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Flame length measurements of hydrogen jets

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Summary:

The use of hydrogen is increasing rapidly and the research on hydrogen safety must follow. The implementation of hydrogen filling stations and cars are steadily on the rise. In the case of a leakage the hydrogen will most likely ignite, it is therefore essential to map out and reduce the risk of accidents. In addition to mapping out the risks, it is necessary to have safety-related data for potential hazardous scenarios in the case of an accident.

Experiments were conducted with different nozzle configurations as to investigate the impact this would have on the flame length of hydrogen jets. This report has taken a new direction by studying a more complex geometry of the nozzle. In addition to measure the flame length with a single upstream nozzle, it was investigated how a larger downstream nozzle would impact the flame length.

All the jets were placed vertical with inner nozzle diameters ranging from 0.5 mm to 4 mm. The spouting pressure from the reservoir was in the range of 20 to 100 bars.

The results are compared with the HySAFER model, which is the most current engineering method for calculating flame length. All the results, with one exception, obtained from the executed experiments are within the margin of error set for the HySAFER model.

Preface

This thesis is written as the last step to finishing the master program Process Technology at the University College of Southeast Norway.

The safety issues surrounding the use of hydrogen was the motivation for this thesis. The use of hydrogen is increasing rapidly and the research on hydrogen safety must follow. The main focus in this thesis is on measuring flame length of hydrogen jets. The full task description is presented in Appendix A.

Software used in this project is Microsoft Word, Microsoft Excel, Photron and MATLAB.

It is assumed that the reader has a general understanding of fluid mechanics. The programming tool MATLAB is applied to measure the flame length of the hydrogen jets. Photron has been used to record the flame lengths. It is not assumed that the reader has knowledge to neither MATLAB nor Photron.

A big thank you is given to my supervisor André V. Gaathaug for good consistent guidance, good discussions and genuine interest in my work. He has helped me when I met obstacles and motivated me throughout this process.

Also, thank you Mathias Henriksen for answering all my questions and asking critical questions back. Thank you for contributing to this report by providing a necessary MATLAB code.

A special thank is given to my study group who have spread much joy and laughter through this entire process.

Porsgrunn, 15.05.2017

Nora Løvaasen

Nomenclature

Symbols

A	Cross sectional area of nozzle	[m^2]
M	Molecular weight	[kg/mole]
Ma	Mach number	[-]
$\dot{m}_{choked}$	Choked mass flow	[kg/s]
P_{choked}	Maximum pressure downstream from a nozzle	[Pa]
P_o	Pressure inside the pipe	[Pa]
T	Temperature	[K]

Constants

C_o	Discharge coefficient	1
R_g	Ideal gas constant	8.314 [J/mole*K]
γ	Ratio of heat capacities (C_p/C_v) for hydrogen	1.41

Abbreviations

Fps	Frames per second
IR	Infrared
NTP	Normal temperature and pressure (20 °C and 1 bar)
SJA	Safe Job Analysis
UV	Ultraviolet

Contents

1 Introduction

Hydrogen is a non-pollutant energy source, and has great potential as an alternative energy source [1]. The energy density of hydrogen in mass is 2.5 times greater than that of natural gas [2], which gives hydrogen an advantage when it comes to handling.

The commercialization of hydrogen vehicles is steadily on the rise. The challenge of implementing hydrogen as an accessible energy source is safe handling, such as infrastructure and storing. A common situation when hydrogen is unintentionally released is during handling of pressurized equipment [3, 4].

Unintentional release of hydrogen is hazardous because of the very low minimum ignition energy of hydrogen. The hydrogen will almost for a certainty ignite at release by ignition sources such as static electricity [5]. If the hydrogen is compressed to high pressures, a high-speed jet could be formed when ignited. Because of this it is essential to understand the characteristics of hydrogen jet flames to ensure safety.

1.1 Background

Today there exist five public hydrogen-fueling stations in Norway and it is planned to expand this network with another 20 fueling stations by 2020 [6]. The focus on hydrogen stations is large in many countries. Denmark is the first country in Europe to have a nationwide network of hydrogen stations. The most impressive investment on infrastructure in Europe is done by Germany as they plan to have a hydrogen network with 400 fueling stations by 2023. Japan wants to stand out as a modern hydrogen society in the 2020 Olympic games and has therefore a large focus on expanding their hydrogen network [6].

Norway has decided to phase out fossil cars from 2025 [6], which will put pressure on private car owners to obtain zero-emission cars. Since 2013 there has been an explosive growth in the electric car market in Norway, which makes the introduction of private hydrogen cars challenging. Therefore it is critically important to establish a nationwide network of hydrogen stations to make hydrogen cars an attractive alternative. This will require a substantial investment and financial risk to achieve. A sustainable and profitable business model for establishing hydrogen stations is therefor needed [6].

In order for a hydrogen station to be profitable it requires regular customers and the private car sector is not enough to meet this demand alone [6]. It is therefore of importance to find customers in the business community.

Today, all mass-produced hydrogen cars are from Asia. These cars are probably sold with loss. To make the hydrogen car marked more attractive for car producers it is necessary for Norway to convince the car manufacturers to export more cars to Norway. This will give the hydrogen car manufacturers an advantage in terms of greater exposure in the media. For example, a guarantee that their cars will make up a significant share of Taxi Parks will give the hydrogen cars good exposure to the public [6].

It is recommended by SINTEF [6] that the focus on implementing hydrogen should initially target businesses such as taxis, forklifts and luggage handling at airports. All these have a predictable filling pattern. These filling stations should also be open to private car owners.

Many hydrogen vehicles are in development, such as busses, lorries, ferries, ships and major industrial vehicles. However, the private market for hydrogen driven cars will not evolve until a nationwide network is in place, and will therefore be among the latest hydrogen markets to be established [6].

Smaller vehicles such as private cars would need high-pressurized hydrogen at 700 bars [6, 7]. At this pressure the consequences of unintentional leakage and mechanical failures can be severe. According to Proust et al [7], the hydrogen will most likely ignite in the case of a leakage. It is therefore essential to map out and reduce the risk of accidents. In addition to mapping out the risks, it is necessary to have safety-related data for potential hazardous scenarios in the case of an accident.

1.2 Objective

The objective of this thesis is to examine the flame length when igniting hydrogen gas. Experiments will be conducted at a laboratory in the University College of Southeast Norway. In the experiments different nozzle configurations will be used to investigate the impact this have on the flame length. The new direction this report will take is to study a more complex geometry of the nozzle. In addition to measure the flame length with a single upstream nozzle, it will be investigated how a larger downstream nozzle impact the flame length.

All the jets will be placed vertical with inner nozzle diameters ranging from 0.5 mm to 4 mm. The spouting pressure from the reservoir is in the range of 20 to 100 bars.

The length of the flames will be captured using a high-speed camera and MATLAB used to process the data. The results will be compared with the HySAFER model, which is currently the best model for calculating flame length of hydrogen jets [8].

The original task description is presented in Appendix A.

1.3 Report structure

This report is structured in such a way that the reader gets necessary information to understand one chapter in the previous chapters. It is therefore recommended to read the report from start to finish.

Chapter two presents some theory and literature relevant for the objective of this thesis as well as previous studies conducted on this subject. The method of conducting the experiments and process the results are explained in chapter three while the results are presented in chapter four. Finally the method and results are discussed in chapter five and a short conclusion is given in chapter six.

2 Theory

For a fire or explosion can occur, three conditions must be met at the same time. A fuel and oxygen must exist in certain proportions and an ignition source must be present. Hydrogen has a minimum ignition energy at only 0.019 mJ, which is extremely low [2]. In addition the lower flammability limit of hydrogen is also high compared to other hydrocarbons. The energy produced from electrical equipment sparks etc. is more than is required to ignite hydrogen at the lower flammability limit.

The density of air is 1.204 kg/m^3 at NTP (20C and 1 bar). The density of hydrogen is significantly lower at 0.0838 kg/m^3. This makes buoyancy a huge aspect of safety surrounding handling of hydrogen. The risk is greatly reduced with un-ignited releases of hydrogen compared to other hydrocarbons in open spaces because of the buoyancy [2].

One of the challenges with handling hydrogen is diffusion. Hydrogen has the possibility to diffuse through intact materials, especially organic materials. This may lead to accumulation of hydrogen in confined spaces. It is possible to add an odorant or colorant to easier detect leakage, however according to Molkov [2] this possibility is small for most scenarios. Proper selection of materials such as special steel alloys is necessary, as hydrogen will cause embrittlement in mild steel.

2.1 Safety surrounding the use of hydrogen

If hydrogen is not ignited during release in confined spaces it will accumulate and the consequences can be even more severe compared with initial ignition. When the leak is ignited at the source a jet will form, while if the leak is not ignited a gas cloud will accumulate and an explosion can occur.

In the case of intentional ignition at the leak, blow-off is referring to a situation where the flame is extinguished as soon as the ignition source is removed [5]. If the flow of hydrogen is not extinguished in this situation a gas cloud can accumulate.

The separation distance of non-reacting jets is the hydrogen concentration in the axial direction that is high enough to be ignited [8]. The separation distance is relevant when designing new hydrogen infrastructure to determine the safety distance to the surroundings.

2.2 Choked flow

From a safety perspective it is necessary to know the maximum mass flow rate of a gas through a nozzle. The maximum pressure downstream from a nozzle gives the maximum flow and is here referred to as P_{choked}. The maximum pressure can be calculated by equation 2.1 [9].

$$\frac{P_{choked}}{P_o} = \left(\frac{2}{\gamma + 1}\right)^{\gamma/(\gamma-1)} \qquad 2.1$$

Where P_o [Pa] is the pressure inside the pipe, and γ is the ratio of the heat capacities, which for hydrogen is 1.41. If the downstream pressure is larger than P_{choked} [Pa] the flow is characterized as choked [9].

Hydrogen is considered an ideal gas at pressures below 200 bar [7]. Equation 2.2 [9] can be used to calculate choked flow for ideal gasses.

$$\dot{m}_{choked} = C_o A P_o \sqrt{\frac{\gamma M}{R_g T_o}\left(\frac{2}{\gamma + 1}\right)^{(\gamma+1)/(\gamma-1)}} \qquad 2.2$$

Where C_o is the discharge coefficient and is set to 1 [9]. The discharge coefficient is constant and tells about the frictional losses in the leak. When the downstream pressure decreases, the discard coefficient increase in choked flows. A conservative value of 1 is recommended for choked flows [9]. A [m^2] is the cross sectional area of the nozzle outlet, while M [kg/mole] is the molecular weight of the escaping gas, T_o [K] is the temperature of the gas and R_g [J/mole*K] is the ideal gas constant.

2.3 Flame characteristics

When the flow is defined as choked, it forms an underexpanded jet when released from a high-pressure storage vessel. Through a series of expansion shocks, the flow will expand to atmospheric pressure [2].

When hydrogen leaks out of a small orifice it initially create a momentum-controlled jet. Then the ambient air will be entrained into the jet to dilute the hydrogen. As soon as the initial momentum is lost, the buoyancy will take over and lead the jet upwards [10]. A turbulent jet is achieved when high-pressure hydrogen is ignited [4].

Mach (Ma) 1 is equal to a velocity of 343 m/s at room temperature and is categorized as a choked flow. If the velocity of the fluid is lower than Mach 1 it is defined as subsonic. If the velocity is above Mach 1 it will be supersonic [11].

In the case of a convergent-divergent nozzle the flow will decelerate or accelerate closer to Ma = 1 in the convergent section of the nozzle. It is only possible to achieve choked flow at the throat of the nozzle. If a subsonic flow does not reach choked conditions at the throat the velocity will decrease in the divergent section of the nozzle. Figure 2-1 gives an example of a convergent-divergent nozzle.

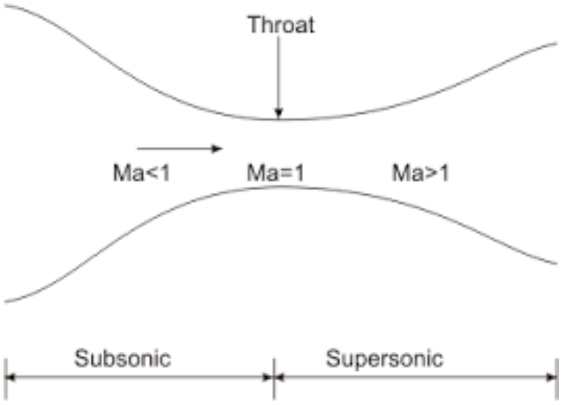

Figure 2-1 Example of convergent-divergent nozzle which creates a subsonic flow before the throat and a supersonic flow after the throat [12]

2.4 The HySAFER model

The HySAFER model was compiled by Saffers and Molkov [8] after discovering that the standard NFPA 55 (2010) could overestimate the safety distance up to 160 percent. After surveying 123 experimental data they compiled a model to measure flame length that only gives 20 percent scattering from experimental data. The model is presented in Equation 2.3. The data points used for the model were taken from eight separate studies. The methods used in these studies are presented in chapter 2.4.1.

$$54(\dot{m}_{noz} \cdot d_{noz})^{0.312} \qquad 2.3$$

Where $\dot{m}_{noz}$ is the mass flow [kg/s] and d_{noz} is the inner diameter of the nozzle [m]. Only the mass flow and the physical leak diameter are needed to apply the model, which makes it practical to use by many. The HySAFER model does not take frictional losses into account giving it a conservative approach, and it is only valid for momentum-controlled jets [8].

Saffers and Molkov show that with an increase in mass flow the flame length will also increase with constant diameter of the nozzle. With constant mass flow the flame length will increase with a smaller nozzle diameter. The HySAFER model has an error up to 20 percent in determining the correct flame length.

2.4.1 The studies

In the study done by Schefer et al [3] a total of three tests were run to determine the flame length on large-scale vertical hydrogen jets. The spouting pressure on the hydrogen cylinders were set to approximately 155 bars, but decreased rapidly during the blowdown. The hydrogen was run through a narrowing at 3.175 mm to a 7.94 mm diameter 7.6 m straight pipe before it was ignited at the end of the pipe.

Visible, infrared (IR) and ultraviolet (UV) recordings were executed. Because of the falling pressure all the video images were taken in the first five seconds, this was to capture the highest flame. The visible, IR and UV recordings were averaged to determine the flame length. Photos from five successive frames were averaged to determine the final flame height.

Shortly after Schefer et al released their study on large-scale vertical hydrogen jets [3], they published another study with a higher pressure range [4]. Also in this study a total of three blowdown tests were run. Vertical jets were ignited with the highest spouting pressure at 438 bars. A stagnation chamber were mounted just before the jet exit, this was done to achieve a controlled, well-defined flow into the jet. Temperature and pressure were measured continuously in the stagnation chamber.

The flame length was recorded using two digital cameras, which stored the images at a 30 fps frame rate. Multiple images were averaged together to determine the flame length. The flame length was recorded over the entire duration of the blowdown (600s). To determine the time-average flame length, five successive frames were averaged.

Studer et al published a study [13] where they investigated the flame length of a horizontal, homogenized mix of hydrogen and methane by blowdown. The maximum pressure of the gas cylinder was 100 bar. Nozzles with an inner diameter of 4, 7 and 10 mm were applied. The pressure was measured close to the nozzle.

The video images were stored at 25 fps and the flame length was averaged over five consecutive frames. Right after ignition, the flame length is too high for the camera angle. The uncertainty of the flame length is assumed to be approximately 10%.

Kalghatgi [14] conducted experiments on vertical jets with pure hydrogen, methane and ethylene. The nozzle diameters were from 1.08 mm to 10.1 mm. Each burner was mounted at the end of a settling chamber with an internal diameter of 152 mm. The flame length were identified from still photographs and averaged.

In the study done by Proust et al [7], the nozzle and the hydrogen cylinder is connected by a 10 m pipe with constant internal diameter of 10 mm. The tests are run as blowdown, and the flame is placed horizontally. The pressure is measured on the head of the cylinder. The reservoir is mounted on a weight cell to monitor mass flow. Nozzle sizes were 1, 2 and 3 mm, the spouting pressure was 900 bar.

The recordings of the flame were 25 fps, and a video reduction technique was used to determine the flame length. The uncertainty of the flame length is approximately ± 20 cm.

In a study done by Imamura et al [1] a horizontal hydrogen jet were ignited. The pressure is measured at the nozzle outlet. To visualize the flame easier a NaCl aqueous solution was sprayed. By using a digital video camera the flame length was visualized and averaged over 90 successive frames over a period of 20 – 23 s after the ignition of the hydrogen flame.

Mogi et al [5] studied the flame length of hydrogen by spraying an aqueous Na_2CO_3 solution over the horizontal burner for better visualization. The pressure range was from 10 to 400 bars, the pressure was measured close to the nozzle outlet. The sizes of the nozzles ranged from 0.1 mm to 4.0 mm. The flame lengths were read from video camera images.

The last study written by Shevyakov and Komov [15] do not explain how they conducted their experimental method.

3 Method

In this chapter the experimental setup, preparations and experimental procedure are described. The method for measuring the flame length and possible sources of error is also addressed. In this report, the flame length is defined as the distance from the exit of the nozzle configuration to the top of the visible flame.

3.1 Experimental setup

The experiments were carried out in an indoor facility at the University College of Southeast Norway. The hydrogen was stored in a singe 50-liter cylinder with a delivery pressure of 200 bars. To eliminate the oxygen in the system, a cylinder with nitrogen was also provided. Figure 3-1 shows the experimental setup in the laboratory.

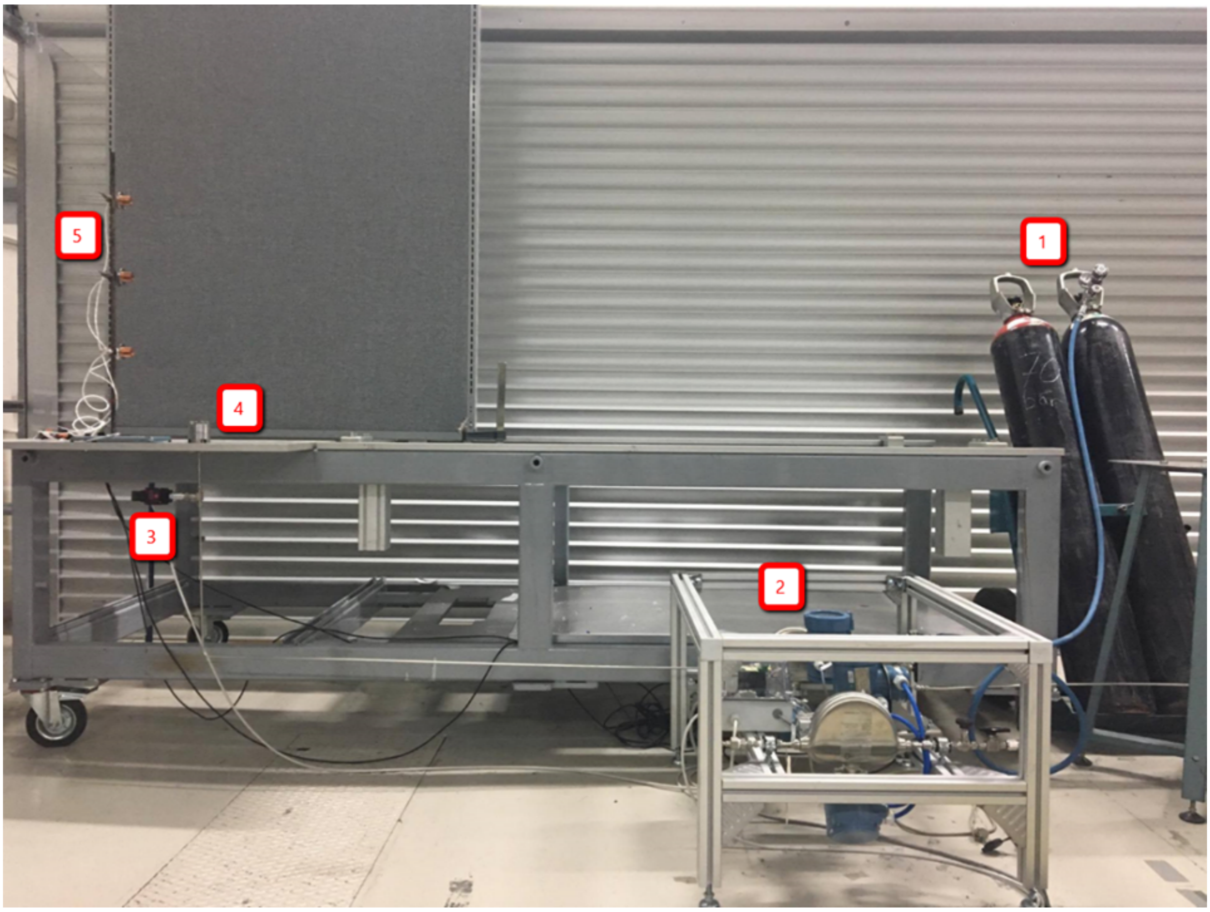

Figure 3-1 Experimental setup. 1) hydrogen and nitrogen gas cylinder 2) Coriolis flow meter 3) pressure sensor 4) nozzle configurations 5) radiation sensors (not in use)

The hydrogen goes through a 1.0 m flexible pipe before it enters the main pipe with an inner diameter of 4 mm. The main pipe has a total stretch of 4.6 m. On the piping there is mounted a Coriolis flow meter to measure the mass flow and temperature, a pressure sensor measures the gauge pressure. Right before the nozzle there is a 0.03 m expansion of the inner diameter of the pipe to 8 mm, while the height of each nozzle is 0.01 m.

The expansion of the main pipe is in this report considered as part of the nozzle configuration. However when addressing the upstream and downstream nozzles this is referring to the interchangeable nozzles stacked on top. This is illustrated in Figure 3-2.

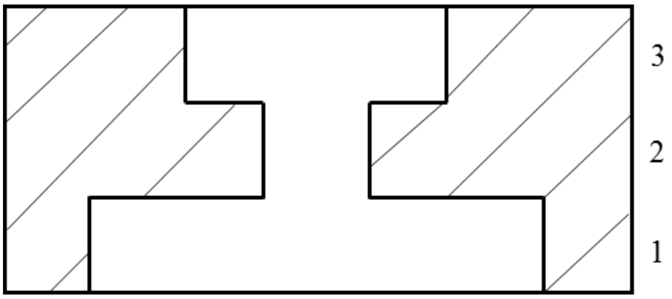

Figure 3-2 Illustration of the cross sectional area of the complex nozzle geometry where the gas enters at the bottom and exit at the top.

1) Expansion of the main pipe 2) upstream nozzle 3) downstream nozzle

The interchangeable nozzles are stacked on top of each other and were held together with bolts. Packings designed for high pressures were placed between each nozzle to assure minimum to none leakage.

The Coriolis flow meter is a CMFS010M model delivered by Emerson constructed in stainless steel. The maximum mass flow the model can measure is 110 kg/h [16], the maximum tolerated pressure is 125 bar.

Because of pressure restrictions on the equipment the pressure limit regulated at the hydrogen cylinder were 100 bars. The gauge pressure was measured approximately 0.2 m upstream of the nozzle. It was assumed that this was the exit pressure of the nozzle.

The high-speed camera used was a Photron FASTCAM SA1.1. All the variables were measured in voltage and registered in an oscilloscope. Each flame length was recorded for 5 seconds. The high-speed camera registered 1250 frames in this time, while the oscilloscope registered 9999 measuring points each for the mass flow, temperature and pressure.

The high-speed camera and oscilloscope were connected to a puls generator that assured the recordings started simultaneously.

The high-speed camera was placed such as to obtain the best possible visualization of the flame. The position of the camera was therefor placed closer or further away based on the expected flame length. If the camera was not positioned correctly during a recording, the camera was moved and the experiment was run again.

The pressure range for the experiments was between 20 and 100 bars. All the different nozzle configurations were run at 20, 40, 60, 80 and 100 bars. The exception was two situations that gave blow-off at 20 bars. This issue is described further in chapter 4.

3.2 Preparations for the experiments

When executing the experiments, safety was always the main priority. Before starting the experiments a Safe Job Analysis (SJA) was carried out. This was done to map out all potential risks to humans and surroundings, and measures to reduce the risks. The completed SJA is presented in Appendix B. It was essential that all the participants read through and understood the risks and safety measurements before participating in the experiments.

To make sure the experiments were performed consistently, as well as the possibility for other people to carry out the same experiment, a detailed experimental procedure is displayed in Appendix C. A brief description of the experimental procedure is found in chapter 3.2.3.

3.2.1 Determining choked mass flow

Equation 3.1 can be derived from Equation 2.1 by calculating the right side of the equation.

$$\frac{P_{choked}}{0.5266} < P_o \tag{3.1}$$

This means that if the hydrogen is released to atmospheric conditions the flow is considered as choked if the upstream pressure of the nozzle is greater than 1.92 bars. This number is confirmed by Molkov [2]. The lowest pressure regulated at the cylinder for the experiments was 20 bar. It was therefore assumed that all the experiments would achieve choked flow.

3.2.2 Nozzle sizes

There were four different sized nozzles available for the experiment, all with circular cross sections. The size of the nozzle is in this report referring to the inner diameter of the nozzle. The sizes available were 0.5 mm, 1 mm, 2 mm and 4 mm. Equation 2.2 [9] was used to get a reference on the expected mass flows.

It was unknown how much pressure loss there would be through the system. Considering the safety aspect, the pressure set at the gas cylinder was considered as the outlet pressure when choosing the nozzle size. This was a safety precaution based on the indoor location of the experiments. The calculated choked mass flow for the relevant pressures is illustrated in Figure 3-3.

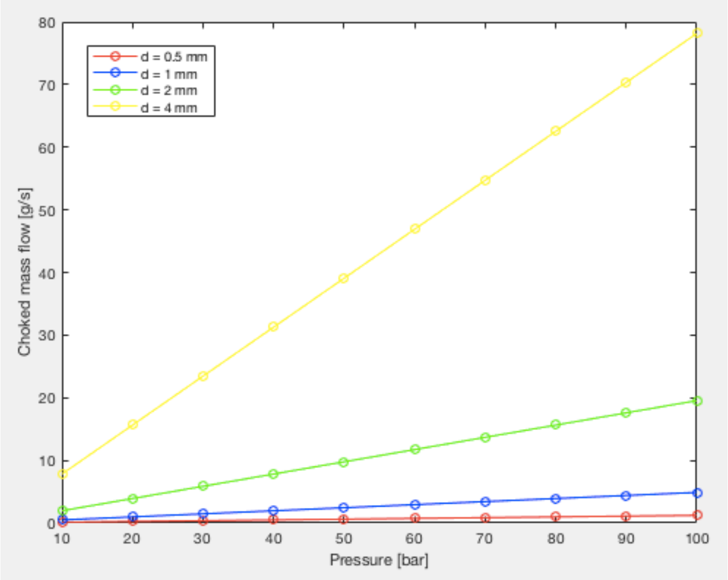

Figure 3-3 Calculated choked mass flow [g/s] plotted against the relevant pressure [bar] range for the different nozzle sizes

To get a reference on the expected flame length obtained, the HySAFER model (Equation 2.3) was applied for calculating the expected flame length. This is illustrated in Figure 3-4, the MATLAB code used for these calculations can be viewed in Appendix D.

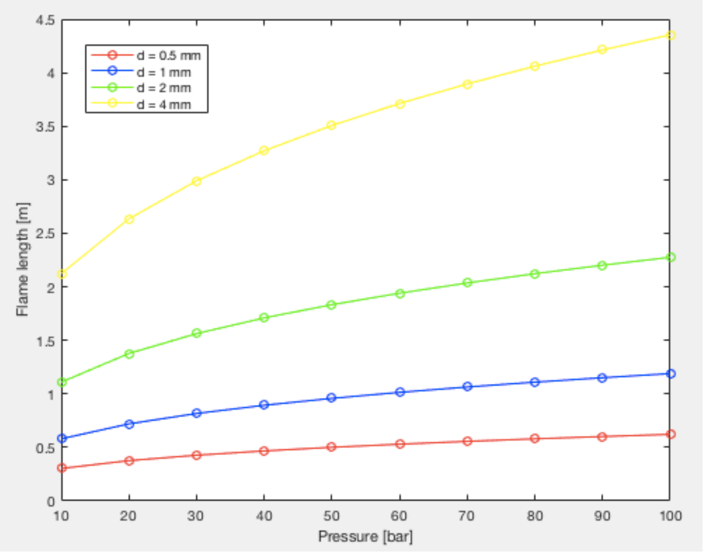

Figure 3-4 Assumed flame length [m] based on calculations plotted against pressure [bar]

The flame length obtained from the 4 mm sized nozzle, as seen in Figure 3-4, was deemed too high to safely perform indoors. The largest nozzle was therefore eliminated as the upstream nozzle. The 0.5 mm, 1 mm and 2 mm nozzles were applied as upstream nozzles. All the available nozzle sizes were used as downstream nozzles to obtain different nozzle configurations.

3.2.3 Experimental procedure

The experimental procedure can be divided into three parts: the startup, experiment and shutdown. Because of the amount of experiments carried out, it was not feasible to perform all the experiments in a single day. The startup of the procedure contains the preparations before the experiment itself. This was only needed to do once in one day. The experiment itself was done multiple times in a day, while the shutdown was only done when all the experiments for the day were completed.

3.2.3.1 Startup

During the startup it was necessary to facilitate for running the experiment. First and foremost all participants had to put on their safety gear, which was fire resistant coat, helmet with shield and hearing protection. The fire alarm was deactivated and the location secured for outsiders. The ventilation system was switched on and a fire extinguisher placed within reach.

Next, the rig was prepared by switching on all components and connecting the high-speed camera to the computer and the pulse generator.

The pressure on the nitrogen cylinder was regulated to between 3-4 bars and the system was flushed with nitrogen for approximately 15 s. This was done to displace the oxygen in the system. Opening and switching over to the hydrogen cylinder completed the startup procedure.

3.2.3.2 Experiment

The high-speed camera was positioned at a suitable distance from the nozzle exit. The frame was cut to a suitable size and the frame rate set to 250 fps. The high-speed camera recorded for 5 seconds for each experiment. This resulted in a total of 1250 frames for each hydrogen flame.

The position of the nozzle in the frame was written down and stored for later. A 1 m long ruler was placed on top of the nozzle; a snapshot was taken with the high-speed camera. This was saved for later to calibrate the pixel values for the length measurements.

The puls generator and oscilloscope must be reset. The wanted nozzle size was assembled and mounted at the exit of the main pipe, as to produce a vertical jet.

To be able to execute the experiment in a safe manner, a minimum of three people had to be present. One had to regulate the flow of hydrogen, one ignited the flame and the last had to be ready to trigger the system to start recording.

At this time all participants had to adjust their safety gear; take the shield down and the hearing protection on. The person that ignited the flame put on fire resistant gloves. The pressure on the hydrogen gas cylinder was adjusted. The propane-torch was switched on and placed over the exit of the nozzle. To obtain a better visualization of the flame, all sources of lights were removed. The valve on the hydrogen cylinder was opened and simultaneously the flame was ignited.

The oscilloscope and camera started recording by activating the puls generator. This was done when the pressure had stabilized. This was visually observed on a display on the pressure sensor. When the recordings had stopped, the valve on the hydrogen cylinder was closed and the flame extinguished. The lights were switched on and the recordings saved.

3.2.3.3 Shutdown

The shutdown procedure started by closing and depressurizing the regulator on the hydrogen cylinder. Nitrogen was then run through the system for approximately 15 seconds to flush out the hydrogen. The regulator on the nitrogen cylinder were closed and depressurized.

All the components were switched off, and the location opened for outsiders. The fire alarm was activated and the ventilation switched off.

3.3 Flame length measurements

The flame length for each recording was obtained by using MATLAB. The method used to process the data in MATLAB is described shortly below. For the completed code see Appendix E.

When using MATLAB to process the images, one experiment was run at a time. First all the 1250 raww files was imported to the code. The resolutions of the pixel values were 256 in the x-axis and 1024 in the y-axis.

Individual matrixes for the colors red, green and blue was created. The code was constructed to measure the flame length for each color, but to reduce the computation time only the red color was used to determine the flame length.

Because hydrogen is burning with a very weak flame, a method to eliminate the flame from the background was necessary. This was achieved by setting a threshold value and using Equation 3.2. The pixel values are normalized, giving them a value between 0 and 1.

$$\frac{pixel\ value}{\max pixel\ value} > threshold\ value \qquad 3.2$$

All the pixel values that were above the threshold value were defined as flame. This value was determined by trial-and-error and looking at which values indicated the top of the flame most correctly. By doing this, the highest point of the flame in each frame was located.

By using the trial-and-error method it showed that a threshold value below 0.08 cut the flame length. When running through the experiments the threshold value of 0.08 was first tried, if this gave poor results the threshold value was increased. This is described further in Chapter 3.4.

To assure that the top of the flame were correctly placed in the frame, every 50 frame were printed and visually controlled. As seen in Figure 3-5 the top of the flame were indicated with a red line.

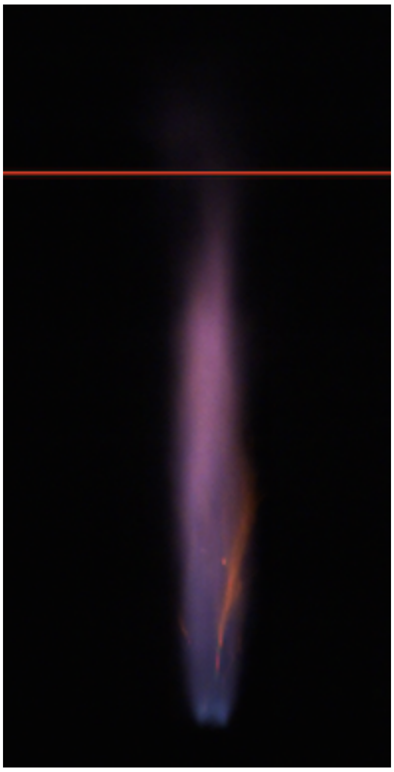

Figure 3-5 Picture of the flame in MATLAB. The red line indicates the top of the flame

The location of the nozzle outlet in the frame is identified in the Photron software. By removing the pixels below the nozzle and above the highest point of the flame, a pixel value of the flame length is obtained. By using the Photron software and the snapshot of the ruler, the flame length is scaled to meters. The standard deviation for each data series is also calculated to assure that the correct threshold value is chosen.

To get the mean values of the mass flow, gauge pressure and temperature an in-house MATLAB code, developed by Mathias Henriksen were used.

3.4 Possible sources of error

To investigate the possible sources of error project 109, test 1 is used. An experimental matrix of all the experiments are presented in Appendix F. Project 109, test 1 was run with the singe nozzle configuration at 0.5 mm nozzle and 60 bars reservoir pressure. This experiment was chosen to be investigated further because it had the highest threshold value for obtaining good results for the flame length.

Figure 3-6 illustrates the flame height for each frame when running project 109, test 1 with a threshold value of 0.08. It is observed that the noise in the background is too high for this threshold value. The flame is not separated from the background and the flame lengths displayed in Figure 3-6 are of the background and not the flame.

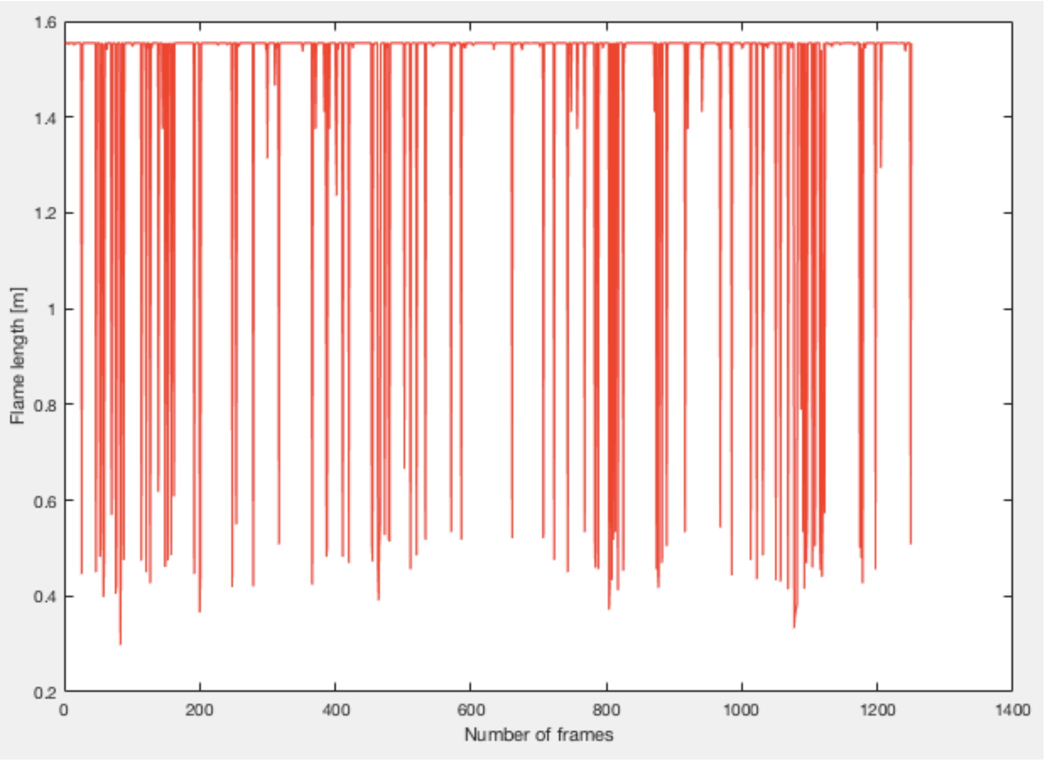

Figure 3-6 Flame length [m] for each frame with threshold value of 0.08

This threshold gives an average flame length of 1.47 m and a standard deviation of 0.29. This is clearly not correct for the chosen nozzle size and mass flow.

By increasing the threshold value to 0.13 it is visualized in Figure 3-7 that more correct flame length values are obtained. However the background is still visible in the results. This threshold gave an average flame length of 1.17 m and standard deviation of 0.48. This standard deviation is larger of that at threshold value 0.08, this is because more correct flame lengths is registered.

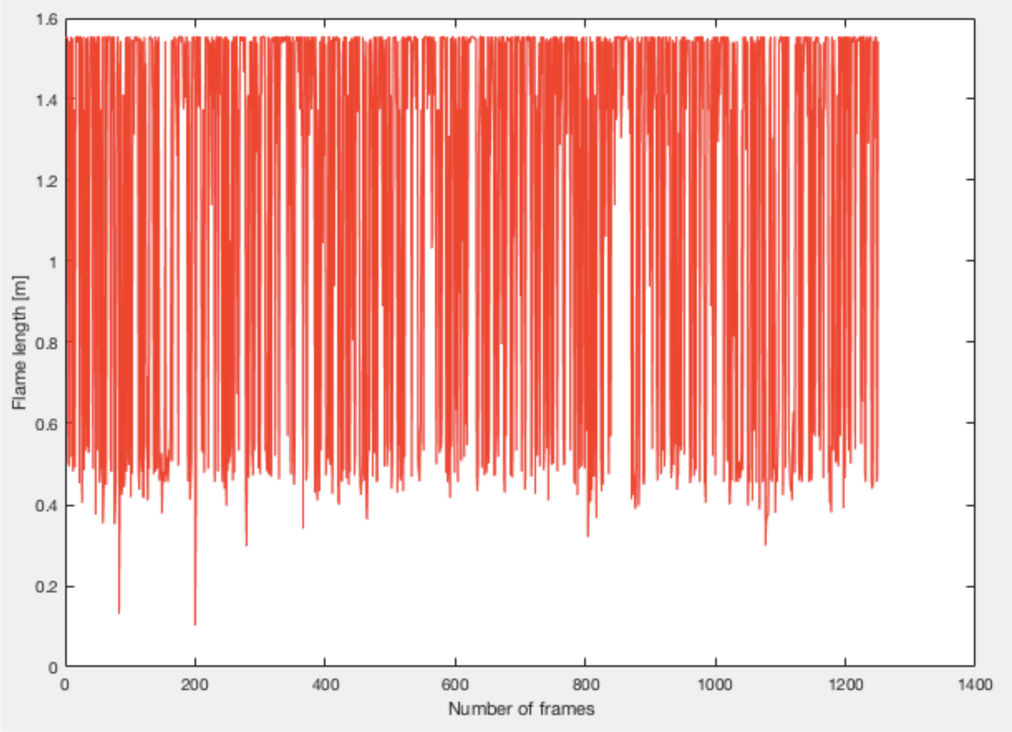

Figure 3-7 Flame length [m] for each frame with threshold value of 0.13

By following this technique of increasing the threshold value the results are good when it reaches 0.18. This is presented in Figure 3-8. At this threshold value the average flame length is 0.48 m and the standard deviation is 0.057.

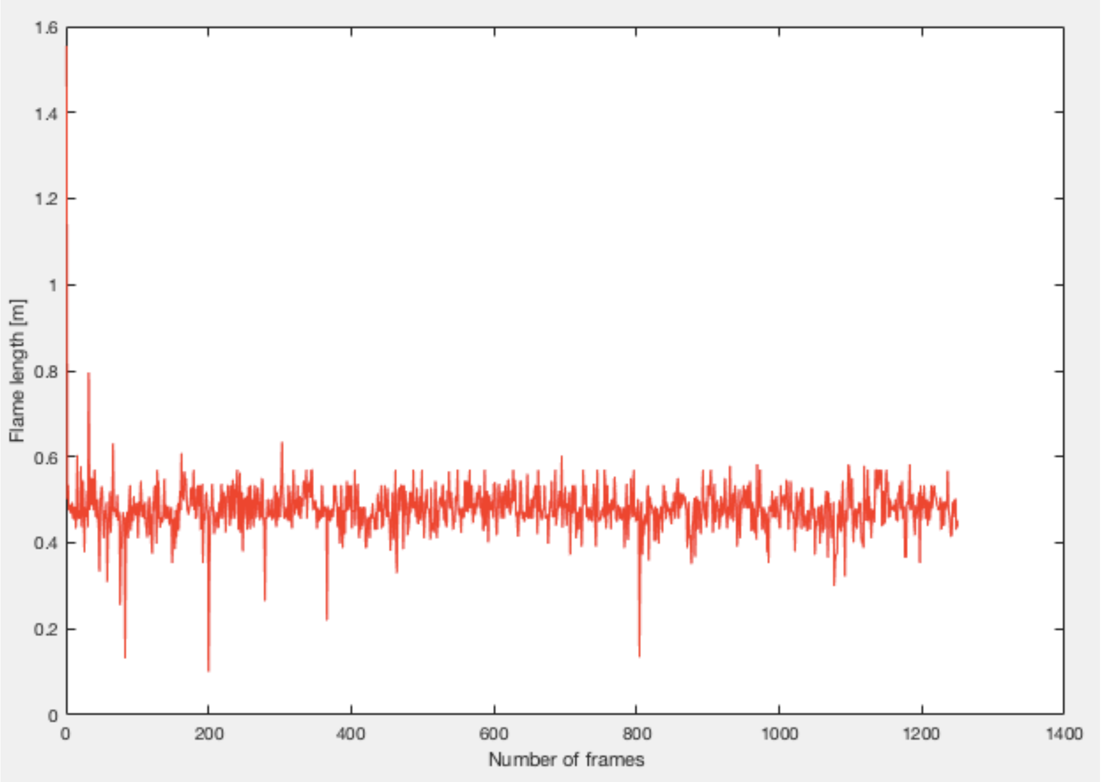

Figure 3-8 Flame length for each frame with threshold value of 0.18

Because of the method used in the MATLAB code there are some deviations at the beginning of the series, but considering the amount of measuring points in one series this is considered acceptable.

The scaling of the pixel values to meter is also a possible source of error. To be able to pinpoint the scale of each pixel a calibration picture were taken for each project by manually holding up a ruler at 1 m. If the ruler is not placed correctly when taking the snapshot, this error will influence all the tests in the project. It is however not possible to state how large this error could be.

When the calibration image was taken, the scaling factor [mm/pixel] was determined by measuring the number of pixels inside the 1 m ruler. To achieve this it was necessary to zoom in on the image, this influenced the resolution and the ruler became blurry. Because of the blurriness in the image it was possible to miss read the total number of pixels by two pixels.

To determine how big influence this error could have on the mean flame height project 109, test 1 was run by altering the scaling factor by two pixels. By doing this the average flame length for the chosen project altered with no more than ± 0.0016 m. This was assumed to be a negligible error.

4 Results

In this chapter the results from the experiments are presented. An experimental matrix with all the results are presented in Appendix F. All the results have been compared with the HySAFER model. The HySAFER model is only based on singe nozzle configurations, despite of this it will be compared to all the experiments done.

The inner diameter of the nozzle is illustrated with d_x^y, where x is the size [mm] of the upstream nozzle and y is the size [mm] of the downstream nozzle. The results for $d_{0.5}$ and $d_{0.5}^1$ at 20 bars are not presented as these situations gave blow-off. Results were achieved when increasing the size of the downstream nozzle to larger than 1 mm.

The measured flame lengths with the single configuration and the flame length calculated by the HySAFER model are presented in Figure 4-1.

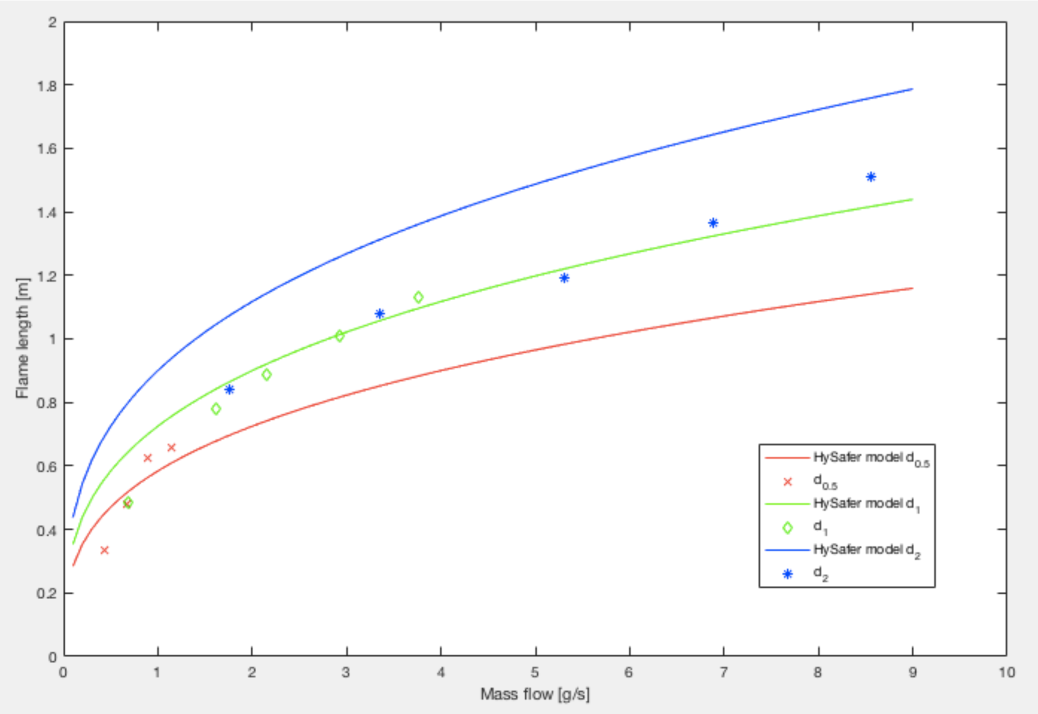

Figure 4-1 Comparing the HySAFER model with the measured flame length with single nozzle configurations

When going through the results for the single nozzle configurations, it was observed that in most cases the HySAFER model over calculates the flame length compared to the experimental values. Changing the size of the nozzle result to corresponding change in mass flow with the same applied pressure from the reservoir. The 1 mm nozzle had the smallest deviation compared with the HySAFER model with only 8%. The 0.5 mm and 2 mm nozzles had an average deviance of 13% and 18% respectively compared with the HySAFER model.

By comparing all the experiments with the same sized upstream nozzle, it is visualized that the flame length increases by increasing the size of the downstream nozzle. This is illustrated in Figure 4-2.

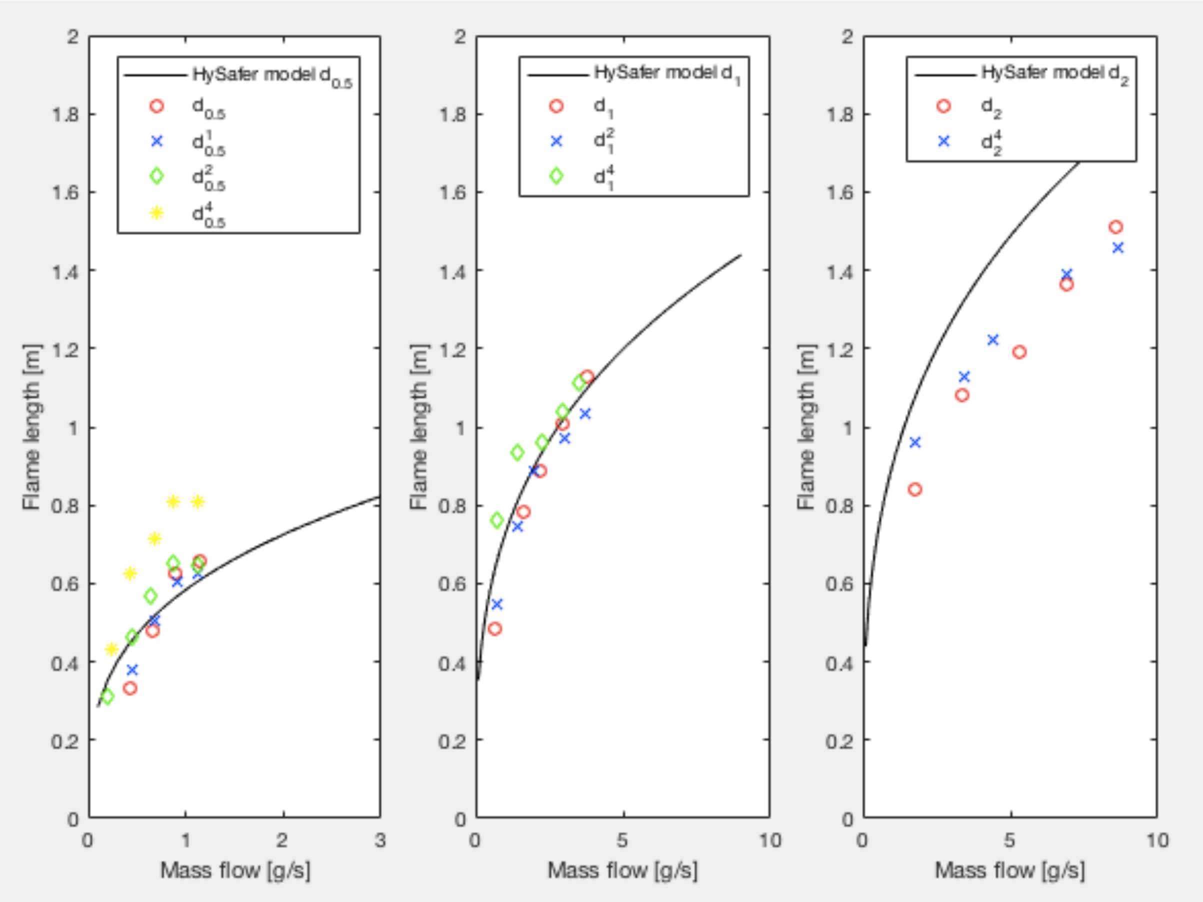

Figure 4-2 Comparisons of the same sized upstream nozzle with different or none downstream nozzles. The graph on the left is in a different scale for better visualization.

By comparing the results for the different upstream sized nozzles it is viewed that the presence of the downstream nozzle is more significant for the height of the flame with the smaller diameters. The $d_{0.5}^{4}$ configuration has a 29% increase in flame length compared to the single 0.5 mm nozzle for a reservoir pressure at 80 bars.

The difference in flame length is also larger at lower mass flows. For the single 1 mm upstream nozzle the difference in flame length to d_1^4 is 57 % at the lowest mass flow compared to a difference of only 1 % for the largest mass flow.

The upstream nozzle at 2 mm has only one comparison, the d_2^4. By looking at this graph it is visualized that the flame length with the stacked configuration creates a smoother curve.

When calculating the average deviance between the stacked nozzles with the HySAFER model, all had an average deviance below 18%, except the $d^4_{0.5}$, which had an average deviance from the HySAFER model on 33%. When doing these comparisons the size of the upstream nozzle is used in the HySAFER model, as this is the nozzle that determines the mass flow.

Figure 4-3 compares the same sized downstream nozzle with the different sized or none upstream nozzle.

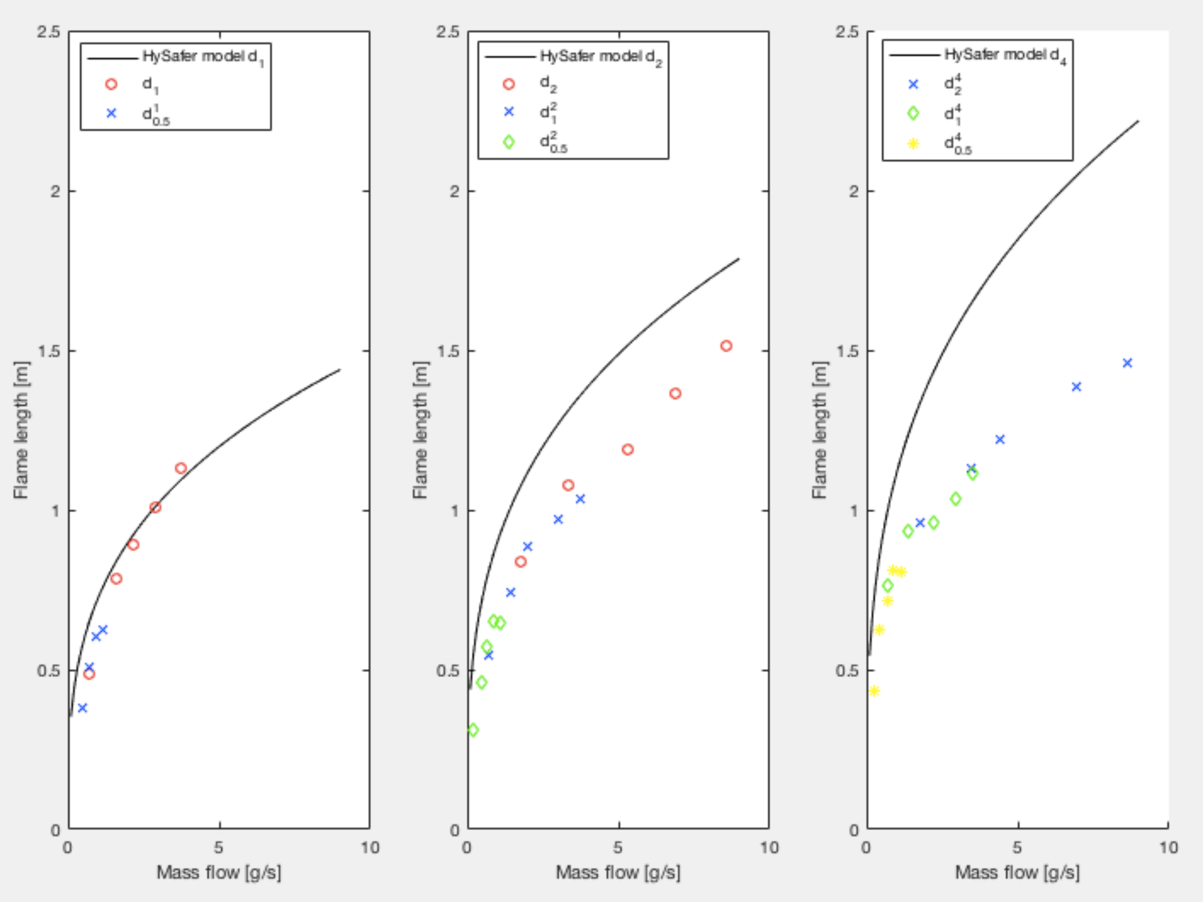

Figure 4-3 Comparisons of the same sized downstream nozzle with different or none upstream nozzle.

It is observed in Figure 4-3 that the mass flow increase when the size of the upstream nozzle is increased. As a result it is the upstream nozzle that has the largest influence on the flame length. The flame length of the single 4 mm nozzle was not completed due to the indoor location of the experiment.

The lowest exit pressure for all the experiments was for project 104, test 6. This experiment was run with a single nozzle of 2 mm at a reservoir pressure of 20 bars. At the exit the pressure were measured at 9.64 bar. This value is well above the critical pressure at 1.92 bar, which means all the experiments achieved choked flow.

The measured mass flow for the single nozzle configurations is compared with the mass flow calculated with Equation 2.2 in Figure 4-4. It is observed that the measured mass flow with the smallest nozzle, $d_{0.5}$, fits well with the equation. The discrepancy between the measured mass flow and the calculated mass flow increase when increasing the size of the nozzle. The discrepancy is also larger at higher pressures.

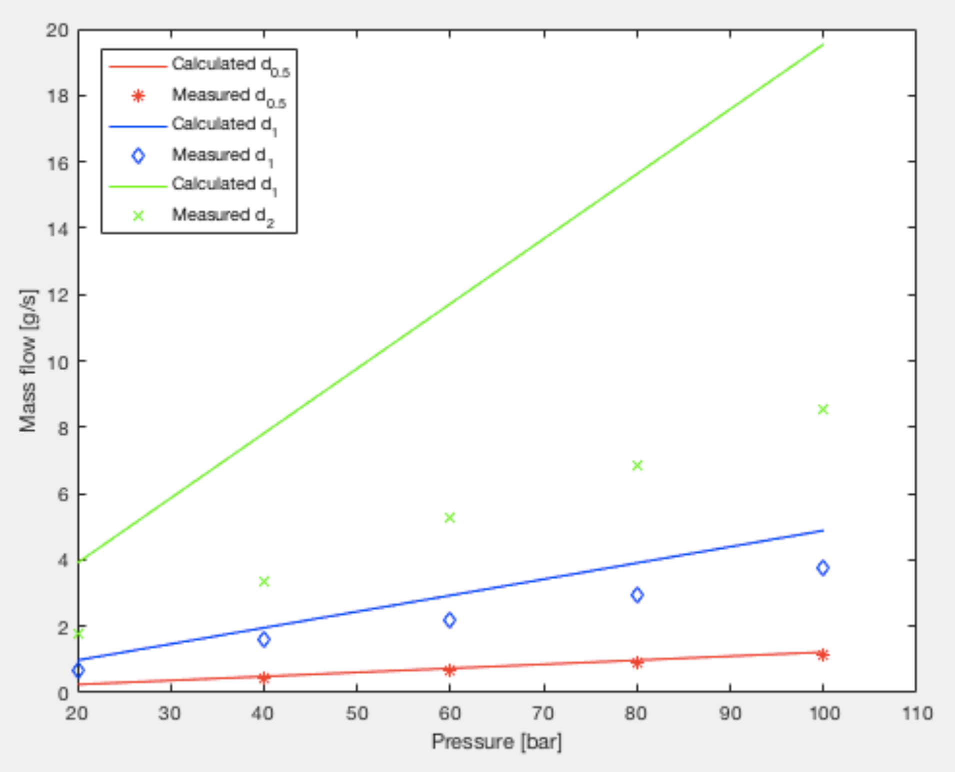

Figure 4-4 Comparison of the calculated mass flow [g/s] and the measured mass flow [g/s] with spouting pressure [bar] from the hydrogen cylinder

When using the measured pressure in Equation 2.2, the calculated mass flow corresponds better with the measured mass flow. This is visualized in Figure 4-5. It is observed that the deviance between the values is much lower than when using the spouting pressure from the hydrogen cylinder in the calculations.

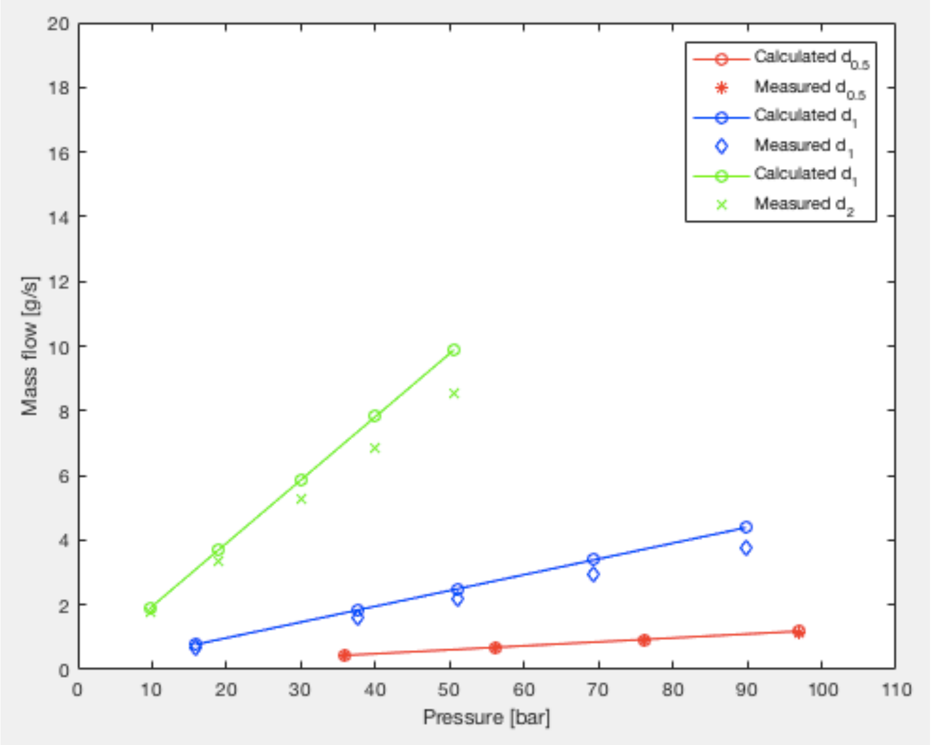

Figure 4-5 Comparison of calculated mass flow and measured mass flow with measured pressure

5 Discussion

The aim of this thesis is to compare the results from experimental values of flame length to current engineering methods. The new direction of this report is to study a more complex geometry of the nozzle. In addition to measure the flame length with a single upstream nozzle, it is investigated how a larger downstream nozzle impact the flame length.

The experiments were carried out in an indoor location at the University College of Southeast Norway. The experiments were first run with single nozzle configurations at 0.5 mm, 1 mm and 2 mm. Then the nozzles were stacked with a nozzle with a larger inner diameter to create a converging-divergent nozzle.

The pressure range of the experiments is from 20 to 100 bars, these pressures were set at the head of the hydrogen cylinder. To get an accurate measurement of the pressure at the outlet it is measured with a pressure sensor close to the nozzle exit.

A Safe Job Analysis (SJA) was prepared to assure the experiments were conducted in a safe manner. To make sure all the experiments were performed consistently a thorough experimental procedure were conducted. By taking these precautions prior of the experiments no accidents or dangerous situations occurred. The results show that all the experiments were done consistently.

It was assumed that all the experiments would achieve choked flow conditions. The results show that this assumption was accurate as all the experiments had an exit pressure above the critical value of 1.92 bar.

It is observed in the results that when increasing the size of the upstream nozzle the discrepancy between the measured mass flow and the calculated mass flow increase. The deviance is particularly large when calculating the mass flow using the spouting pressure from the reservoir. This is due to the fact that there is significant pressure loss in the system.

When using the gauge pressure in the mass flow calculation the mass flow corresponds better with the measured mass flow. The deviance may be because of the discharge coefficient. Based on recommendations found in the literature this coefficient was set to 1. These observations show that it is of importance to measure the mass flow with equipment when performing thorough experiments and the discharge coefficient is unknown.

The flame length was recorded with a high-speed camera. The flame length was measured in each frame and averaged to get the mean flame length for each scenario. According to Schefer et al [3], ultraviolet (UV) recording of the flame will give the shortest flame length, infrared (IR) recordings will give the longest flame lengths, while recordings with a regular camera will give a flame length between the UV and IR. This shows that by recording the flame length with a high-speed camera and averaging the flame length gives credible results of the flame length.

To get a proper comparison for the experiments the same spouting pressures were set on the hydrogen gas cylinder. Because of significant pressure loss in the system, a pressure sensor was mounted close to the nozzle exit. To assure a steady pressure it was always assured that the hydrogen cylinder had a high enough pressure. Before starting to record with the high-speed camera it was assured that the flow had reached a steady pressure.

To get a good comparison and understanding of the HySAFER model, the methods used in the eight different studies are compared with the method used in this report. All the studies used video camera images to determine the flame length.

Schefer et al [3] captured the flame length during blowdown. All the video images were taken in the first five seconds because of the falling pressure. For the experiments executed for this report it was observed that if constant pressure were not obtained the pressure drop could be as much as 10 bar for five seconds of recording. This will have an influence on the flame length.

The HySAFER model is based on eight different studies that all use different methods for obtaining the flame length. Most of the studies used blowdown in their tests. This will result in falling pressure, a decrease in mass flow and a shorter flame length if the video recordings were not taken quickly enough.

For the experiments done in this report the high-speed camera recorded 250 fps for 5 seconds. Because constant pressure were assured 1250 pictures for each experiment were achieved for each test.

Both Studer et al [13] and Proust et al [7] only captured 25 fps. Studer et al deemed the uncertainty in flame length to be 10 % and Proust et al had an uncertainty of ± 20 cm in their recordings. Schefer et al [4] stated that 30 fps is not a sufficient resolution to follow the movement of the flame.

Schefer et al [3, 4] and Studer [13] used five successive frames to calculate the mean flame length. This is not enough frames to get a correct measurement of the flame length. This is illustrated in Table 5-1 where the results for the average flame length in project 111, test 2 is compared when altering the number of frames to five.

Table 5-1 Average flame length over 1250 frames compared to five frames

Project 111, test 2		
Average flame length (m) 1250 frames	Average flame length (m) five frames	Deviance
1.3878	1.4789	7%

It is observed that when only using five successive frames the mean flame length is 7% larger than when using 1250 frames, this deviance will alter at different intervals in the measured series, as the movement of the flame is not consistent. Because the experiments done for this report had a much higher frame rate it is possible that the uncertainty for [3, 4, 13] could be even larger.

It is speculated in when measuring the flame length with horizontal jets it would be shorter compared to vertical jets because of the buoyancy. It is however observed by Mogi et al [5] that the horizontal jets were barely affected by buoyancy.

When examining the different studies that were used to develop the HySAFER model, it is obvious differences in the methods used. However the HySAFER model can still be a good model for calculating flame length of hydrogen jets.

When comparing the flame length calculated with the HySAFER model and the experiments with the single nozzle configuration it is observed that in most cases the HySAFER model overestimates the flame length.

The largest deviance between the HySAFER model and the single nozzle configurations was 18 %. When taking into consideration that the HySAFER model has an error up to 20 %, these results contributes to the credibility of the HySAFER model.

It is determined that when creating a nozzle configuration with an upstream and downstream nozzle it is the upstream nozzle that determines the mass flow. The presence of the downstream nozzle is more significant at lower mass flows and helps to stabilize the flame. This is clearly observed for the $d_{0.5}$ and $d_{0.5}^{1}$ nozzles that gave blow-off at 20 bars, but were able to produce a jet when increasing the downstream nozzle to 2 mm and 4 mm.

The HySAFER model is developed for single nozzle configurations. The upstream nozzle determines the mass flow, but the downstream nozzle also has an impact on the flame length. However when comparing the HySAFER model to the experiments with an upstream and downstream nozzle configuration, it shows that the HySAFER model can be applied.

The comparison showed that the average deviance was below 18% for all the nozzle configurations, except the $d_{0.5}^{4}$. This nozzle configuration has the largest difference in the inner diameter of the upstream and downstream nozzle, which may be the reason for the discrepancy. However, this is something that should be investigated further.

As the HySAFER model only is dependent on the mass flow and the inner diameter of the nozzle it is an easy method to get a reference on an expected flame length.

6 Conclusion

The purpose of this report was to conduct experiments on the flame length obtained when igniting hydrogen with different nozzle configurations. This report has taken a new direction by examining how a more complex nozzle geometry will influence the flame length.

The experiments were carried out at the University College of Southeast Norway. The results are compared with the HySAFER model, which is currently the best model for calculating flame length of hydrogen jets.

To validate the experiments executed for this report the method used is compared with the different methods used to develop the HySAFER model. By examining the possible sources of error and comparing the method used in this report with other studies, it is concluded that the method used is optimal for determining flame length of hydrogen jets.

When creating the complex nozzle geometry, it is concluded that the upstream nozzle determines the mass flow, while the downstream nozzle also have an impact on the flame length. The presence of the downstream nozzle is more significant at lower mass flows and helps to stabilize the flame.

It is concluded that the HySAFER model is an easy and good engineering method to apply when it is necessary to get a reference on an expected flame length. All the results, with one exception, obtained from the executed experiments are within the margin of error set for the HySAFER model. The results showed one discrepancy for the nozzle configuration $d_{0.5}^{4}$, this should be investigated further.

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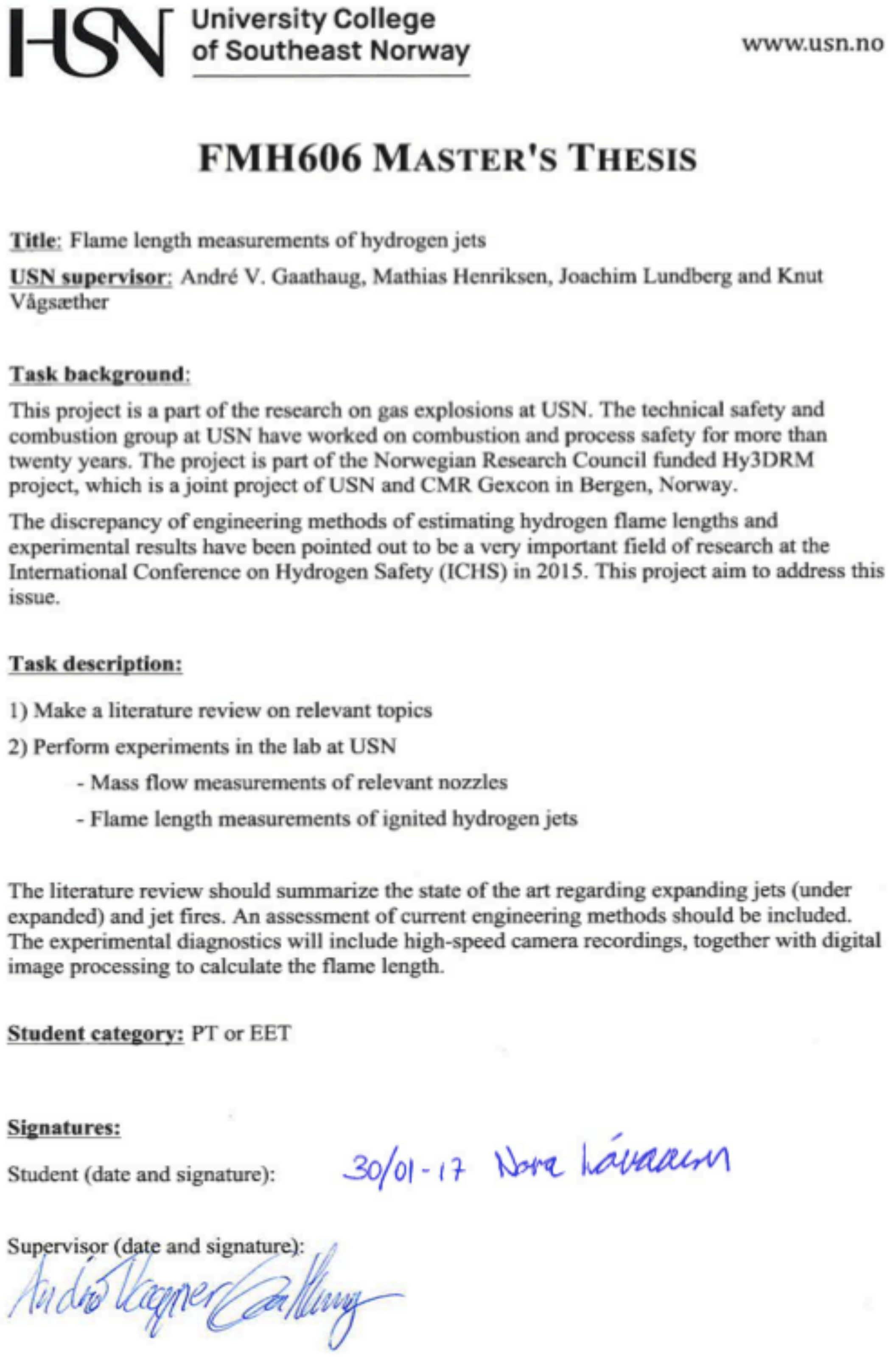
Appendices

Appendix A Task description



University College of Southeast Norway

www.usn.no

FMH606 MASTER'S THESIS

Title: Flame length measurements of hydrogen jets

USN supervisor: André V. Gaathaug, Mathias Henriksen, Joachim Lundberg and Knut Vågsæther

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

The discrepancy of engineering methods of estimating hydrogen flame lengths and experimental results have been pointed out to be a very important field of research at the International Conference on Hydrogen Safety (ICHS) in 2015. This project aim to address this issue.

Task description:

1) Make a literature review on relevant topics

2) Perform experiments in the lab at USN

   - Mass flow measurements of relevant nozzles
   - Flame length measurements of ignited hydrogen jets

The literature review should summarize the state of the art regarding expanding jets (under expanded) and jet fires. An assessment of current engineering methods should be included. The experimental diagnostics will include high-speed camera recordings, together with digital image processing to calculate the flame length.

Student category: PT or EET

Signatures:

Student (date and signature): 30/01-17 Nora

Supervisor (date and signature): André Vagner Gaathaug

Appendix B Safe Job Analysis (SJA)

EXECUTED BY: Nora Løvaasen					
AREA: A-102 Machine hall					
DATE:			**HSE - MSDS: YES - NO X**		
PARTICIPANTS:	**DEPARTMENT**	**SIGNATURE**	**PARTICIPANTS:**	**DEPARTMENT**	**SIGNATURE**
Nora Løvaasen	**PEM**		**Erik Nygaard**	**PEM**	
Andrè Vagner Gaathaug	**PEM**		**Joachim Lundberg**	**PEM**	
Mathias Henriksen	**PEM**				

NO	**ACTIVITY DESCRIPTION**	**RISK DESCRIPTION**	**SAFETY MEASURES**	**RESPONSIBLE / DEADLINE**
1	The experiment as a whole	Other than the participants getting injured	- Lock the door - Turn on warning lights	Nora Løvaasen
		The fire alarm goes off	- Deactivate the fire alarm	Nora Løvaasen
2	Switch on the coriolis meter and pressure sensor	Falling over loose cords	- Secure all cords	All participants
3	Open the gas cylinders	Potential leakage	- Listen after leakage sources - Make sure the check valves are closed	All participants

		Open to closed valves	- Make sure the selector valve is positioned at the correct gas cylinder - The needle valve must be opened	Nora Løvaasen
4	Opening the check valve on the nitrogen cylinder	Gas poisoning	- Make sure there is good ventilation - Do not flush the system more than 30 seconds - Be aware of potential leakage - Close the gas cylinder	All participants
		The hose disconnects	- Make sure all connections are secured properly	Nora Løvaasen
5	Opening the check valve on the hydrogen bottle	Explosion	- Make sure all released gas is burned - Be aware of potential ignition sources - Be aware of potential leakage - Close the gas cylinder	All participants

		Gas poisoning	- Make sure there is good ventilation - Make sure all released gas is burned - Be aware of potential leakage - Close the gas cylinder	All participants
		The pipe disconnects	- Make sure all connections are secured properly	All participants
6	Igniting the hydrogen	Uncontrolled fire	- Have fire extinguisher nearby - Close the gas cylinder	All participants
		Fire damage to skin	- Use protective gear: fire resistant gloves, fire resistant coat and helmet with shield	All participants
		Loud noise	- Use hearing protection	All participants
7	Preparing the camera, osciloscope and puls generator	Falling over loose cords	- Secure all cords	All participants
8	Closing the gas cylinders	The regulator on the bottles stays pressurized	- Open the check valve after closing the cylinders	All participants

Appendix C Experimental procedure

Startup

1. Put on safety gear: Fire resistant coat, helmet with shield and hearing protection
2. Deactivate the fire alarm by calling Statsbygg
3. Turn on the warning light
4. Lock the door
5. Write on message board
6. Turn on the ventilation system
7. Provide fire extinguisher
8. Close the window blinds
9. Connect the computer to the camera
10. Switch on the TV
11. Connect the puls generator to the camera
12. Switch on the Coriolis meter and temperature measurement
13. Make sure the pipe from the nitrogen cylinder is connected to the Coriolis meter
14. Open the nitrogen cylinder
15. Set the nitrogen pressure to 3-4 bar
16. Use the selector valve, select nitrogen
17. Open the needle valve before the Coriolis meter
18. Open the check valve on the nitrogen cylinder
19. Flush the system for approximately 15 seconds
20. Close the nitrogen check valve
21. Use the selector valve, select hydrogen
22. Open the hydrogen cylinder

During the experiment

23. Adjust the camera
    - Position the camera focus
    - Adjust the resolution
    - Set the frame rate to 250 fps
    - Take a snapshot of the calibration ruler
24. Prepare the oscilloscope
25. Prepare the puls generator
26. Switch to wanted nozzle configuration
27. Adjust safety gear: fire resistant coat, helmet with shield and hearing protection
28. Safety gear: put on fire resistant gloves
29. Regulate the valve on the hydrogen cylinder to wanted pressure
30. Prepare the torch

31. Lights off
32. Open the check valve on the hydrogen gas bottle, ignite the flame
33. Trigger the system to start recording measurements and video recordings
34. Close the hydrogen check valve
35. Lights on
36. Save the recordings

Shutdown

37. Close the hydrogen cylinder
38. Open the hydrogen check valve to depressurize the system
39. Close the hydrogen check valve
40. Use the selector valve, select nitrogen
41. Open the check valve on the nitrogen cylinder
42. Flush the system for approximately 15 seconds
43. Close the nitrogen cylinder
44. Close the nitrogen check valve
45. Switch off the Coriolis meter
46. Turn off the camera
47. Place the lense cap on the camera
48. Close the oscilloscope
49. Turn off power to signal generator
50. Turn off TV
51. Turn off the warning light
52. Unlock the door
53. Wipe the message board
54. Turn off the ventilation system no sooner than 15 minutes after the experiment
55. Activate the fire alarm by calling Statsbygg

Appendix D MATLAB code for calculating flame length

```
d = 5*10^-4;            % [m]
r = d/2;                % [m]
A = pi*r^2;             % [m^2]
M = 2*10^-3;            % [kg/mole]
R = 8.314;              % [J/mole*K]
T = (20+273);           % [K]
C = 1.0;
k = 1.41;
P_bar = 10: 10: 100;    % [bar]
P = P_bar*10^5          % [Pa]

% Calculating the different surface areas of nozzles
d1 = 5*10^-4;
d2 = 10^-3;
d3 = 2*10^-3;
d4 = 4*10^-3;

A1 =((pi*d1^2)/4);
A2 = ((pi*d2^2)/4);
A3 = ((pi*d3^2)/4);
A4 = ((pi*d4^2)/4);

% Calculating the choked mass flow
x = (2/(k+1)).^((k+1)/(k-1));
mf1 = C*A1*P*sqrt(((k*M)/(R*T))*x);
mf2 = C*A2*P*sqrt(((k*M)/(R*T))*x);
mf3 = C*A3*P*sqrt(((k*M)/(R*T))*x);
mf4 = C*A4*P*sqrt(((k*M)/(R*T))*x);

% Calculating the flame length
Lf1 = 54*(mf1*d1).^0.312;
Lf2 = 54*(mf2*d2).^0.312
Lf3 = 54*(mf3*d3).^0.312;
Lf4 = 54*(mf4*d4).^0.312;


plot (P_bar, Lf1, 'r-o')
xlabel ('Pressure [bar]')
ylabel('Flame length [m]')
hold on
plot (P_bar, Lf2, 'b-o')
hold on
plot (P_bar, Lf3, 'g-o')
hold on
plot (P_bar, Lf4, 'y-o')
legend ('d = 0.5 mm', 'd = 1 mm', 'd = 2 mm', 'd = 4 mm')
```

Appendix E MATLAB code for measuring flame length

```
clear all
clc
close all
%load background.mat
resolution = [256 1024];
start= 1;
endd = 1250;
%old_folder=pwd;
cd('/Users/Nora/Desktop/Skole/Master/Nora/17_NLo_P109_T_00001')
liste=dir('*.raww')                    % Listing. raww files

%% Conversion to grayscale
for i= start:endd;

    if mod(i,20)==0
        display(i)
    end

file = liste(i).name;
%file=char(file);
res=resolution;
fid = fopen(file, 'r');                            % open file
x = fread(fid, [res(2)* res(1)*3], '*int16');     % Read binary data to double
fclose (fid);                                      % close file

%% Extracting the RGB values, storing them in each plane.
R=double(x(1:3:end-2));
G=double(x(2:3:end-1));
B=double(x(3:3:end));

%% Reshaping the extracted values to full image resolution
RR=reshape(R,resolution);
GG=reshape(G,resolution);
BB=reshape(B,resolution);

%% Finding flame length
% Red

tv=find(RR./max(max(RR))>0.18);      % finds all values above the threshold
avg=zeros(size(RR));                 % zero matrix, same size as RR
avg(tv)=1;                           % values above threshold is set to 1
[aI,aJ]=ind2sub(resolution,tv);      % allocates the tv values to the
                                      correct place in the resolution matrix

nl = zeros (size(RR));               % creates zero matrix
nl(:) = 962;                         % sets the values to the y- value of
                                      the nozzle

hr(i) = 1024-min(aJ);                % flame length + nozzle height
```

```
nr(i) = 1024-min(nl(:));                % height of nozzle
fr(i) = hr(i)-nr(i);                    % flame length



mean_r = mean(fr(:));                   % mean value of flame length
sr = std(fr);                           % standard deviation
if i>5

    if fr(i)>mean_r+2*sr
        fr(i) = mean_r;
        display('Outlier')
    end
end

fr(i) = round(fr(i));




pixel = 1.612903226;                     % size of pixel in mm
fr_mm(i) = pixel*fr(i);                  % flame length in mm
fr_m(i) = fr_mm(i)*10^(-3);              % flame length in m

mean_r = mean(fr_m(:));                  % mean value of flame length
sr = std(fr_m);                          % standard deviation


% Green
tv=find(GG./max(max(GG))>0.2);
avg=zeros(size(GG));
avg(tv)=1;
[aI,aJ]=ind2sub(resolution,tv);

nl = zeros (size(GG));
nl(:) = 975;

hg(i) = 1024-min(aJ);
ng(i) = 1024-min(nl(:));
fg(i) = hg(i)-ng(i);

pixel = 1.3761;
fg_mm(i) = pixel*fg(i);
fg_m(i) = fg_mm(i)*10^(-3);

sg = std(fg_m);


% Blue
tv=find(BB./max(max(BB))>0.2);
avg=zeros(size(BB));
avg(tv)=1;
[aI,aJ]=ind2sub(resolution,tv);

nl = zeros (size(BB));
nl(:) = 975;
```

```
hb(i) = 1024-min(aJ);
nb(i) = 1024-min(nl(:));
fb(i) = hb(i)-nb(i);

pixel = 1.3761;
fb_mm(i) = pixel*fb(i);
fb_m(i) = fb_mm(i)*10^(-3);
sb = std(fb_m);


%% Scaling an image of n bit to a full stretching of 16bits
n=10;
rr = RR./(2.^n).*2.^16;
gg = GG./(2.^n).*2.^16;
bb = BB./(2.^n).*2.^16;

%%

F_IMAGE = zeros(resolution(2),resolution(1),3);
F_IMAGE =uint16(F_IMAGE);
F_IMAGE(:,:,1)=rr';
%F_IMAGE(1024-fr(i),:,1)=ones(1,256).*2^16;
F_IMAGE(:,:,2)=gg';
%F_IMAGE(1024-fg(i),:,2)=ones(1,256).*2^16;
F_IMAGE(:,:,3)=bb';
%F_IMAGE(1024-fb(i),:,3)=ones(1,256).*2^16;

filnavn = 'FlamePicture_';
    if mod(i,50)==0
        imshow(F_IMAGE)
        g=getframe();
        imwrite(F_IMAGE,[filnavn,num2str(i),'.png'])
        display('lagrer bilde')
    end

end

y = [1:1:1250];
plot(y, fr_m, 'r')
xlabel ('Number of frames')
ylabel ('Flame length [m]')
%plot(y, fg_k, 'g');
%plot(y, fb_k, 'b');
```

Appendix F Experimental matrix

This appendix presents all the measured and calculated values for each experiment. Nozzle diameter 1 is referring to the upstream nozzle, while nozzle diameter 2 is the downstream nozzle. Spouting pressure is the pressure regulated at the hydrogen cylinder. Std flame is the standard deviation. The mean flame length, std flame and threshold value is all determined using MATLAB. The mean gauge pressure, mean mass flow and temperature are values from the oscilloscope, which has also been processed in MATLAB.

Project	Test	Nozzle diameter 1 (mm)	Nozzle diameter 2 (mm)	Spouting pressure (bar)	Mean flame length (m)	Std flame
103	3	0.5	None	40	0.3339	0.0387
104	1	1	None	100	1.129	0.0699
104	2	1	None	80	1.0082	0.0657
104	3	1	None	60	0.8885	0.0666
104	4	1	None	40	0.782	0.0642
104	5	1	None	20	0.4866	0.049
104	6	2	None	20	0.8388	0.0603
104	7	2	None	40	1.0786	0.0643
105	1	2	None	60	1.1899	0.103
105	2	2	None	100	1.5115	0.0828
105	3	2	None	80	1.3634	0.0975
106	1	0.5	1	40	0.3792	0.0478
106	2	0.5	1	80	0.6043	0.0702

Project	Test	Nozzle diameter 1 (mm)	Nozzle diameter 2 (mm)	Spouting pressure (bar)	Mean flame length (m)	Std flame
106	4	0.5	2	80	0.6538	0.0698
106	5	0.5	2	60	0.5705	0.0732
106	6	0.5	2	40	0.4609	0.0501
106	7	0.5	2	20	0.313	0.0467
106	9	0.5	4	80	0.8091	0.1072
106	10	0.5	4	60	0.7133	0.0735
106	12	0.5	4	20	0.4331	0.0705
106	16	1	2	40	0.7443	0.0796
106	17	1	2	20	0.5468	0.0732
106	18	1	4	40	0.9356	0.0853
106	19	1	4	20	0.7632	0.097
107	1	1	4	100	1.113	0.0739
107	2	1	4	80	1.037	0.0733
107	3	1	4	60	0.9587	0.0631
107	4	1	2	100	1.0364	0.0694
107	5	1	2	80	0.9708	0.0676
107	6	0.5	1	100	0.6259	0.0491
107	7	0.5	2	100	0.6471	0.0654

Project	Test	Nozzle diameter 1 (mm)	Nozzle diameter 2 (mm)	Spouting pressure (bar)	Mean flame length (m)	Std flame
108	1	1	4	100	1.1187	0.06
108	2	1	4	80	1.0735	0.0681
108	3	2	4	40	1.1286	0.0658
108	4	2	4	60	1.2215	0.0716
108	5	2	4	20	0.9587	0.0678
109	1	0.5	None	60	0.4785	0.0571
109	4	0.5	None	100	0.656	0.0577
109	5	0.5	None	80	0.6258	0.0443
111	1	2	4	100	1.4592	0.0985
111	2	2	4	80	1.3878	0.0903

Project	Test	Threshold value	Mean gauge pressure (bar)	Mean mass flow (g/s)	Temperature (°C)
103	3	0.1	35.93	0.43	19.41
104	1	0.08	89.80	3.76	20.09
104	2	0.08	69.41	2.92	19.98
104	3	0.08	51.11	2.16	19.96
104	4	0.08	37.67	1.61	20.02
104	5	0.1	15.87	0.69	20.07
104	6	0.08	9.64	1.76	20.00
104	7	0.08	18.82	3.35	20.12
105	1	0.1	29.94	5.30	19.91
105	2	0.08	50.54	8.56	19.61
105	3	0.11	40.04	6.88	19.32
106	1	0.17	37.39	0.45	19.39
106	2	0.12	78.24	0.92	19.73
106	3	0.13	57.35	0.68	19.77
106	4	0.1	74.97	0.88	19.85
106	5	0.11	55.53	0.65	19.90
106	6	0.14	38.92	0.46	19.92

Project	Test	Threshold value	Mean gauge pressure (bar)	Mean mass flow (g/s)	Temperature (°C)
106	7	0.17	17.23	0.20	19.84
106	9	0.14	74.57	0.88	20.01
106	10	0.12	58.79	0.69	19.96
106	11	0.09	37.14	0.44	20.03
106	12	0.13	20.17	0.24	19.97
106	15	0.08	46.95	2.00	20.09
106	16	0.1	33.69	1.44	19.80
106	17	0.12	16.37	0.71	19.55
106	18	0.08	32.58	1.39	19.86
106	19	0.09	16.08	0.70	19.70
107	1	0.08	83.85	3.52	19.81
107	2	0.09	70.54	2.97	20.22
107	3	0.08	52.78	2.23	20.46
107	4	0.08	88.61	3.72	20.37
107	5	0.08	71.86	3.03	19.93
107	6	0.08	96.24	1.13	19.94
107	7	0.1	96.03	1.12	20.17
107	8	0.08	96.34	1.13	20.34

Project	Test	Threshold value	Mean gauge pressure (bar)	Mean mass flow (g/s)	Temperature (°C)
108	1	0.08	85.87	3.61	20.50
108	2	0.08	67.29	2.85	19.78
108	3	0.08	20.42	3.44	19.86
108	4	0.09	26.21	4.42	19.32
108	5	0.08	9.90	1.75	18.11
109	1	0.18	56.0295	0.6628	21.3013
109	4	0.16	96.9275	1.1393	21.6282
109	5	0.15	76.0448	0.8974	21.977
111	1	0.13	52.4076	8.6141	21.1055
111	2	0.13	41.5274	6.9423	19.5442