuates between approximately 0, to 6 m<sup>-1</sup> before and during the obstacle. After the obstacle this span increases slightly, with fluctuating values between -5 and 10 m<sup>-1</sup>. There are also a positive, and a negative spike in change per meter.

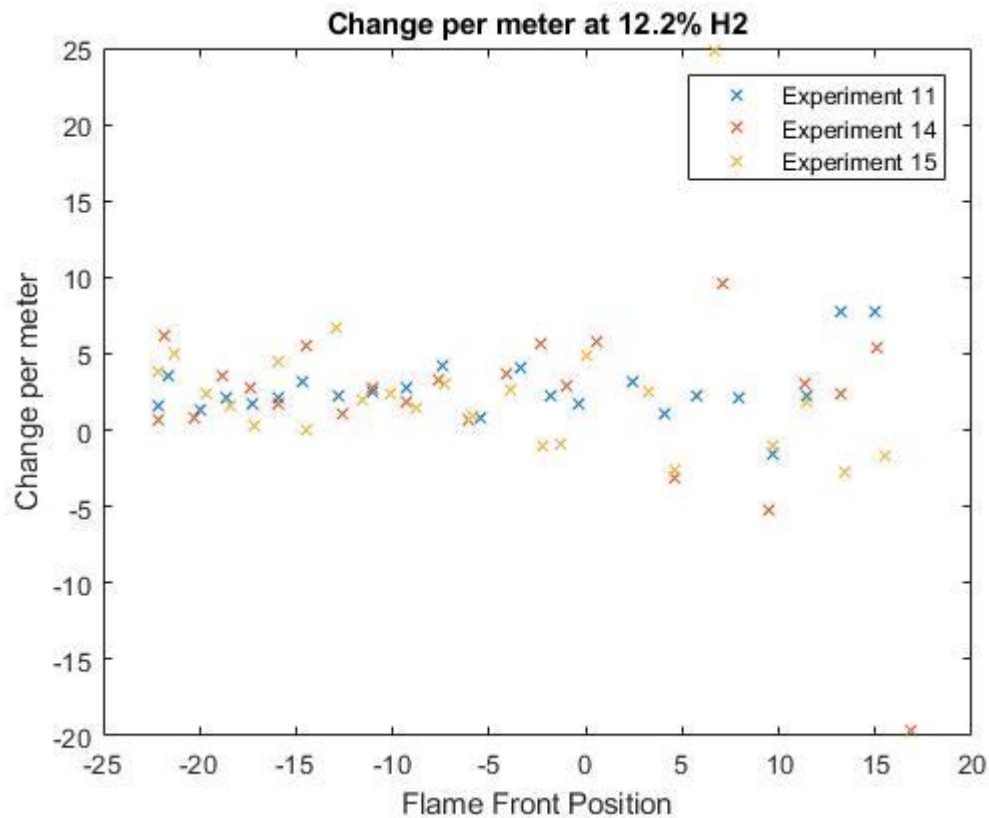


Figure 4-13 Change in area on the cross-section area of the visible part of the combustion chamber, and on the burning velocity of the unburned mixture,  $S$ , and the density difference between the burnt, and unburnt mixtures at 12.2vol% H<sub>2</sub>, dependent on the flame front position in mm

#### 4.2.2.5 13.28% H<sub>2</sub> Concentration

At 13.28 vol% H<sub>2</sub> 4 experiments are done. Before and during the obstacle, aside from some spikes in value at 4 m<sup>-1</sup>, the change per meter fluctuates between 0 and 2 m<sup>-1</sup>. While after the obstacle, change per meter ranges between -1 to 4 m<sup>-1</sup>, while there's also some spikes in value.

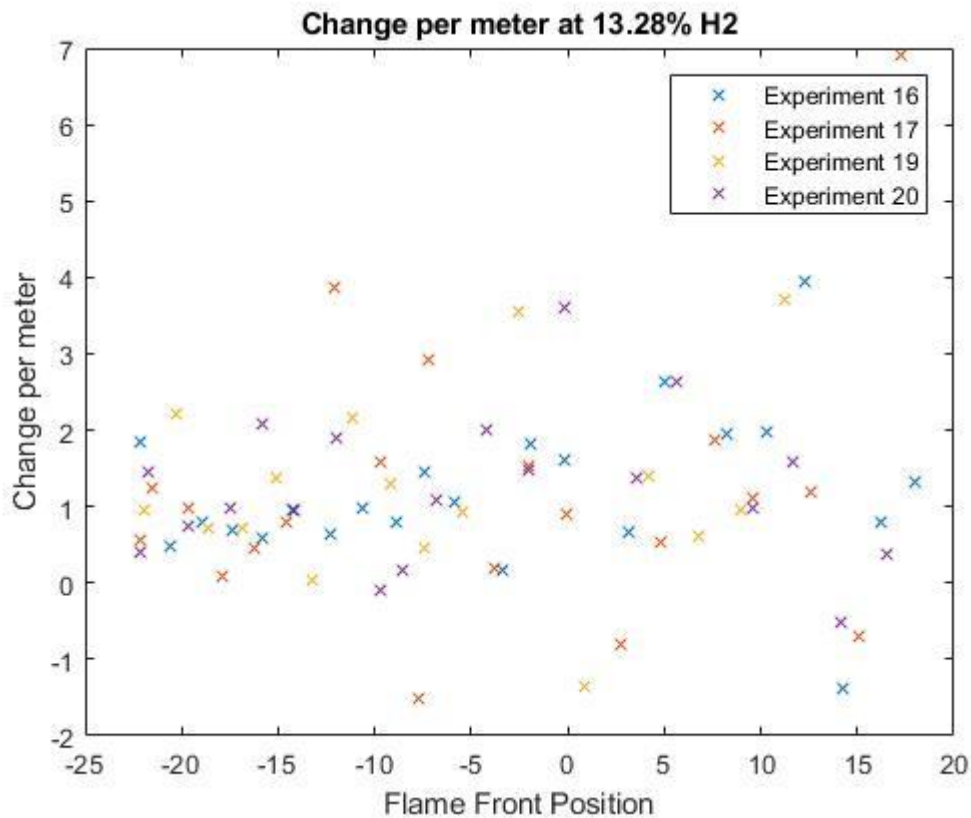


Figure 4-14 Change in area on the cross-section area of the visible part of the combustion chamber, and on the burning velocity of the unburned mixture,  $S$ , and the density difference between the burnt, and unburnt mixtures at 13.28vol% H<sub>2</sub>, dependent on the flame front position in mm

#### 4.2.2.6 14.36% H<sub>2</sub> Concentration

For the experiments done at 14.36 vol% H<sub>2</sub> the values before and during the obstacle spikes at 2 m<sup>-1</sup>, while most of the markers are between 0 and 1 m<sup>-1</sup>. After the obstacle, spikes occur at 6 m<sup>-1</sup>, and most of the values range between -0.5 and 3 m<sup>-1</sup>. This signifies a significant reduction in change per meter compared to the experiments done at lower concentrations

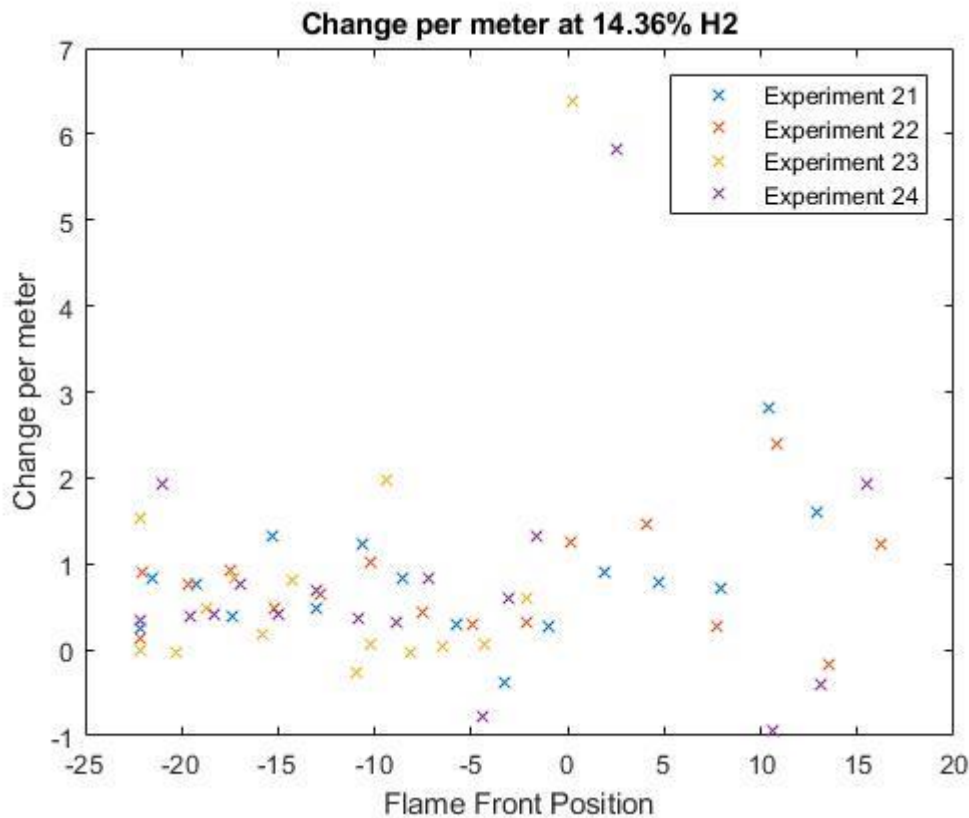


Figure 4-15 Change in area on the cross-section area of the visible part of the combustion chamber, and on the burning velocity of the unburned mixture,  $S$ , and the density difference between the burnt, and unburnt mixtures at 14.36vol% H<sub>2</sub>, dependent on the flame front position in mm

## 5 Discussion

The goal of this thesis was to map the changes in the flame front area over time during premixed combustion of a H<sub>2</sub>-Air mixture across an obstacle and see if there's any correlation between the experiments when scaled to the concentrations used in the experiments, and the cross-section area of the part of the chamber shown in the experiments.

To do this I first made an assumption of the conditions in the chamber, where it was assumed that initially the conditions in the chamber would be laminar, while after the obstacle it could be possible to enter turbulent conditions as eddies larger than the flame thickness would occur. Although the method used in these experiments are not able to track the flame thickness, the sheer size of the eddies in some of these experiments made this seem like it was the case. It was also assumed that the combustion would not enter the corrugated flamelet regime, which also seemed to be the case as flamelets very rarely occurred throughout the experiments.

In the experiments done, there are some major limitations that might impact the results. The code used in the experiments don't always follow the flame front accurately, giving sudden spikes in area for the flame front. The start, and end of the flame front is also manually selected, and the possibility of human error is there for possible from selecting the wrong start/end point, as it's not necessarily clear what the right choice is at all times.

Another limitation is that not the entire chamber is shown. This gives room for error as the scaling assumes that the change in area is uniform across the area of the chamber. The area that is not shown in the frame is then assumed to have the same area change per area as the parts of the chamber shown in the experiments. Should the flame front propagate differently, and the flame propagates more across the top of the chamber, than the bottom, then this could be a source of error.

There were 3 results shown in this thesis, which are all based on the position of the flame front at the given time.

- Area of the flame front
- Change in area of the flame front, scaled to the cross-section area of the combustion chamber shown in the frame
- Change in area of the flame front, scaled to the cross-section area of the combustion chamber shown in the frame, and the laminar burning velocity and density difference of the burnt and unburnt mixtures at the given concentration.

The first set of results is purely the change in area. The graph in figure 4-1 shows a rather linear change, where there is a slight dip across the obstacle, which is recovered once the flame front has passed the obstacle. Once the flame front is past the obstacle however, the area changes for the experiments also seem to diverge more, and the changes in area is not as consistent.

The 2<sup>nd</sup> set of results were the change in area scaled to the cross section of the chamber that is present in the frame. This gives the term change per second (s<sup>-1</sup>). The change per second values are consistent throughout all experiments, regardless of concentration. In figure 4-2 you can see the values of change per second, where it ranges between 0 and 0.5 s<sup>-1</sup> before the

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## 5 Discussion

obstacle, and once passed the obstacle the values range between -0.5 and 1.5, with some peak values outside of this. This could be interesting as this could point to the area change being consistent dependent on position relative to the obstacle. That would mean the correlation for area change between

The last set of results is when it is scaled to both the cross section of the chamber, and the concentration of the unburnt mixture, by scaling it to the laminar burning velocity and difference in the densities of the mixture the results for the experiments at the same concentration show similar values, and ranges between the same numbers, before and after the obstacle, while as the concentration increases, the range at which the change per second varies gets narrower. The highest value can be seen at 10% H<sub>2</sub> (figure 4-10) where before the obstacle the change per meter the highest change is around 20m<sup>-1</sup>, and after the obstacle there's a spike up to 70 m<sup>-1</sup>. The lowest values for change per meter can be seen at the highest concentration 14.36% (figure 4-15), where before the obstacle the change per meter peaked at 2 m<sup>-1</sup>, and after the obstacle it peaked at 6 m<sup>-1</sup>, but most values stayed below 3 m<sup>-1</sup>

From these 3 sets of results we can see that the change in area is rather consistent when based on the flame front position, regardless of the concentrations, and stays consistent when scaled to the size of the combustion chamber. When scaled to the concentrations of the mixtures however, the values begin to diverge between the experiments. From this, it could be possible that the change in area is consistent dependent on the position of the flame front and scaling it to the concentration of the mixture is unnecessary, as the values diverge.

The experiments have more stable results before the obstacle, while during and after the obstacle there is a tendency for the values to spike, to both high and low values. This can probably be explained by the instabilities caused by the obstacle, when the combustion approaches turbulent conditions.

## 6 Conclusion

Through the results provided in this thesis it can be concluded that the change in flame front area can be dependent on flame front position, as the area of the flame front seems to rise at a consistent rate, regardless of the concentrations of the H<sub>2</sub>-Air mixture. This makes it interesting, as it could implicate that the position in the chamber indicates what the area will be, regardless of concentration of the H<sub>2</sub>-Air mixture. This could in turn, with more data result in a function that describes the area of the flame front given by the position of the flame front without having to consider the concentration of the H<sub>2</sub>-Air mixture.

The area being dependent on flame front position, regardless of the concentration of the mixture could be the correlation needed for the area change over time for different concentrations.

When the change in area change between frames is then scaled to the cross-section area of the combustion chamber, the change also continues to stay similar between different concentrations of H<sub>2</sub>-Air mixture.

When the change is scaled on the laminar burning velocity and difference in density in addition to the cross-section area however the values for each concentration begin to diverge, and there doesn't seem to be a correlation between them anymore.

After the obstacle, more instabilities are introduced which results in spikes in area change. This could be described by the introduction into more turbulent, if not turbulent conditions in the moments after the obstacle.

### 6.1 Further work

I would suggest getting the required equipment to get rid of the limitations that occurred in this thesis in the shape of limited view of the chamber.

This would include

- Multiple lasers to light up the obstacle from multiple angles, so that the obstacle won't cast a shade that makes it impossible to track the flame front.
- A wider laser to be able to track a longer distance in the chamber.
  - Alternatively do extensive experiments to map the conditions before and after the obstacle more accurately with separate experiments from the ones on the obstacle

I would also suggest extensive experimental work on the conclusion that the flame front area is dependent on the flame front position, as more data is needed to verify this claim.

To be able to do these experiments more effectively, I would also suggest improving upon the limitations caused by the code. Making it able to more effectively follow the flame front, as well as finding the start and end of the flame front automatically. This would make it possible to use higher shutter speeds and getting more detailed information about the development of the flame front. It would also remove the human error introduced by having to find this manually.

*The University College of Southeast Norway takes no responsibility for the results and conclusions in this student report.*

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# Appendices

Appendix A - Master thesis task description

Appendix B – Experimental Procedure



# Appendix A – Master thesis task description

## FMH606 Master's Thesis

**Title:** Change in flame front area over time with premixed combustion across an obstacle.

**USN supervisor:** André Vagner Gaathaug, Knut Vågsæther

**External partner:** Gexcon

### **Task background:**

This project is a part of the research on gas explosions at USN. The technical safety and combustion group at USN have worked on combustion and process safety for more than twenty years.

This project is a part of the Norwegian Research Council funded Hy3DRM project, which is a joint project of USN and CMR Gexcon in Bergen, Norway.

### **Task description:**

1. Make a literature review on relevant topics.
2. Perform experiments in the lab at USN with flame tomography
3. Assess the change in flame front area over time, across an obstacle.

The literature review should summarize the state of the art regarding flame front area and turbulent premixed combustion. The experimental diagnostics will include laser illumination and highspeed camera recordings. Images produced from highspeed camera recordings will be used to analyse the change in flame front area over time.

**Student category:** PT and EET

A background in experimental work and a practical sense is preferred for this work. Interest for reactive flows, photography and image processing is also valued.

### **Practical arrangements:**

A background in fluid dynamics is preferred. Prior experience with the experimental rig is preferred.

### **Signatures:**

Student (date and signature):

06.02.18  
Christian E. Steplund

Supervisor (date and signature):

06.02.2018  
André V. Gaathaug

# Appendix B – Experimental Procedure

## Startup

1. Start up the ventilation system
  - a. First turn on the circuit to the ventilation system (switch on circuit box)
  - b. Push the black button on the ventilation system to start it
2. Turn on the power supply to the ignition and Coriolis flowmeter.
  - a. Test the trigger button
3. Make sure that valve in to the Coriolis flowmeter is closed
  - a. Turn on air compressor, and make the pressure out of the compressor 4-5 bars.
  - b. Open valve before Coriolis flowmeter.
  - c. Check that seeder has the correct pressure (around 50)
  - d. Close valve before Coriolis flowmeter
4. Turn on air for the pneumatic system controlling the valves on the rig.
  - a. First open the valve on the wall, then the valve on the oil filter to make the pressure around 5 bars.
  - b. Test whether the pressure is high enough to make the valves turn.
    - i. NB! Very important that the pressure pneumatics controlling the valves is sufficient or the inlet might not close, causing the flow to catch fire, burning up the chamber, and causing a backdraft when you hit the ignition.
5. Turn on, and connect the camera to computer
  - a. Start-up PFV
    - i. Set wanted frames per second
  - b. Start-up laser
    - i. Adjust settings on laser to fit your frames per second
6. Make sure that everybody in the lab is aware that you are doing an experiment, and that only qualified people are in the room.
  - a. Turn on the red warning light
  - b. Put out experiment poster with your number on it outside the lab
7. Nitrogen
  - a. Connect the nitrogen flask to the rotameter board
  - b. Open valve on top of flask
  - c. Open valve leading nitrogen out of flask
  - d. Adjust pressure
  - e. Make sure that the rotameter is not closed, and wait for 2 minutes to pass to make sure there is no air in the system
  - f. Close valve leading out of nitrogen flask, and disconnect the hose from the rotameter board.
8. Hydrogen

- a. Connect the hydrogen flask to the system.
- b. First open valve on top of flask
- c. Open valve leading out of flask
- d. Adjust the pressure if needed
  - i. NB! Always use the same pressure on the flask as what you calibrated the system with.
- e. Close valve leading out of flask

9. Open the cover on the laser

## Starting experiments

1. Decide the hydrogen to air ratio you are going to run in the experiment
  - a. Make calculations to find out how much air is needed for your wanted ratio, and open the valve leading into the Coriolis flowmeter, and adjust it accordingly
2. Put on protective gear:
  - a. Firefly glasses
  - b. Hearing protection plugs
3. Open hydrogen valve into system, and adjust to the wanted value in the rotameter
  - a. NB! Stay away from the rig while the hydrogen bottle is open.
4. Start the laser
5. Start the recording on the camera
  - a. It will then start a looped recording which stops after a certain amount of time after you hit the trigger to the ignition.
6. The explosion
  - a. Wait until the chamber is filled up, wait 20-30 seconds to be sure.
  - b. Turn on the
  - c. Flip the switch, changing the position on the valves, stopping the flow into the chamber.
    - i. NB! Very important! This is done to prevent the flow from catching fire, and causing a backdraft to occur.
  - d. Get behind the protective wall
  - e. Hit the trigger button, which starts the final recording on the camera, and ignites the hydrogen in the chamber.
  - f. Close the valve on the hydrogen flask
    - i. Hot air in the ventilation, might ignite the hydrogen in the bypass hose. Close instantly after triggering to prevent it from burning its way back.
7. End of experiment
  - a. Close valve on the hydrogen flask
  - b. Disarm the laser
  - c. Close air valve before the Coriolis flowmeter
8. Decide whether to do another experiment or shut down the rig.
  - a. If another experiment, start from the top of this page.
  - b. If you are shutting down the rig, go to shut down.

## Shut down

1. Close the cover on the laser, and turn the laser off.
2. Hydrogen
  - a. Close the valve on top of flask
  - b. Release remaining pressure in between the two valves on the flask, by opening the one leading out of the flask. Close it again afterwards.
3. Disconnect the hydrogen, and connect the nitrogen flask.
  - a. First open valve on flask
  - b. Open valve leading nitrogen out of flask
  - c. Adjust pressure
  - d. Make sure that the rotameter is not closed, and wait for 2 minutes to pass to make sure there is no hydrogen left in the system
    - i. Flip the valves to make sure that the bypass is also cleared of hydrogen.
  - e. Close valves on nitrogen flask and disconnect the hose from the rotameter board.
4. Turn off the compressor
5. Turn off the camera
6. Turn off the power supply to the ignition, and the camera
7. Turn off the pneumatics
  - a. First shut the valve on the wall, then release the excess pressure on the regulation valve
8. Turn off the ventilation system
  - a. First push the red button on the ventilation
  - b. Then switch off the power circuit for the ventilation