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Statistical analysis of colliding sprays in HCCI-combustion

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Abstract

This diploma thesis is a result of a project in HCCI, homogeneous charge compression ignition, research performed at KTH in collaboration with Scania. The development of the HCCI-engine is under progress with reference to reduce emissions while maintain high efficiency. This research involves rotating nozzles and colliding sprays concerning HCCI-combustion.

A system for visualization of fuel sprays behavior has been developed at Machine Design KTH, Internal Combustion Engines, in which the course of injection can be studied. Among other things, the effect of colliding sprays can be investigated.

The aim of this report is to be a statistical contribution to the research taking place at KTH within HCCI-combustion. The purpose was to design an experiment so that appropriate data, which can be analyzed with statistical methodology, could be collected.

The first approach was to conduct an overall factorial experiment, which turned out to be impossible to conduct. A second approach was chosen, which was to conduct a single-factor experiment and perform a regression analysis under given premises, this implies a restricted statistical analysis.

Preface

This diploma thesis is a result of a collaboration with a group of doctorates at KTH. The aim was to be a statistical contribution to the research taking place within HCCI-combustion.

Even though the overall factorial investigation initially intended could not be conducted, due to circumstances, I think the results can be useful within future research concerning rotational nozzles and colliding sprays in HCCI-combustion. Some understanding about the course of injection and how the different variables effect it can be achieved from this report. Since there exist an interest in learning more about designed experiments and it's advantages, there really is a lot to learn from this report.

In order to cover the development of this investigation the report is disposited as follows:

The first chapter include an introduction to the design of experiments and an introduction to the background, experimental set-up, variables, statement of the problem and other things that are useful to know throughout the report.

The next chapter, chapter 2, includes the first choice of experimental design, a factorial experiment, which unfortunately couldn't be conducted.

In chapter 3, an analysis for one of the nozzles is conducted. The design used is a single-factor experiment, where the factor allowed to be varied will be the injection time.

In the following chapter, chapter 4, the problems that appeared/came to knowledge during the investigation are discussed. This is followed by some recommendations for further investigations.

Some reflections and conclusions are given in the final chapter.

When experiments are involved in research there's always a risk for technical things going wrong, breaking down or just not working as you want. That the conditions for conducting the experiment changes during the investigation is common. This study was not an exception.

Unfortunately, due to circumstances, this report only include a detailed analysis of one of the nozzles that were available. The experimental set-up was very instable and the first choice of design turned out to be impossible to conduct. During the second approach the experimental set-up broke down completely, which explains the lack of valid results for the remaining nozzles.

I would like to thank Jan-Olov Persson and Rolf Sundberg at Mathematical Statistics, Stockholm University, Fredrik Wåhlin at Machine Design, Royal Institute of Technology and Andreas Cronhjort at Scania.

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Contents

Chapter 1

Introduction

Traditional diesel engines suffer from relatively high particulate matter and oxide of nitrogen, NO_x,[1] emissions. Research focused on simultaneous reduction of emissions is being conducted on a large scale. For homogeneous charge compression ignition, HCCI, engines with direct injected diesel fuel, it is important to achieve a lean and homogeneous air-fuel mixture before ignition takes place.

This report aims to be a statistical contribution, by designing an experiment, in the search for an optimal injection for an HCCI-engine with direct injected fuel.

1.1 Design of experiments

In engineering, experimentation plays an important role in the new product design, manufacturing process development, and process improvement.

An experiment can be defined as a test or series of tests in which purposeful changes are made to the input variables of a process or system so that the reasons for changes that may be observed in the output variables, may be observed and identified.

The general approach to planning and conducting experiment is called the strategy of experimentation. The first step is to design an experiment.

When designing experiments it is desired that the design should:

- be as efficient as possible, considering eventual limitations
- give the possibility to make generalization from the results
- serve as a protection from systematically errors
- not lead to any unnecessarily complicated statistic analysis
- be easy to accomplish

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[1] NO_x is a collective noun for sundry nitrogen oxides.

1.1.1 Basic principles

Statistical design of experiments refers to the process of planning the experiment so that appropriate data, that can be analyzed by statistical methods, can be collected resulting in valid and objective conclusions.

The statistical approach to experimental design is essential if one wishes to draw meaningful conclusions from the data. When the problem involves data that is subject to experimental errors, a statistical methodology is the only objective approach to analysis. However, there are two aspects to any experimental problem; the design of the experiment and the statistical analysis of the data. These two subjects are closely related since the method of analysis depends directly on the design employed.

Some guidelines when designing an experiment:

1. Recognition of and statement of the problem
2. Choice of factors, levels, and ranges
3. Selection of the respons variable
4. Choice of experimental design
5. Performing the experiment
6. Statistical analysis of the data
7. Conclusions and recommendations

The first step is to collect as much information as possible. This includes study of previous measurements, if it exists, and/or theoretical information.

1.2 Background

A constant development, [1, 2], of the combustion engine is under progress with the aim of reducing the fuel consumption and emissions. Producers of engines strive after as low emissions as possible. The kind of emissions obtained depends on the type of combustion cycle being used. The most common types of combustion engines are the spark ignition and the diesel engine.

With the spark ignition a premixed fuel-air mixture is ignited with a spark. The combustion result in high emissions but in combination with a catalyst the exhaust emissions are low. The disadvantage is low efficiency, especially on low to intermediate load.

With the diesel engine the fuel is injected with high pressure. During injection the air in the chamber has high pressure and high temperature. The combustion produceres large amounts of NO_x and particulate matter emissions. NO_x is a result of high temperature and particulate matter emissions is a result of high fuel concentrations during combustion. The diesel engine is generally more efficient than the spark ignition engine.

In HCCI-combustion the best of the spark ignition and the diesel engine are tried to be combined. In direct injected HCCI engines, time is needed to mix air with fuel to a homogeneous mixture. In order to get the best combustion, some time must pass between direct injection and ignition, so that air and fuel can form a homogeneous mixture.

A homogeneous air-fuel mixture leads to an almost simultaneous combustion in the whole combustion chamber and the fast combustion results in a high efficiency. The HCCI-combustion result in very low substance of NO$_x$ and particulate matter emissions.

In order to reduce the emissions while maintain high efficiency, HCCI-combustion research is constantly taking place. At Machine Design KTH, Internal Combustion Engines, there has been developed a system called "the Bomb", in which the course of injection can be studied.

"The Bomb" is designed after a diesel engine from Scania (model D12) and is principally a cylindrical pipe with the same diameter as the engine mentioned. More detailed information about it can be found in the report by Johan Wickerfält [1], who is the constructor of the experimental set-up.

Figure 1.1 shows the experimental set-up. The sprays injected into the vessel can be photographed from the sides and from below via a mirror, and be analyzed from a picture evaluation.

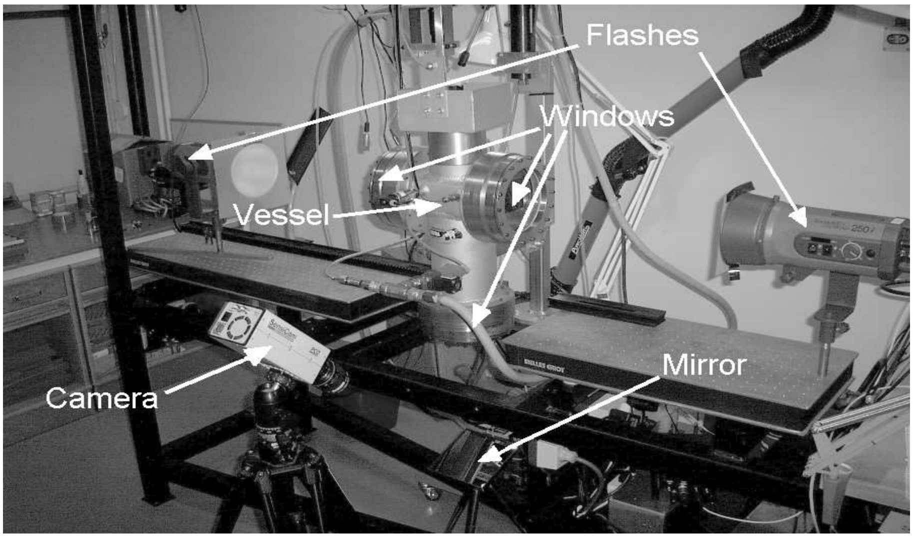

Figure 1.1: A picture of the experimental set-up. The sprays injected into the vessel can be photographed from the sides and from below via the mirror

1.3 Recognition of and statement of the problem

With HCCI-combustion the purpose is to create a homogeneous mixture that is ignited by compression. This could be achieved by an early injection of the fuel. One important parameter for HCCI-combustion is how the fuel is mixed with the air in the combustion chamber.

In HCCI-combustion the fuel needs to be introduced with direct injection into the combustion chamber. The injection consists of a number of repeated sprays, which takes place early in the compression stroke to give sufficient time for the air and fuel to mix properly.

The mixture of the fuel and air in the spray depends on variables such as nozzle, gas back pressure, injection pressure, injection time and injector rotational speed. These variables will be introduced in section 1.4.2. A measurement of the mixture of the fuel and air in the spray can be achieved by investigating the proportion of injected fuel in the spray.

In order to examine which spray that provides the best mixture the shape of the spray can be studied from photographs taken of the spray in the vessel. Via a picture evaluation, which gives the penetration, cone angle and boundary of the spray, and a numerical integration, the spray volume can be estimated. A photograph of the spray is shown in figure 1.2.

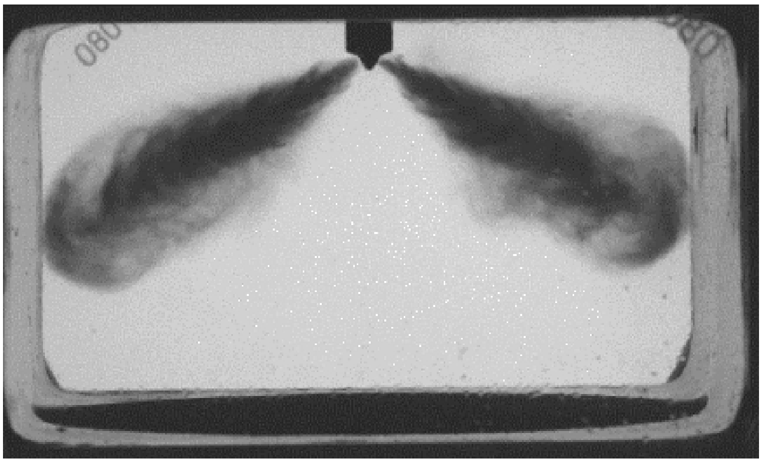

Figure 1.2: A photograph taken of the injected spray in the vessel. To examine which spray that provides the best mixture the shape of the photographed spray can be studied.

1.4 Selection of the response variable

For HCCI-combustion there are two main factors effecting the homogeneity of the mixture before ignition takes place:

- The course of injection
- The mixing time, i.e., the time between injection and ignition

The course of injection is the topic for this investigation. The time between injection and ignition, i.e., the mixing time in the combustion chamber, can only be investigated in engine try outs.

The moment for injection correspond to a specific density in the combustion chamber, which can be described by the gas back pressure in the experimental vessel. The density in the combustion chamber vary with the motion of the piston.

When investigating how lean a spray can become and under which premises this appear, the ratio *injected spray mass by injected fuel/diesel mass* is under investigation. By investigating the mass of the spray and dividing it with the injected fuel mass a comparable measurement of the relation air-fuel mixture is achieved. There are two different specific relations of interest; 14.6 and 21.9.

At the relation 14.6 there is precisely as much oxygen in the spray that is needed for a complete combustion (without EGR, Exhaust Gas Recirculated). However, it's more common with HCCI combustion with EGR, which implies recycling already combusted gases and mix it with incoming air. It's possible to use up to approximately 50% EGR in a HCCI engine. By doing this the concentration of oxygen molecules are being lowered and the fuel is reacting slower which is favorable at higher load on the engine. To achieve enough oxygen molecules for a complete combustion the ratio has to be $14.6 \cdot 1.5 = 21.9$ when using 50% EGR.

Spray volume to spray mass

From the picture taken of the spray, see figure 1.3, the penetration, i.e., the length of the spray, the boundary and the cone angle of the spray is given. Assuming that the spray is symmetric around its axis makes it possible to numerically integrate to achieve the volume by using formula (1.1).

$$V \approx \sum_{i=0}^{p_{max}} \pi r_i^2 \Delta x_i \tag{1.1}$$

Where Δx_i is the width of one pixel, and r_i is defined as

$$r_i = p_i \sin\left(\frac{\alpha_i}{2}\right)$$

where p_i is the length of the penetration at i and α_i is the cone angle to the corresponding penetration p_i.

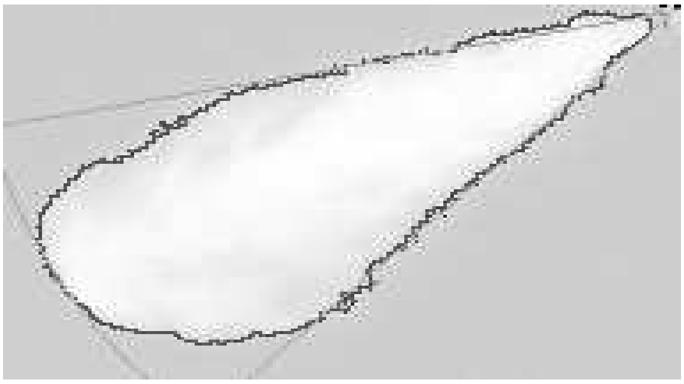

Figure 1.3: A description of the picture evaluation. From the picture taken of the spray; the penetration, the boundary and the cone angle of the spray is given.

The spray mass, m, can then be obtained, from the calculated volume, by using the ideal gas law, $PV = nR_0T$, which gives the following relation

$$m = \frac{PV}{RT}$$

since $n = m/M$ and $R = R_0/M$. Also have that $T = 22$°C$= 294.68$K and $R = 287$, which gives

$$m = \frac{PV}{84573}$$

Injected fuel mass

The fuel injected into the system is the denominator in the ratio, but it can not be automatically measured per spray. To be able to estimate the amount of fuel injected, extra measurements must be made separately. This means that there's not one fuel mass directly associated to one specific measurement of the spray mass.

To estimate the injected fuel mass, 500 injections are made in a beaker and the amount is read of. It is favorable that the injected fuel mass is as large as possible. Any specific fuel mass is difficult to mention, since the amount of injected fuel is proportional to the load. At higher load it's more important that all the injected fuel is mixed homogeneously with the air.

1.4.1 Other important aspects

In addition to the mixture of fuel and air in the combustion chamber, it is also of interest to investigate how the penetration and end of injection, EOI, functions under given premises.

Penetration

One important aspect concerning the respons is the penetration. It is absolutely necessary that the spray does not hit the inner wall in the vessel/combustion chamber. Overpenetration can lead to that the fuel consumption increases since less of the fuel takes part in the combustion, also to detrimental effects on emissions and soot contamination of the lubrication oil which lead to a higher wear of the system.

The maximum penetration allowed is 0.075 m.

End of injection

In figure 1.4 the needle controlling the injection is illustrated. The EOI is the time interval in which the needle allows the fuel to be injected since the start of injection, SOI, is set to zero. The EOI is a result of the injection time, injection pressure and nozzle.

The moment for taking the picture of the spray is decided from the the EOI. In this study the photograph will be taken precisely after the injection is finished. But if wanting to study how the spray has developed after some specific time in the vessel the photograph has to be taken later. This specific moment, e.g., some fixed time after the injection has finished, can be decided from the EOI which makes it interesting to know how it function.

1.4.2 Variables

A summary of the variables and their possible ranges can be found in table 1.1, and a more thoroughly description of them follow below.

Table 1.1: A summary of the variables, which can be used in this study, and their possible ranges.

Variable	Range
Orifice diameter, [mm]	$0.12 - 0.20$
Impingement angle, [°]	$0 - 60$
Injector rotational speed, [Rpm]	$0 - 10000$
Injection time, [ms]	$0-$
Injection pressure, [Bar]	$250 - 1350$
Gas back pressure, [Bar]	$1 - 15$

Nozzle; orifice diameter and impingement angle

There are two variables of interest concerning the nozzle; the orifice diameter and the impingement angle. The latter is of interest when investigating if it's possible to increase the distribution of the fuel spray by letting two sprays collide.

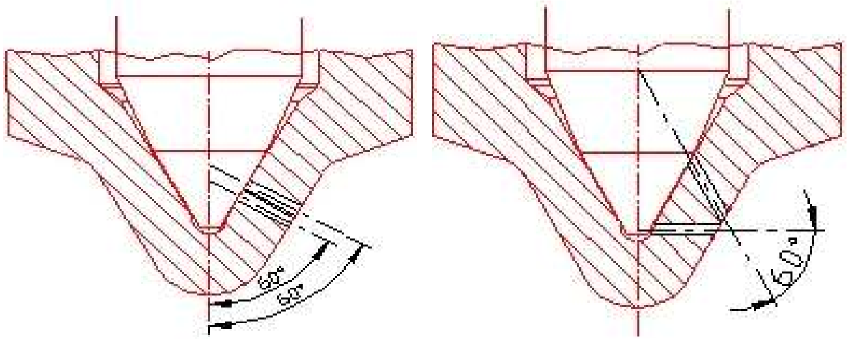

Figure 1.4: Illustration of the components of the nozzle. The left picture in the figure shows no impingement angle and the right picture shows an $60°$ impingement angle. Also illustrated is the needle controlling the injection.

The injection for each spray takes place through two holes, and the orifice diameter is the diameter of each hole and has a valid range of $0.12 - 0.2$ mm. The angle between the two holes is the impingement angle. It has a valid range of $0° - 60°$, where $0°$ means no angle, i.e., two parallell holes. All this is illustrated in figure 1.4, where the left picture in the figure shows no impingement angle and the right picture shows an $60°$ impingement angle.

Injector rotational speed

The injector rotational speed is the speed in which the nozzle can be rotated. By rotating the nozzle one hopes for a better mixture of the fuel and air in the experimental vessel/combustion chamber. The injector rotational speed can be varied between 0 and 10^4 Rpm.

Injection time

The time interval in which the fuel is set to be injected is called the injection time. The valid range rises from approximately[2] 0 ms and it's upper limit is the time just until the spray hits the inner wall in the experimental vessel. The upper limit depends on all the other variables.

Injection pressure

The injection pressure is the pressure in which the diesel is being injected into the experimental vessel. The valid measuring range is 250–1350 Bar and the entire range is of possible interest.

Gas back pressure

The gas back pressure is the pressure within the experimental vessel and it has a valid range of $1 - 15$ Bar. It was mentioned earlier that the gas back pressure in the experimental vessel represent the density in the combustion chamber in an engine.

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[2] It's difficult to receive reliable results with very small injection times.

Chapter 2

First approach

An appropriate approach when dealing with several factors is a factorial design, an experimental strategy in which factors are varied together.

This optimization problem includes six different variables and therefore a suitable approach is to design and conduct a factorial experiment.

A factorial design makes it possible to detect interactions between the variables and it allows the effect of a factor to be estimated at several levels of the other factors. This yield in conclusions that are valid over a range of experimental conditions. It's of interest that the model allows interpolation between different levels of each factor, which a factorial model do.

2.1 Model 1 – Factorial experiment

In this case information from previous measurements consist of measurements from a nozzle which was not to be used in this study, but the principle was said to be the same. The nozzle consisted of eight individual sprays and it was not manufactured to handle rotation. This was the only pre-existing information available about the process and it was therefore studied.

For this nozzle, there were three variables that could be studied; the injection pressure, the gas back pressure and the injection time. The results from these previous measurements indicated that a factorial experiment could be an appropriate approach when wanting to investigate the course of injection. This was a result of the possible sample spaces for the different factor combinations. However, the possible sample spaces would not include any extreme points but this won't be a problem, since the first step of the study would be a screening experiment.

In a screening experiment it's of interest to determine which process variables effect the response, and in what way they might do that. Starting with only two levels of each factor is therefore appropriate. By obtaining some extra measurements in the center point of each factor indications of curvature can be obtained. A climbing method, e.g., steepest ascent, can then be used to locate the optimum or the area in which there might be one.

This problem involves $k = 6$ variables, and for large values of k the higher-order interactions can be assumed to be negligible. This allows the usage of a fractional factorial design, which contain 2^{k-l} runs, i.e., the 2^{-l} fraction of a factorial design.

2.1.1 Choice of levels and ranges

The levels of the different factors should be chosen so that they cover the area of interest and they should be equally distributed over the possible ranges. The experiments will take place for all of the possible combinations of factor levels.

The levels of the factor gas back pressure that is of interest are 3, 6 and 12 Bar, where 6 Bar represent the center point. For the injection pressure the corresponding values of interest are 250, 800 and 1300 Bar. The injection times of interest appear to vary between 0.5 and 1.8 ms which gives the center point 1.15 ms.

Choosing nozzles

The nozzles are expensive to manufacture and with a 2-level factorial model in mind five nozzles were ordered at first. They were chosen after the corner points and the center point of the model, i.e., the nozzles 0.12 mm $\times 0°$, 0.12 mm $\times 60°$, 0.2 mm $\times 0°$, 0.2 mm $\times 60°$ and 0.16 mm $\times 30°$. It's possible to later manufacture more nozzles if there is a certain area of interest to investigate further.

Injector rotational speed

The picture evaluation has been developed under the assumption that the spray is homogeneous around its axis. It is not certain that the picture evaluation stands for the rotation since the spray likely will take the shape of a “banana” when rotating the nozzle. This might not be an issue with very short injection times and low rotational speeds, but the problem will likely appear with longer injection times and higher rotational speeds.

Replication and randomization

In order to determine an estimate of the experimental error and to obtain more precise estimates of the effects, the number of replicates of the spray mass is set to three. The number of replicates of the injected fuel mass is set to two, since they are more complicated to measure.

By randomizing the order in which the experiments are conducted a protection of possible systematical errors is achieved. Since the nozzles are difficult and time consuming to assemble, it's practical to randomize within these.

2.1.2 Choice of experimental design

After investigating the results from previous measurements the first idea was to use a 2-level factorial design for the entire investigation.

As mentioned, the nozzles are difficult and time consuming to assemble. This means that it is not suitable to completely randomize the order of the runs. If to be able to randomize only within the factor nozzle, a generalization of the factorial design has to be done. This results in a design called a split-plot design.

The split-plot design

In a split-plot design each replicate or block is divided into parts called whole plots, and the variables are called whole plot treatments or main treatments. Each whole plot is then divided into subplots, where the treatment combinations are tested in random order.

Applying the split-plot design to this situation and the five different nozzles gives five parts of the design called whole plots, per replicate. From each whole plot a 2^{k-l}-fractional factorial design will represent the subplot. This is possible since the decision is made that the higher-order interactions can be assumed to be negligible. The subplot will consist of four variables so that a subplot on the form 2^{4-1} can be suitable.

A schematic illustration of the split-plot designs components is shown in table 2.1. The design matrix for each replicate is given in table 2.2, where; $-$ denotes the lower level, $+$ the higher level, and 0 the center point. The design generator used is $I = CDEF$, so that the factor F is given by CDE. If to limit the replicates to two, it would be appropriate to let the second replicate be given by the generator $I = -CDEF$.

Table 2.1: A schematic illustration of the components divided into whole plot and subplot in the split-plot design.

Whole plot:	
(A)	Orifice diameter
(B)	Impingement angle
Subplot:	
(C)	Gas back pressure
(D)	Injection pressure
(E)	Injection time
(F)	Injector rotational speed

2.2 Results

In order to decide which specific injection times to use some complementary experimental runs were made. While these were performed it was discovered that something was wrong with the experimental set-up. The results achieved wasn't reliable at all. The most impending problem involved the EOI. It was working irregular and the problem did not seem solvable. A model that could explain how the EOI was working as a function of the injection time was tried, but it turned out that it wasn't possible to find a function that could do this. This implied that the problem was more dominating and extensive than just the involvement of the EOI. This meant that a more thoroughly verification of the experimental set-up had to be done.

2.2.1 Verification of the experimental set-up

The verification of the experimental set-up was principally about finding the source of error and all components were thoroughly tested.

After the verification was done the conclusion was made that it was a special component, which was needed for the possibility of rotation, that was non-functional. The only solution found was to remove that part, which consequently involved the removal of the variable injector rotational speed.

When the experimental set-up was working again it turned out that the conclusions that were made earlier, which led to the decision about a factorial design, wasn't holding anymore.

It turned out that it wasn't possible to find any squared sample spaces with the "new" experimental set-up. The width of the possible intervals for the injection times differed considerable. Results of the possible injection times from one of the nozzles, two different gas back pressures and four different injection pressures are shown in figure 2.1.

In a factorial model all possible combinations of the levels of the factors are investigated. This will be impossible in this case, since it's not possible to find two (or more) levels of the factor injection time for one combination of the other factors that could be possible to investigate under another combination of remaining factors. This is clearly depicted in figure 2.1.

Some transformations, codings and scaling of the variables was tried out in order to gain control over the shapes of the sample space of intrest, without any encouraging results.

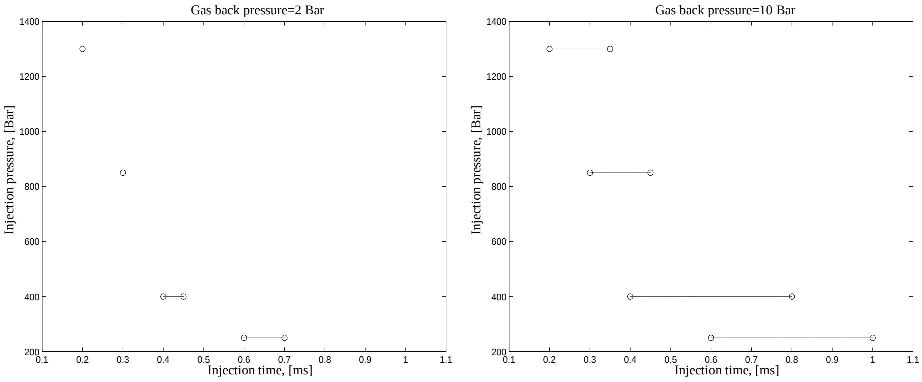

Figure 2.1: The possible sample spaces concerning the injection time and injection pressure for the nozzle 0.12 mm $\times 0^{\circ}$. The figure shows the results of the possible injection times for two different gas back pressures and four different injection pressures.

2.2.2 Conclusions, Model 1

The model employed, the factorial model with the chosen levels, turned out to be impossible to conduct in this investigation. Therefore, no results were gained.

It was also found out during this investigation that no results could be achieved when using the higher injection pressures for the nozzles with no impingement angle. The variable injector rotational speed will be completely removed from the study.

The only conclusion that can be made this far is that this factorial design is not the best approach for this investigation, under these circumstances, in search for an optimal injection in a HCCI-combustion. Another solution has to be found.

In order to find another solution some of the problems that was discovered during the verification of the experimental set-up has to be solved. One of the more impending problems is the different sprays within injection.

Different sprays per injection

As mentioned earlier each injection consist of two sprays, and one impending problem which has been discovered is that there is a difference between these two sprays. One of the sprays, the same spray every time, is always a bit larger than the other. Figure 2.2 illustrate this.

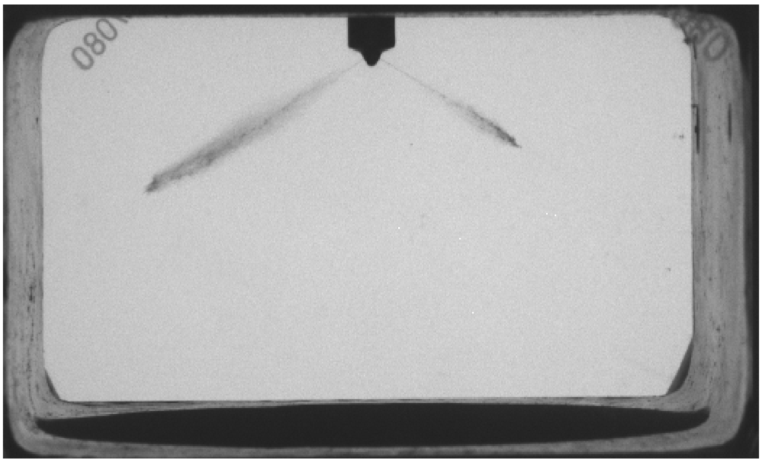

Figure 2.2: Picture illustrating the difference between the two sprays within each injection due to the needle being skew. One of the sprays, the same spray every time, is always a bit larger than the other.

The difference in shape is a result of the needle controlling the injection being skew, i.e., when the injection takes place the needle throttles the supply of fuel a bit for one spray resulting in additional contribution for the second spray.

This effects all of the responses; the penetration, the cone angle and consequently the calculated volume. These problems have to be solved, before continuing the study.

2.2.3 Theoretical solution of the problems related to the skew needle

There appeared some problems when trying to perform the experiments by this factorial design, and these must be taken under consideration when trying to fit a new model to the data.

Since the penetration is one of the problems caused by the skew needle, this was stated in section 2.2.2, only the larger penetration can be taken under consideration and into the calculations. This could seem a bit misleading, but the other option is to use the average penetration and this could definitely be more misleading, since this can give the impression that the spray is far from hitting the wall, when there actually is a huge risk that the wall already has been touched by the spray. By using the maximum penetration this risk will be minimized.

The different shapes of the two sprays also lead to that the calculations must be done using the sum of both sprays masses. This is also appropriate because the fuel mass measurements can not be done for the sprays separately. And since there is no telling of the distribution of fuel between the two sprays within an injection this is a suitable solution.

The cone angle is also effected, but the effect only shows in the volume, and consequently the calculated mass, which problem is solved by reasoning above.

Table 2.2: The design matrix for a wholeplot in the split-plot design per replicate. The $-$ respectively $+$ represent the lower respectively the higher factor level, and 0 represent the center point.

Run	$A\ B$	$C\ D\ E\ F$	Run	$A\ B$	$C\ D\ E\ F$
1	$-\ -$	$-\ -\ -\ -$	31	$-\ +$	$-\ +\ +\ -$
2	$-\ -$	$+\ -\ -\ +$	32	$-\ +$	$+\ +\ +\ +$
3	$-\ -$	$-\ +\ -\ +$	33	$-\ +$	$0\ 0\ 0\ 0$
4	$-\ -$	$+\ +\ -\ -$	34	$-\ +$	$0\ 0\ 0\ 0$
5	$-\ -$	$-\ -\ +\ +$	35	$-\ +$	$0\ 0\ 0\ 0$
6	$-\ -$	$+\ -\ +\ -$	36	$-\ +$	$0\ 0\ 0\ 0$
7	$-\ -$	$-\ +\ +\ -$	37	$+\ +$	$-\ -\ -\ -$
8	$-\ -$	$+\ +\ +\ +$	38	$+\ +$	$+\ -\ -\ +$
9	$-\ -$	$0\ 0\ 0\ 0$	39	$+\ +$	$-\ +\ -\ +$
10	$-\ -$	$0\ 0\ 0\ 0$	40	$+\ +$	$+\ +\ -\ -$
11	$-\ -$	$0\ 0\ 0\ 0$	41	$+\ +$	$-\ -\ +\ +$
12	$-\ -$	$0\ 0\ 0\ 0$	42	$+\ +$	$+\ -\ +\ -$
13	$+\ -$	$-\ -\ -\ -$	43	$+\ +$	$-\ +\ +\ -$
14	$+\ -$	$+\ -\ -\ +$	44	$+\ +$	$+\ +\ +\ +$
15	$+\ -$	$-\ +\ -\ +$	45	$+\ +$	$0\ 0\ 0\ 0$
16	$+\ -$	$+\ +\ -\ -$	46	$+\ +$	$0\ 0\ 0\ 0$
17	$+\ -$	$-\ -\ +\ +$	47	$+\ +$	$0\ 0\ 0\ 0$
18	$+\ -$	$+\ -\ +\ -$	48	$+\ +$	$0\ 0\ 0\ 0$
19	$+\ -$	$-\ +\ +\ -$	49	$0\ 0$	$-\ -\ -\ -$
20	$+\ -$	$+\ +\ +\ +$	50	$0\ 0$	$+\ -\ -\ +$
21	$+\ -$	$0\ 0\ 0\ 0$	51	$0\ 0$	$-\ +\ -\ +$
22	$+\ -$	$0\ 0\ 0\ 0$	52	$0\ 0$	$+\ +\ -\ -$
23	$+\ -$	$0\ 0\ 0\ 0$	53	$0\ 0$	$-\ -\ +\ +$
24	$+\ -$	$0\ 0\ 0\ 0$	54	$0\ 0$	$+\ -\ +\ -$
25	$-\ +$	$-\ -\ -\ -$	55	$0\ 0$	$-\ +\ +\ -$
26	$-\ +$	$+\ -\ -\ +$	56	$0\ 0$	$+\ +\ +\ +$
27	$-\ +$	$-\ +\ -\ +$	57	$0\ 0$	$0\ 0\ 0\ 0$
28	$-\ +$	$+\ +\ -\ -$	58	$0\ 0$	$0\ 0\ 0\ 0$
29	$-\ +$	$-\ -\ +\ +$	59	$0\ 0$	$0\ 0\ 0\ 0$
30	$-\ +$	$+\ -\ +\ -$	60	$0\ 0$	$0\ 0\ 0\ 0$

Chapter 3

Second approach

> Since the use of the factorial design was shown to be impossible to conduct, another approach had to be used.
>
> The existing problems, with reference to possible sample spaces, that was described in chapter 2, cause disturbances. To be able to do any analysis, the investigation has to be broken into smaller parts. This lead to the design and analysis of a single-factor experiment with a fix number of levels of the variable.
>
> This analysis is mainly done for the achievement of indications. It's not suitable to assume that this approach will make it possible to draw generalized conclusions about the course of injection. There are still to many things that are non-functional concerning the experimental set-up.

3.1 Model 2 – Experiment with a single factor

In this single-factor experiment the factor allowed to be varied will be the injection time. The investigation will be made for every combination of nozzle, injection pressure and gas back pressure where it's possible to achieve results. During the investigation in chapter 2 it turned out that no results could be achieved when using the higher injection pressures in combination with the nozzles with no impingement angle. This lead to 33 different factor combinations, which can be viewed in table 3.1. The variable injector rotational speed was removed, since it was the cause of some of the problems.

In chapter 2 some decisions were made about the different gas back pressures and injection pressures. These choices were made because they seemed interesting for the issue, and they will therefore be kept unchanged through the forthcoming analysis. The nozzles will be the same five.

3.1.1 Choice of levels, randomization and number of replicates

The number of levels, a, for the factor injection time is set to three. Choosing the injection times turned out to be a time consuming problem, since every combination of injection pressures, gas back pressure and nozzle must be examined separately. It turned out that the most appropriate way to choose the injection times was to look at the shortest possible one, the longest possible one and the one in the middle of the two extreme times.

The chosen injection times are summarized in table 3.1. The number of replicates, n, of the spray mass is set to three, and the number of replicates concerning the injected fuel mass is set to two. The experiments will be performed one nozzle at a time so the randomization will be done within these.

Table 3.1: Table of the chosen injection times per nozzle, injection pressure and gas back pressure. The injection times are chosen after the shortest possible one, the longest possible one and the one in the middle of the two extreme times.

Nozzle	Injection pressure	Gas back pressure								
		3			6			12		
0,12 x 0	250	0.6	0.65	0.7	0.6	0.75	0.9	0.6	0.8	1
0,2 x 0	250	0.6	0.7	0.8	0.6	0.75	0.9	0.6	0.8	1
0,16 x 30	250	0.65	0.8	1	0.8	1.15	1.5	1	1.5	2
	800	0.3	0.35	0.4	0.4	0.6	0.8	0.6	0.8	1
	1300	0.2	0.25	0.3	0.3	0.4	0.5	0.4	0.5	0.6
0,12 x 60	250	0.8	1.25	1.7	1.4	2.2	3	2	3	4
	800	0.4	0.6	0.8	0.6	1	1.4	0.8	1.4	1.8
	1300	0.3	0.4	0.5	0.4	0.6	1	0.6	0.9	1.2
0,2 x 60	250	0.6	0.9	1.2	0.9	1.35	1.8	1.2	1.8	2.4
	800	0.3	0.4	0.5	0.4	0.6	0.8	0.6	0.8	1
	1300	0.2	0.3	0.4	0.4	0.5	0.6	0.4	0.6	0.8

3.2 Results

The results analyzed in this chapter only involves the nozzle with impingement angle 60° and orifice diameter 0.2 mm. This because it was only possible to achieve valid results from this nozzle before the experimental set-up broke down completely. The analysis only involves the combinations of variables which led to a ratio above the wanted values 14.6 and/or 21.9.

The main issue is how well the fuel and air is mixed in the vessel, and as a measurement of the relation fuel-air mixture the ratio injected spray mass by injected fuel mass is investigated, as described in section 1.4. The ratio will be investigated as a function of the injected fuel mass under given premises. The injected fuel mass will be investigated as a function of the end of injection, and the latter as a function of the injection time.

The penetration isn't reliable and it will be investigated separately under given premises for the possibility to get an appreciation of it. It's of interst to have some knowledge of its development, because it's important that the spray doesn't hit the inner wall in the combustion chamber. The penetration will be examined as a function of the injected fuel mass, just like the ratio injected spray mass per injected fuel mass.

Single-factor experiment

The observations from a single-factor experiment can be described by the model

$$y_{ij} = \mu + \tau_i + \epsilon_{ij}$$

where $i = 1, 2, ..., a, j = 1, 2, ..., n$, μ is the overall mean, τ_i is the ith level effect and ϵ_{ij} is a random component that incorporates all sources of variability in the experiment. The model, called the fixed effects model, is a linear statistical model; i.e., the response variable y_{ij} is a linear function of the model parameters.

3.2.1 Model adequacy checking

Before making any practical interpretations about the course of injection, the underlying assumptions and the variation within the data has to be checked and investigated.

The model mentioned to describe the data is a method for obtaining estimates and tests under certain assumptions. Specifically, these assumptions are that the observations are adequately described by the model $y_{ij} = \mu + \tau_i + \epsilon_{ij}$ and that the errors, ϵ_{ij}, are normally and independently distributed with mean zero and constant but unknown variance σ^2. Violations of the assumptions can be investigated by examination of residuals.

The examination of residuals

By examining the residuals it should be established either that the assumptions appear to be violated or not. To establish that the assumptions not are violated merely implies that there are no reason to doubt them, it doesn't necessary mean that they are correct.

The residuals for observation j in level i is defined as $e_{ij} = y_{ij} - \widehat{y}_{ij}$ that is, the difference between observation y_{ij} and the estimate of y_{ij}; $\widehat{y}_{ij} = \overline{y}_{i.}$ A general inspection can be carried out by plotting the residuals against the estimated values $\widehat{y}_{ij}$, since the residuals should be unrelated to the level of the response.

Figure 3.1 shows the residuals plotted against the estimated values of the spray mass. They appear to be structureless, i.e., they contain no obvious pattern. Considerable fluctuation do occur, but the figure doesn't indicate that the assumptions are violated. It does indicate that the variance on occasion appear to be quite large, specially for the larger spray masses, which is depicted in figure 3.2 on page 30.

3.2.2 Variability of the data

In all the selected measure points, except a few, there has been three replicates of the spray mass[1]. In some places there are data missing, and the explanation for this was said to be that it just wasn't possible to do any replicates, or more than one replicate, under some conditions.

If this is true, the data is questionable. Questionable because if an optimum is to be found around those combinations of variable levels, where replicates couldn't be made, it isn't sure that the same optimum can be achieved once again. This is clearly a limitation, and

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[1] The spray mass is calculated from the volume, as described in section 1.4.

although it doesn't effect the calculations it might be good to bear it in mind. However, this problem doesn't appear among the few factor combinations that are analyzed in this chapter.

To examine the variability of the data, nine repeated measurements of the spray mass, including the penetration and cone angle, were made under the same combination of variable levels; nozzle: 0.2 mm $\times$ 60°, injection pressure: 800 Bar, gas back pressure: 6 Bar and injection time: 0.6 ms. The measurements of the injected fuel mass was also done repeatedly, eight times, under these conditions.

These measurements along with the measurements from the design, three of the spray mass, penetration and cone angle, and two of the injected fuel mass, makes it possible to estimate the variances of the quantities of interest; spray mass, m, injected fuel mass, δ, and ratio, r. The two quantities, m and δ, can be assumed to be approximately Normal distributed. The collected data can also be used to further investigate the differences between the two sprays within each injection.

The standard deviation for the spray mass and injected fuel mass is given by

$$s_x = \widehat{\sigma}_x = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_i - \overline{x})^2}$$

where x denotes any of the two quantities mentioned. The results from these experiments gave that $s_m = 46.15$ mg and $s_\delta = 2.42$ mg.

It can also be of interest to compare the coefficients of variation, ν, $\widehat{\nu} = s_x/\widehat{\mu}_x$ which gives the standard deviation as a proprotion of the mean value. The mean values of the spray mass and the injected fuel mass are $\widehat{\mu}_m = 334.44$ mg respectively $\widehat{\mu}_\delta = 26.79$ mg. The calculated quantities gives that $\widehat{\nu}_m = s_m/\widehat{\mu}_m = 14\%$ and $\widehat{\nu}_\delta = s_\delta/\widehat{\mu}_\delta = 9\%$.

The standard deviation, concerning the injected fuel mass, can be assumed to be constant under any combinations of variables. It's reasonable to assume a constant standard deviation for it with reference to how the measurements have been carried out, see section 1.4.

The standard deviation concerning the spray masses can't be seen as constant for every combinations of variables, this is implicated by the residualplots in figure 3.1.

The calculated ratio, r, consists in this case of two measured values, the injected spray mass and the injected fuel mass, and the standard deviation of each measured value can be estimated. This implies the use of the formula for propagation of errors, when wanting to calculate the standard deviation. The standard deviation is then approximately given by, expressed in the coefficients of variation, as

$$s_r = \widehat{\sigma}_r \approx \widehat{\mu}_r\sqrt{\widehat{\nu}_\delta^2 + \widehat{\nu}_m^2}$$

where $\widehat{\mu}_r = \widehat{\mu}_m/\widehat{\mu}_\delta = 12.48$.

The standard deviation calculated as above gave $s_r = 2.06$, where the variation in the spray mass gives the largest contribution to the standard deviation for the ratio. The coefficient of variation becomes this time $\widehat{\nu} = 16\%$ The standard deviation concerning the ratio can neither be assumed to be constant for every combination of variables, which is a result from the standard deviation concerning the spray masses. The above calculated s_r is for some cases an obvious underestimation. However, for most of the cases this estimation of the standard deviation for the ratio can be seen as reasonable although the variability of the data can't be seen as satisfying.

Variation between the two sprays within each injection

In section 2.2.2 it was stated that there exist a difference between the two sprays within each injection. As a result of this only the larger penetration was decided to be taken under consideration. If there exists a considerable difference between the two sprays it can be tested with a paired t-test[2] for the penetration and the cone angle. The null hypothesis H_0: $\mu_d = 0$ is then rejected when $|t_0| > t_{\alpha/2,n-1}$, where, $t_0 = \dfrac{\overline{d}}{s_d/\sqrt{n}}$, $\overline{d} = \dfrac{1}{n}\sum_{j=1}^{n} d_j$ and $d_j = y_{1j} - y_{2j}$, $j = 1, 2, ..., n$. s_d is the standard deviation of the differences d_j. The results from the test concerning the penetration and the cone angle, by using the measurements from the design and the repeated measurements, which gives a total number of 12 measurements, are given in table 3.2. The table includes the test statistic t_0, the p-values for rejecting the null hypothesis if the hypothesis is true and a 95% confidence interval for the true difference in means.

The hypothesis of no difference can be rejected, and the decision about investigating them separately is thereby supported. The confidence interval for the difference in penetration between the two sprays isn't remarkable large among these specific measurements. However, the difference in penetration is clearly illustrated in figure 2.2.

Table 3.2: Results from the t-test when investigating the differences in means between the two sprays within each injection. The table include the test statistic, p-value and a 95% c.i. for the difference in means.

	Test statistic, t_0	p-value	95% c.i.
Penetration	4.08	0.0018	$0.0015 \leq \mu_d \leq 0.0051$
Cone angle	9.87	$8.40 \cdot 10^{-7}$	$6.05 \leq \mu_d \leq 9.52$

3.2.3 Analysis of the fixed effects model

If the injection time is increased, the spray mass and the injected fuel mass are increased. However, it isn't certain that the ratio is effected, which motivates to test the equality of level means. When using the effects model to test the equality of the a level means[3], with the hypothesis of no differences in level means the hypothesis used are H_0: $\mu_1 = ... = \mu_a$ against H_1: $\mu_i \neq \mu_j$ for at least one pair (i, j). For the test statistic F_0, the null hypothesis is rejected if

$$F_0 = \frac{MS_{Treatment}}{MS_E} > F_\alpha(a-1, N-a)$$

The p-values achieved from the tests found in table 3.3, and the hypothesis can be rejected for all, except 1300×12, of the combinations of pressures taken under consideration.

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[2] This is a frequent test in litterateur and more can be read about, e.g., in [5].

[3] This is a frequent test in litterateur and more can be read about, e.g., in [5].

Since the null hypothesis, all means equal, is rejected for most of the cases further comparisons and analysis among level means can be interesting. One multiple comparison method that can be used when trying to find exactly which level mean that differs from the others, is to use a t-test with the involvement of contrasts.[4] The null hypothesis H_0: $\mu_i = \mu_j$ is then rejected when $|t_0| > t_{\alpha/2,N-a}$, where:

$$t_0 = \frac{\sum_{i=1}^{a} c_i y_{i.}}{\sqrt{nMS_E \sum_{i=1}^{a} c_1^2}}$$

The c_i is called contrast constants, valued $0, \pm 1$, and they are chosen so that they are summarized to zero. The results are summarized in table 3.3.

Table 3.3: The different p-values when testing the hypothesis about no differences in level means. The table shows the results when testing H_0: $\mu_1 = ... = \mu_a$ and H_0: $\mu_i = \mu_j$.

Pressures	$\mu_1 = \mu_2 = \mu_3$	$\mu_1 = \mu_2$	$\mu_2 = \mu_3$	$\mu_1 = \mu_3$
250×12	0.0048	0.063	0.11	0.010
800×3	< 0.0001	$4.1 \cdot 10^{-4}$	0.023	$6.4 \cdot 10^{-5}$
800×6	0.021	0.057	0.41	0.041
1300×3	< 0.0001	$1.1 \cdot 10^{-4}$	0.0023	$9.1 \cdot 10^{-6}$
1300×6	< 0.0001	$5.8 \cdot 10^{-4}$	0.24	$3.1 \cdot 10^{-4}$
1300×12	0.77	0.34	0.40	0.44

In most of the cases, when investigating for eventual differences in level means, the hypothesis about no difference can be rejected, see table 3.3. As a consequent less consideration is needed to be taken of the injection time and more can be taken of the injected fuel mass, i.e., the injection times can on occasion be chosen from the amount fuel injected into the system. This can be of interest if there is a specific amount of injected fuel of interest for a specific value of the homogeneity.

3.2.4 Practical interpretation

After conducting the experiment and investigating the underlying assumptions, it's time to draw practical conclusions about the course of injection. Since the factor injection time is an quantitative factor the entire range of values are of interest, especially the response from a subsequent run at an intermediate factor level.

It's usually of interest to develop an interpolation equation for the response variable. An equation that allows this of the process under study is called an empirical model. The general approach when fitting empirical models is regression analysis. With only one independent variable a linear regression model of the form

$$y_i = \beta_0 + \beta_1 x_i + \epsilon \tag{3.1}$$

can be tried. The parameters are estimated by the use of the method of least squares. The simple linear regression model can be applied to all of the situations when wanting to draw conclusions about the; spray mass, penetration, ratio, injected fuel mass and EOI.

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[4] This is a frequent test in litterateur and more can be read about, e.g., in [5].

In the regression analysis concerning the ratio versus the injected fuel mass the predictor is a subject of experimental error. In section 3.2.2 it was stated that the variance for the spray mass is considerable higher than the variance concerning the injected fuel mass. In the analysis, the experimental errors concerning the injected fuel mass has been assumed to be negligible and the usual least squares analysis has been performed.

Test of lack of fit

After fitting a linear regression model, e.g., on the form (3.1), and breaking up the residual sum of squares into lack of fit and pure error an F-test can be conducted to test the significance of lack of fit[5]. The test statistic for lack of fit is

$$F_0 = \frac{MS_{LOF}}{MS_{PE}} = \frac{\sum_{i=1}^{a} n_i(\overline{y}_{i.} - \widehat{\beta}_0 - \widehat{\beta}_1(x_i - \overline{x}))^2}{(a-2)s_e^2}$$

and if the true regression function is linear the statistic follows a F-distribution. The null hypothesis H_0: $\mu(x) = \beta_0 + \beta_1 x$ is rejected when $F_0 > F_p(a-2, N-a)$, where $N = \sum_i n_i$.

If there exists significant lack of fit there is no point to further investigate the model. If the lack of fit test isn't significant, there is no reason to doubt the adequacy of the model.

If the model passes the lack of fit test it doesn't mean that it's the correct model, it merely means that it is a plausible one which has not been found inadequate by the data. In those cases when the lack of fit test shown significance one could try to fit a different model, e.g., a quadratic one, as in equation (3.2).

$$y_i = \beta_0 + \beta_1 x_i + \beta_2 x_i^2 + \epsilon \tag{3.2}$$

3.2.5 Spray mass versus injection time

The results from the collected data concerning the calculated spray masses from each injection time in table 3.1 can be found in figure 3.2 on page 30, where the spray mass is plotted as a function of the injection time. The sum of the two sprays masses has been used since there exists a difference between the two sprays within injection, as mentioned in section 2.2.2.

Only one pressure combination, 1300×12 Bar, shows significant lack of fit. In this case an quadratic model, on the form (3.2), was tried. The results can be found in figure 3.2 and in table 3.4. The other combinations show no significant lack of fit and thereby the nullhypothesis can't be rejected. Results from the simple linear regression can also be found in figure 3.2 and in table 3.4. The coefficient of determination, R^2, which measures the variation about y explained by the regression, can be found in table 3.4.

3.2.6 Penetration

As mentioned earlier the variation between the two sprays at each injection makes it difficult to use the penetration in the analysis, and therefore it will be examined separately. Only the

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[5] This is a frequent test in litterateur and more can be read about, e.g., in [6].

Table 3.4: Results from the regression models concerning the spray mass, m, as a function of the injection time, t. The table include a suggested model with the corresponding value of R^2.

Pressures	Model	R^2
250×12	$m = -192.96 + 320.06t$	0.985
800×3	$m = -121.49 + 723.7t$	0.969
800×6	$m = 1.74 + 568.34t$	0.658
1300×3	$m = -34.23 + 722.17t$	0.970
1300×6	$m = -131.96 + 1257.2t$	0.973
1300×12	$m = -622.68 + 3375.9t - 1870.4t^2$	0.980

larger penetration will be examined as a function of the injected fuel mass. The penetration will also only be examined under the conditions which led to a result of interest.

Since it is important that the penetration isn't too long, it will be the first thing to investigate. If overpenetration would appear, it should be taken under consideration when later analyzing the ratio.

The penetration as a function of the injected fuel is plotted in figure 3.3 on page 31. Overpenetration occur in some cases, the maximum penetration allowed is 0.075 m, and this limit is violated for some of the longer injection times. The injection times that results in overpenetration is the longest ones concerning the following pressures; 800×6, 1300×3, 1300×6 and 1300×12 Bar.

The diameter in the experimental vessel is 0.132 m, and the expected angle from the top of the vessel in which the spray is being injected gives the maximum penetration allowed as 0.075 m. The skew needle doesn't only contribute to different sizes of the sprays, it also can redirect the direction in which the spray is injected, which makes it possible to detect longer penetrations than 0.075 m.

The penetration appear to be quite well fitted by a linear model on the form (3.1). The results from the lack of fit test is that it's only the pressure combination 1300×3 Bar that show significant lack of fit, where the nullhypothesis can be rejected, and a quadratic model was tried.

In table 3.5 a suggested model for the penetration, p, as a function of the injected fuel mass, δ, and the corresponding values of R^2 for all the different pressure combinations of interest can be found.

3.2.7 The Ratio versus the Injected fuel mass

All the different combinations of variables didn't result in any interesting estimates of the ratio, most of them gave results considerably lower than the values of interest. The combinations that actually led to something interesting, i.e., results above the values 14.6 and/or 21.9, can be found in table 3.6.[6]

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[6] Above 21.9 naturally means above 14.6 also, but if the $\times$-marker is placed only in the column for the value 21.9 it merely means that the results, all or almost all of them, are higher than 21.9. In those cases where the $\times$-marker is shown in both columns there's a bigger spread among them.

Table 3.5: Results from the regression models for the penetration, p, as a function of the injected fuel mass, δ. The table include a suggested model with the corresponding value of R^2.

Pressures	Model	R^2
250×12	$p = 0.025 + 0.0011\delta$	0.980
800×3	$p = 0.047 + 0.0014\delta$	0.921
800×6	$p = 0.040 + 0.0011\delta$	0.935
1300×3	$p = 0.043 + 0.0027\delta - 5.1 \cdot 10^{-5}\delta^2$	0.990
1300×6	$p = 0.052 + 0.0007\delta$	0.916
1300×12	$p = 0.045 + 0.0006\delta$	0.949

If the ratio is higher than any of the values 14.6 or 21.9 it merely implies that there is more oxygen than necessary in the spray, which is a good thing, see section 1.4. The value 14.6 should on the other hand preferable not be undermined. The results not included in this analysis involves values significant lower than 14.6, i.e., around and lower than 10.

The results, from the nozzle 0.2 mm $\times 60°$, can be found in figure 3.4 on page 32, where the ratio is plotted as a function of the injected fuel mass. The horizontal lines in the figures represent the levels for the two different values of interest for the ratio, i.e., 14.6 respective 21.9.

In those cases, that were mentioned in section 3.2.6, that overpenetration occur the results of the ratio must be considered more carefully.

Remembering the results in section 3.2.3, where it was established that there are no significant differences between some of the level means. In the figure 3.4 on page 32 this becomes obvious for some cases. E.g., for μ_2 and μ_3 under injection pressure 1300 Bar in combination with the gas back pressure 6 Bar or for any pair of μ_i, μ_j under the pressures 1300×12 Bar.

There exist significant lack of fit for the pressure combinations 800×3, 1300×3 and 1300×6, and in these cases a quadratic regression model has been tried. The suggested models along with their corresponding value of R^2 can be found in table 3.7. Note the extremely low value of the coefficient of determination for the pressure combination 1300×12, this correspond to the large spead in data.

3.2.8 Injected fuel mass and End of injection

To decide which injection time to use from a specific amount of injected fuel mass a regression model of the injected fuel mass as a function of the EOI is fitted. Where the latter is fitted as a function of the injection time. In section 1.4.1 it was mentioned that it might be of interest to chose a different moment for photographing, and the moment for photographing is chosen after the EOI.

The measurements of the injected fuel mass and EOI are done within nozzle, injection pressure and injection time. The variable that doesn't effect the injected fuel mass or the EOI is the gas back pressure, and the analysis is consequently simplified. The data is more reliable concerning these responses, and more measurements are available.

Table 3.6: The different combinations of variables which led to results near and/or above the values 14.6 and/or 21.9. The table include results from all the five nozzles, but it is only the results from the nozzle $0.2 \times 60°$ that are further analyzed in this chapter.

Nozzle	Injection pressure	Gas back pressure	14.6	21.9
$0,12 \times 0$	250	12	×	
$0,2 \times 0$	250	12	×	
$0,16 \times 30$	250	12	×	
	800	3	×	
		6	×	
		12		×
	1300	6		×
		12		×
$0,12 \times 60$	250	6	×	
		12		×
	800	3	×	
		6	×	
		12		×
	1300	3	×	
$0,2 \times 60$	250	12	×	
	800	3	×	×
		6	×	×
	1300	3	×	×
		6	×	
		12	×	

The injected fuel mass as a function of the EOI and the latter as a function of the injection time is plotted in figure 3.5 on page 33 for the different injection pressures and the nozzle 0.2 mm $\times 60°$. Both replicates of the injected fuel mass has been used in the calculations.

The results from the lack of fit test for the injected fuel mass do show significance for all of the pressure combinations. It's possible to detect some curvature when examining the plots in figure 3.5. But since the coefficient of determination is very high for all of the straight lines fitted and the lines look suitable, these models can be kept.[7] In table 3.8 suggested models for the injected fuel mass, δ, as a function of the EOI, τ, with the corresponding values of R^2 can be found.

There exists no replicates of the EOI so the lack of fit test can't be conducted for the EOI. That a quadratic model could be better suited than a straight line, can be depicted from the plots in figure 3.5. The two models can be compared using the values of R^2, which are given in table 3.9 along with the results from the fitted regression models concerning the EOI, τ, as a function of the injection time, t. There doesn't exist any major differences in the value of R^2 for the different models, so that any of the two models would suffice.

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[7] If to try another model, a cubic or a quadruple model would likely be an appropriate approach, but it's probably not worth the extra work, since the straight line is well fitted.

Table 3.7: Results from the regression models concerning the ratio, r, as a function of the injected fuel mass, δ. The table include a suggested model with the corresponding value of R^2.

Pressures	Model	R^2
250×12	$r = 8.27 + 0.17\delta$	0.830
800×3	$r = 34.16 - 2.33\delta + 0.069\delta^2$	0.976
800×6	$r = 26.80 - 0.43\delta$	0.660
1300×3	$r = 32.40 - 1.83\delta + 0.040\delta^2$	0.987
1300×6	$r = 33.26 - 1.25\delta + 0.022\delta^2$	0.962
1300×12	$r = 19.41 + 0.011\delta$	0.021

Table 3.8: Results from the regression models concerning the injected fuel mass, δ, as a function of the EOI. The table include a suggested model with the corresponding value of R^2.

Injection pressure	Model	R^2
250	$\delta = -14.19 + 15.8\tau$	0.999
800	$\delta = -22.06 + 32.26\tau$	0.997
1300	$\delta = -25.81 + 42.05\tau$	0.994

3.2.9 Conclusions, Model 2

The nozzle that has been investigated in this chapter is the one with impingement angle $60°$ and orifice diameter 0.2 mm. The lack of results for the other nozzles is due to the experimental set-up breaking down.

From these results, using only one nozzle, it's impossible to draw any general conclusions about whether or not a better mixture of fuel and air is achieved when letting two sprays collide. However, it's possible to say that the mixture might be better. Table 3.6 indicate that more values of interest are achieved when using an impingement angle.

For the nozzles with no impingement angle no results at all could be achieved with the higher injection pressures. The injection times when using the lower injection pressure, 250 Bar, are very short. The amount of fuel injected in that short time is probably to low to

Table 3.9: Results from the regression models of the EOI, τ, as a function of the injection time, t. The table include a suggested model, for both the straight line and a quadratic model, with the corresponding value of R^2.

Injection pressure	Straight line model	R^2	Quadratic model	R^2
250	$\tau = 0.36 + 1.29t$	0.985	$\tau = -0.14 + 2.08t - 0.26t^2$	0.998
800	$\tau = 0.40 + 1.52t$	0.973	$\tau = -0.044 + 3.10t - 1.21t^2$	0.998
1300	$\tau = 0.43 + 1.66t$	0.967	$\tau = 0.10 + 3.24t - 1.57t^2$	0.998

be of any major interest. The highest value of the ratio achieved was just a bit above 14.6, so it is probably not very appliable in further investigations.

The difference between the two sprays within each injection, that was stated in section 2.2.2 has been shown to be significant. This support the decision made about the way to handle the penetration and the spray mass.

The results from this single-factor experiment contain some information, that might be of interest in further investigations, about how the different variables effect the ratio.

When the spray masses were plotted as a function of the injection time it was established that the masses, in most of the cases, can be fitted quite well by a straight line. The most dominating problem in this part of the analysis was that the variance on occasion is very large, especially among the larger spray masses.

The ratio 14.6 is usually attained for the larger amounts of injected fuel mass, i.e., for the longer injection times. Since overpenetration occur for some of the longest injection times, only a small interval of the injection times are interesting.

The ratio 21.9 is attained only for a few pressure combinations, and only for the shortest injection times. The amount of fuel injected for the shortest injection times are all less than 10 mg/injection for these specific pressure combinations.

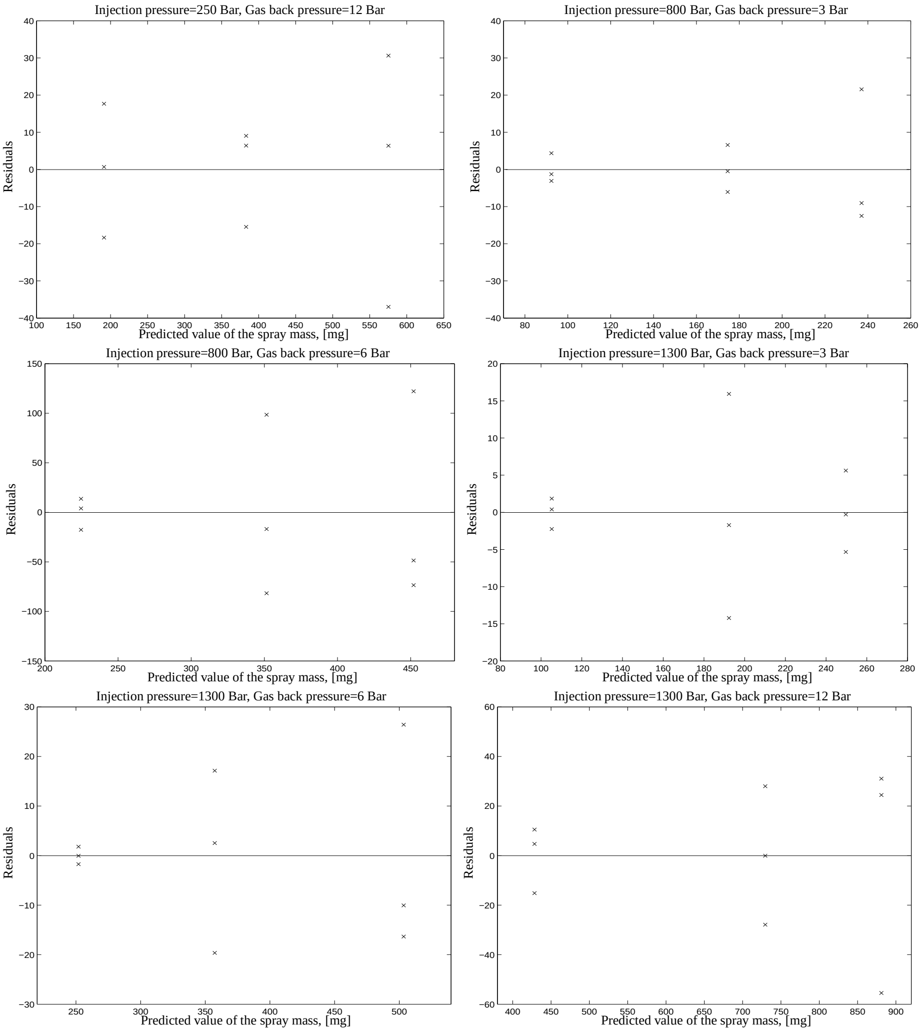

Figure 3.1: The residuals plotted against the predicted value of the spray mass. Note that the scale for the residuals vary between the plots.

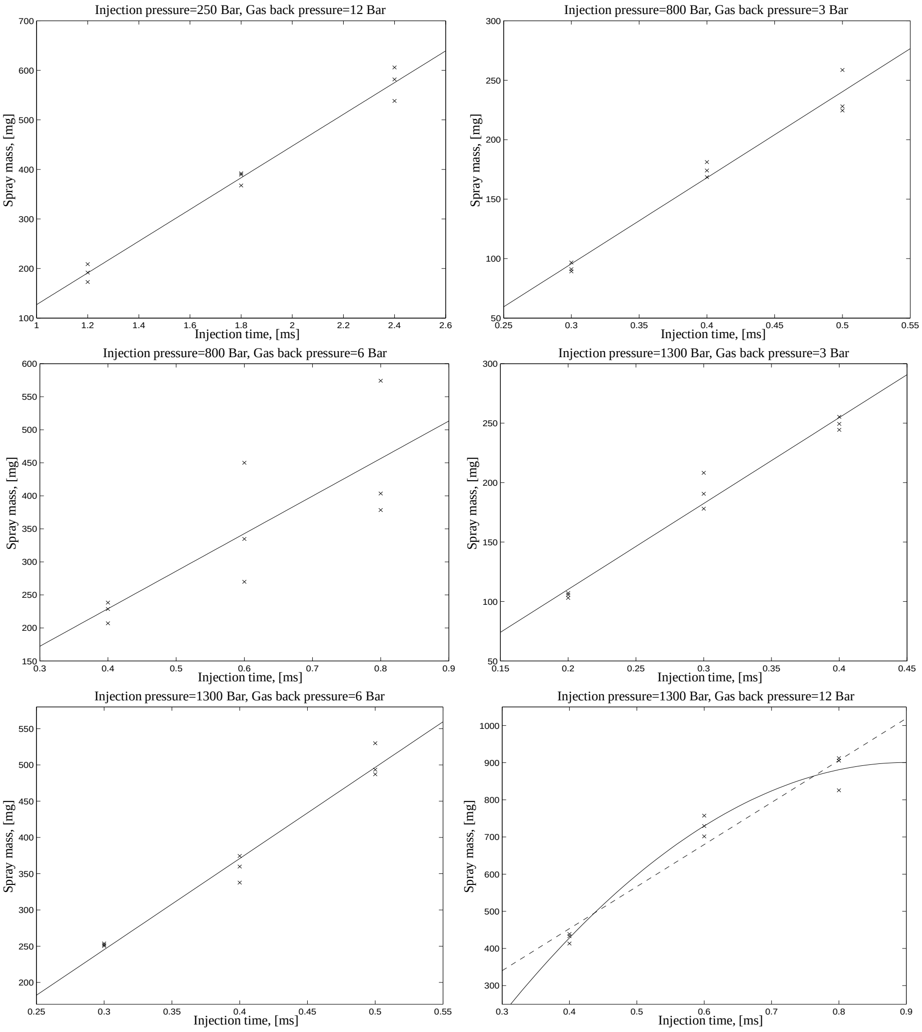

Figure 3.2: The spray mass plotted as a function of the injection time. The dashed line represent the rejected, due to lack of fit, linear model.

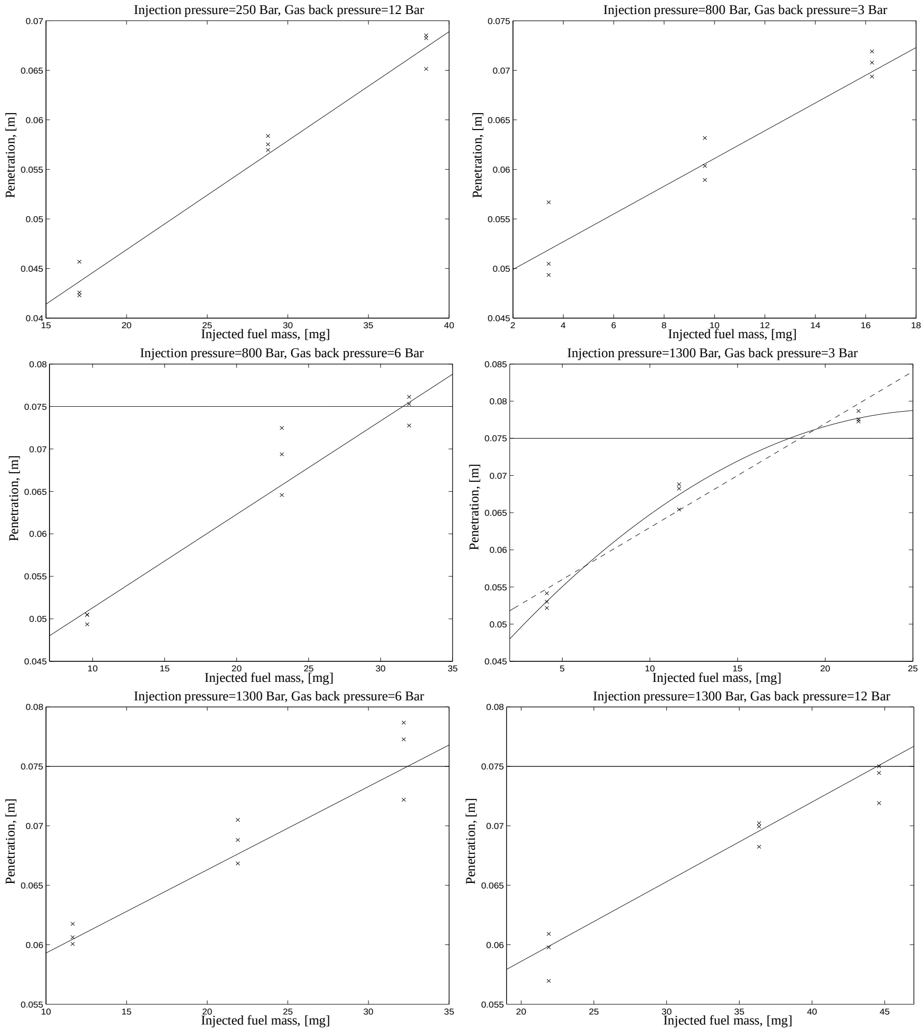

Figure 3.3: The penetration as a function of the injected fuel mass. The horizontal lines represent the maximum penetration allowed, i.e., 0.075m. The dashed line represent the rejected, due to lack of fit, linear model.

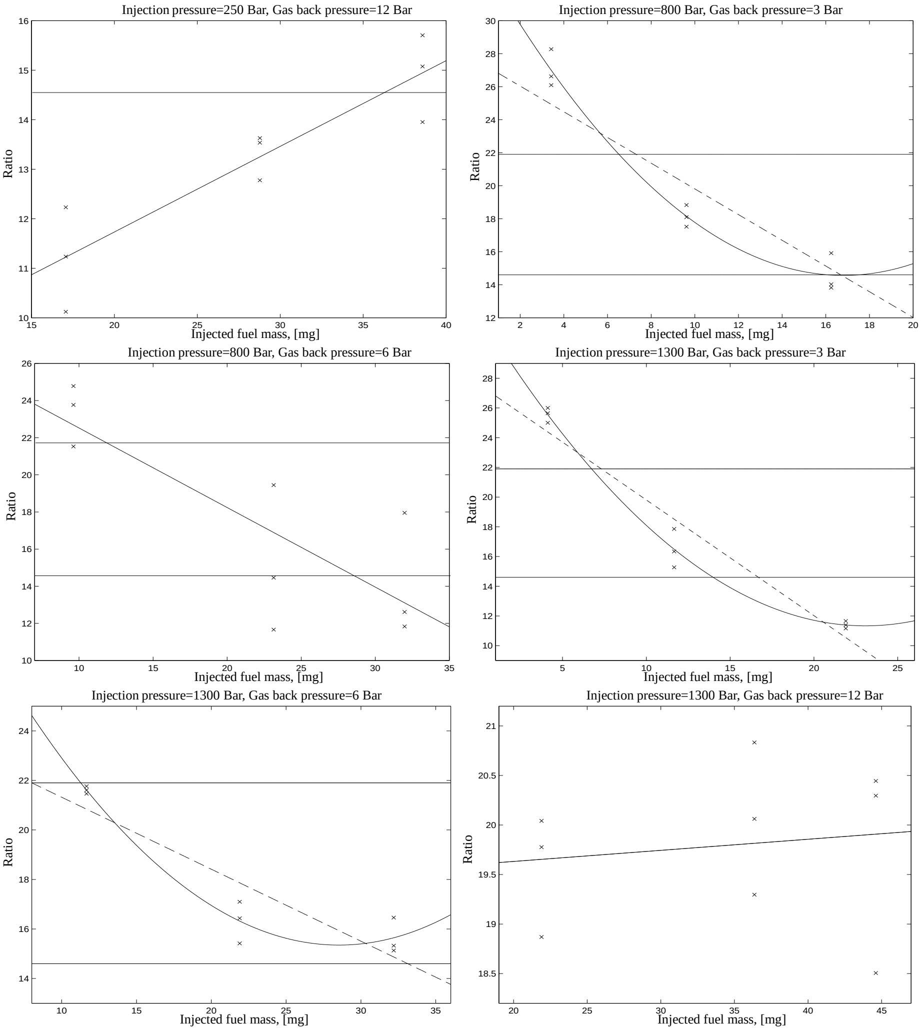

Figure 3.4: The ratio plotted as a function of the injected fuel mass. The dashed line represent the rejected, due to lack of fit, linear model. The horizontal lines represent the reference levels 14.6 and 21.9.

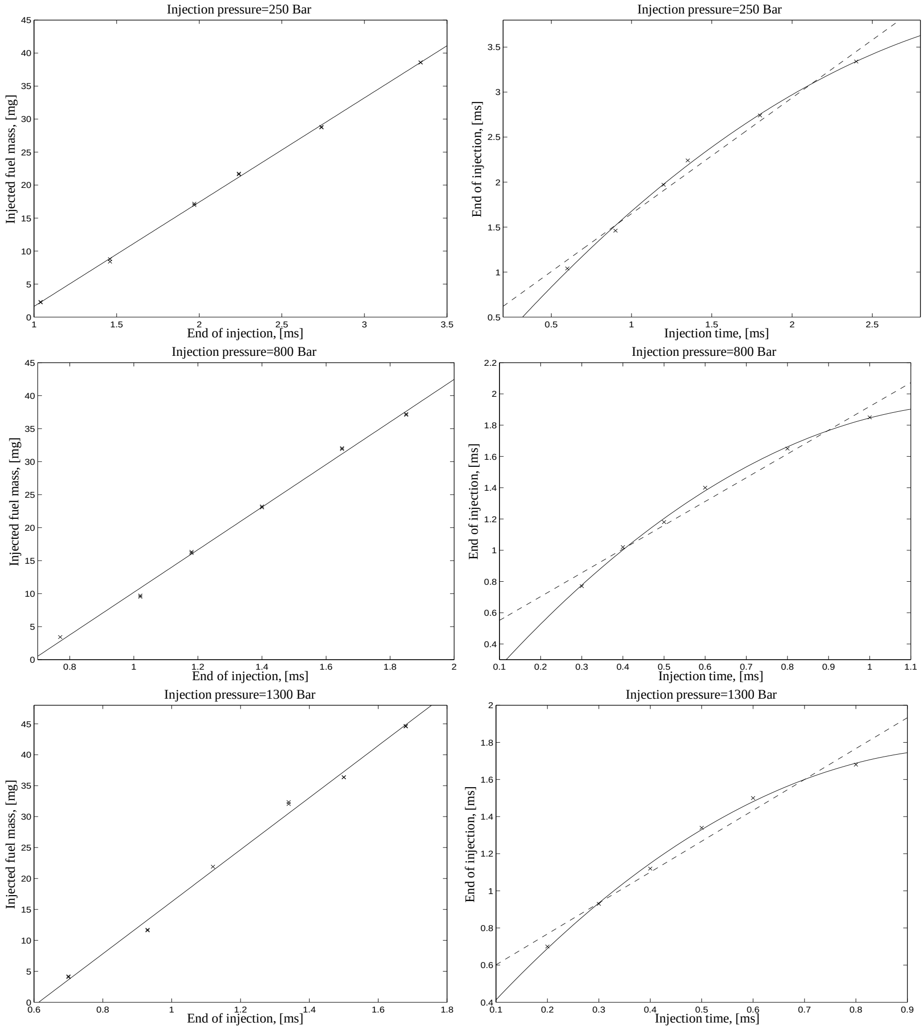

Figure 3.5: Left column: The injected fuel mass as a function of the end of injection at the injection pressures 250 Bar, 800 Bar and 1300 Bar respectively. Note that each plot contains 12 points. Right column: The end of injection as a function of the injection time at the injection pressures 250 Bar, 800 Bar and 1300 Bar respectively. No consideration is needed to be taken of the gas back pressure.

Chapter 4

Recommendations and further analysis

> The results achieved by the methods used in this investigation can be seen as satisfying in that way that indications has been achieved.
>
> If to conduct any research, concerning the course of injection in HCCI-combustion involving colliding sprays and rotational nozzles, on this experimental set-up the existing problems have to be solved.

4.1 Things to solve before any further analysis

Before any decisions are made about any forthcoming investigation, the impending problems have to be solved. If it turns out that the existing problems can not be solved, i.e., that the experimental set-up will not work satisfactory, it's not reasonable to continue the research about the course of injection in HCCI-combustion with this approach/experimental set-up.

Some of the problems and limitations will be discussed more thoroughly in the following sections.

4.1.1 The needle

It turned out that the needle controlling the injection is skew. It is not clear whether it has been wrongly manufactured or if there is something wrong with the set-up or its assembly that may have caused damage to the needle. Either way, it has to be fixed. Consequences of the needle being skew are:

- The injected fuel is not equally distributed between the two sprays within each injection. This difference between the two sprays is not measurable in any reasonable way.
- The cone angle is effected. There's a difference in the cone angle between the two sprays within each injection.

- The penetration is effected in the same way as the cone angle.
- The spray volume is also effected since everything that is used to calculate the spray volume is effected.

Through the analysis of this investigation, the sum of the two sprays masses and the longest penetration has been used in the calculations.

As a result of these consequences no indications of how one (1) specific spray behaves has been achieved. Neither is it possible to say anything about where the spray is located at a certain moment in relation to the inner wall in the vessel.

4.1.2 Injected fuel mass

I might be of interest to be able to measure the amount injected in each of the two sprays per injection, to be able to investigate if there exists any difference between them. That there is a difference today is obvious since the needle is skew, and there is no way to tell if the injected fuel mass is equally distributed.

Though, this will probably not be an important issue if the needle is fixed.

4.1.3 Injector rotational speed

The variable injector rotational speed was completely removed early in the study. Therefore it hasn't been possible to investigate if a better mixture of fuel and air can be achieved by rotating the nozzle. Hence, it's of interest to investigate the influence of rotation so it's probably a good idea to make it possible.

4.1.4 Development of the spray; with reference to penetration and cone angle

In the beginning of this study the intention was also to investigate things like the development of the spray, with reference to the penetration and cone angle, as a function of injection time under remaining variables.

This couldn't be performed because the reliability of the data is not sufficient enough, partly with reference to the skew needle. The difference in length of the penetration makes it hard to investigate the development of the spray with satisfying results. The same reasoning goes for any thoroughly investigation of the cone angle.

4.1.5 Reliability of the data

The variance of the data is not satisfactory, this is not only a result of the needle being skew. The variance is on occasion very large and it's necessary that the results becomes more reliable.

As mentioned in section 3.2.2, there exist factor combinations where it wasn't possible to conduct replicates.

4.2 Further analysis

Since there exist an interest in investigating the course of injection of fuel in HCCI-combustion in search for the optimal injection, further analysis has to take place. In order to perform further analysis the experimental set-up has to become more reliable.

4.2.1 Choice of nozzles

Since data was hard to achieve when using the nozzles with no impingement angle, it might be a good idea to focus only on nozzles with an impingement angle.

If wanting to investigate the influence on the results when using nozzles with an impingement angle the design should be completed, so that a factorial experiment can take place. If the nozzles with no impingement angle are removed, they could be substituted with nozzles containing another angle.

The nozzles could for example consist of the same orifice diameters, but the impingement angle could be 30° or 45° as a complement to the nozzles that already has been manufactured with the impingement angle 60°.

4.2.2 A split-split-plot design

The choice for the first approach for this investigation was an factorial design. It was generalized into a split-plot design. This is probably still a good approach if it's of interest to do an overall investigation. Although, it might be suitable to further generalize the model. Since it was difficult to find adequate levels for the different variables to conduct a 2^{4-1}-factorial model within the nozzles for the split-plot design, i.e., for each subplot, the model can be further generalized into a split-split-plot design.

Where the nozzles could represent the the whole plots, just as before. The injection pressures can be represented by a subplot and the remaining variables will be represented by an sub-subplot.

The reason for letting the injection pressure be represented by the subplot is that it turned out to be easier to find suitable sample spaces within nozzle and injection pressure.

Table 4.1: The components divided into whole plot, subplot and sub-subplot in the split-split-plot design.

Whole plot	(A)	Orifice diameter
	(B)	Impingement angle
Subplot	(C)	Injection pressure
Sub-subplot	(D)	Gas back pressure
	(E)	Injection time
	(F)	Injector rotational speed

4.2.3 A smaller investigation

Another approach could be to break down the investigation into smaller parts, and conduct e.g., a factorial experiment. The investigation that was carried out during this study have the contribution of some process knowledge that wasn't available earlier, and when knowing more about the process it might be easier to chose suitable factors and levels.

There's a good chance that a smaller investigation would be easier to conduct, since an impending problem have been to find adequate levels for all of the different factors.

Chapter 5

Summary

Several things went wrong and some problems were revealed during this investigation, most of them concerning the experimental set-up. All this made it impossible to do any statistical analysis as planned, to investigate course of injection in HCCI-combustion. These problems have been discussed and analyzed throughout this report.

Before any final conclusions are made I would like to take the opportunity to make some reflections on the investigation and how it was carried out.

5.1 Reflections

One of the more major issues when planing to conduct an experiment is to make sure that the experimental set-up is reasonably correct and mostly functional. This was not the case when I was contracted to conduct the statistical analysis on this project.

One of the first things that came to my attention was that the variables were everything but stable. For example, when the injection pressure was set to, e.g., 500 Bar, the actual injection pressure was varying between 800 and 900 Bar. Similar faults were discovered among the other variables, during my theoretical verification.

The serious problems with the experimental set-up eventually turned into a complete break down, and this has obvious been a obstacle when aiming to perform the statistical analysis.

If more, or more reliable, data had been available, valuable information about the optimization of the course of injection in HCCI-combustion could have been gained. Even though this could not be achieved under present circumstances, benefits can be taken of the investigation of the *accessible* data, and the planning and design of a more thourough analysis.

Therefore, I hope that the development of this investigation doesn't deterrence. The problems that occurred during this investigation wasn't of statistical nature.

But, it also puts some pressure on the scientists doing the research. Trying to perform an optimization on a broken experimental set-up is not a good idea. *Not even* when a statistician is involved in the project.

5.2 Conclusions

There were two main factors of interest in this investigation concerning the course of injection in HCCI-combustion. These two are the impingement angle and the injector rotational speed. It's likely that these have a positive influence on the mixture of fuel and air in the combustion chamber.

During the first approach, the overall factorial experiment, some problems appeared/came to knowledge that made it impossible to conduct the experiment. The problems involved different shapes of the two sprays within each injection, which led to some modifications about how to handle the different responses. Another problem was that one of the variables, the injector rotational speed, had to be completely removed. The latter problem resulted in a technical modification of the experimental set-up, which had some impact on the original assumptions that led to the factorial experiment.

In the second approach the investigation was broken into smaller parts, and a single-factor experiment were performed with the factor allowed to be varied was the injection time. Before all experiments were conducted the experimental set-up broke down and valid results could only be achieved from one of the available nozzles.

From these results, using only one nozzle, it's impossible to draw any general conclusions about whether or not a better mixture of fuel and air is achieved when letting two sprays collide. However, it's possible to say that the mixture might be better. That more values of interest are achieved when using an impingement angle has been indicated.

Neither has it been possible to make any comparisons between different orifice diameters, or to examine the effect that eventually could have been achieved from rotation.

It would be interesting to continue the research concerning the course of injection in HCCI-combustion and conduct an experiment where these comparisons are possible.

List of Tables

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