ISRN LUTMDN/TMHP-15/5350-SE

ISSN 0282-1990

Combustion Homogeneity with PPC in a LD Optical Engine

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Thesis for the degree of Master of Science in Engineering

Division of Combustion Engines
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Combustion Homogeneity with Partially Premixed Combustion a Light Duty Optical Engine

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June 2015, Lund

This degree project for the degree of Master of Science in Engineering has been conducted at the Division of Combustion Engines, Department of Energy Sciences, Faculty of Engineering, Lund University.

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ABSTRACT

The objective of this Master Thesis is to investigate the homogeneity level of the Partially Premixed Combustion using different injection strategies, for low load engine conditions.

In order to achieve this aim, it is necessary to understand the Partially Premixed Combustion process of an engine through the performance of optical measurements in an optical setup. Partially Premixed Combustion (PPC) is a process that can provide a combustion with low emissions and high efficiency. The term Partially Premixed Combustion is used to describe an engine which is operating somewhere between fully homogeneous combustion HCCI and diffusion controlled diesel combustion. Hence, the goal of this work is to increase the knowledge base of PPC.

This project will be performed in a light duty engine based on a Volvo D5. This engine has been modified to be run in an optical setup, in order that the engine was converted into a single cylinder with a Bowditch piston extension.

Optical diagnostic methods based on combustion chemiluminescence were carried out to determinate the homogeneity level of the combustion. These events will be recorded by a high speed camera, a device capable of capture processes in the combustion chamber.

The analysis of the combustion homogeneity is carried out through a frequency analysis which allows to compare the different injection strategies that have been studied and analysed in this master thesis.

NOMENCLATURE

ATDC After Top Dead Centre

BDC Bottom Dead Centre

BTDC Before Top Dead Centre

CAD Crank Angle Degree

CI Compression Ignition

CN Cetane Number

CO Carbon Monoxide

CO_2 Carbon Dioxide

DFT Discrete Fourier Transform

EGR Exhaust Gas Recirculation

EOI End of Injection

EVC Exhaust Valve Closing

FFT Fast Fourier Transform

FPGA Field-Programmable Gate Array

F-S Fuel-Silica

HC Hydrocarbons

HCCI Homogeneous Charge Compression Ignition

HDL Hardware Description Language

HTC High Temperature Combustion

IMEP Indicated Mean Effective Pressure

IVO Intake Valve Opening

LIF Laser Induced Fluorescence

LII Laser Induced Incandescence

LTC Low Temperature Combustion

MON Motor Octane Number

NO_x Nitrogen Monoxide and Dioxide

NVO Negative Valve Overlap

ON Octane Number

PCCI Premixed Charge Compression Ignition

PM Particulate Matter

PPC Partially Premixed Combustion

PRF Primary Reference Fuel

RON Research Octane Number

SI Spark Ignition

SOC Start of Combustion

SOI Start of Injection

TDC Top Dead Centre

VI Virtual Instrument

CONTENTS

1. INTRODUCTION AND AIMS OF THE STUDY

Increasing demands of emission legislation make the new combustion strategies start to be develop. Among these strategies, Partially Premixed Combustion is found. PPC allows a longer premixed duration of fuel and air mixture, meeting the new emission legislation and improving fuel efficiency.

The aim of this master thesis is the development of a better understanding of the PPC by studying the combustion homogeneity. To carry out this study, chemiluminescence imaging is used in an optical setup. This makes possible the collection of a number of images which show the combustion process for different injection strategies.

A frequency analysis is used in this project to analyse the homogeneity. A frequency analysis consists of analysing a mathematical function with respect to frequency, rather than time. In other words, whereas a time analysis shows how a function changes over the time, the frequency domain shows how much of the function lies on each given frequency band over a range of frequencies. Mathematical operators such as Fourier Transform or Laplace Transform can be used to convert signals between the time and frequency domains. Fast Fourier Transform is the one used in this master thesis.

2. THEORETICAL BACKGROUND

2.1 Introduction

Since the first working engine was built by Cecil in 1820, internal combustion engines have been developed and improved by many inventors. Both Nikolaus Otto in 1876 and Rudolf Diesel in 1892 carried out two of the most important developments regarding internal combustion engines. Otto was the one who developed the spark ignited engine, whereas Diesel was the first one who applied thermodynamics to an internal combustion engine, giving rise to the compression ignited engine.

After these two inventions, internal combustion engines became more significant to the society, both in fields of power generation and in transport [9], undergoing several improvements at the same time as they started finding a place in different applications. One of the most important of these improvements were in terms of efficiency. Compression ignition engines for instance experimented an increased in brake efficiency from 30% up to 44% during the twentieth century [1].

In later years, environmental concerns have become more important and emissions start taking part in the development of internal combustion engines. Both global emissions, which contribute to the greenhouse effect, and local emissions are important when trying to develop clean combustion engines which reduce the environmental impact.

Carbon Dioxide (CO_2) is the most important greenhouse gas from combustion engines and, in order for its emission to be minimised, more fuel-efficient engines must be developed. On the other hand, local emissions must also be considered since as well as being harmful to the environment, they are also harmful to the human health. Local emissions from combustion engines are Carbon Monoxide (CO), Hydrocarbons (HC), Nitrogen Oxide (NO_x) and Particulate Matter (PM). Due to the existence of these two different types of emissions, a trade-off exists between local and global emissions with classical internal combustion engines.

In the middle of the 1990s, local emission regulation became tighter and it caused, for instance, a drop in the average brake efficiency in heavy duty applications from 44.5 to 41.5% [1]. This emission regulation led to the development of advanced combustion strategies, since it was necessary to find new methods which both comply with the emission legislation and meet the customer requirements.

2.2 Advanced Combustion Strategies

It is known that compression ignition (CI) engines generally have a higher efficiency than spark ignition (SI) engines. However, levels of particulate matter (PM) and NO_x emissions in compression ignition engines are higher compared to the spark ignition engines levels when three-way catalyst is used. Therefore, the engine research was focused on the development of an engine concept as efficient as a CI engine, but with a reduction of the emission levels. It was then advanced combustion strategies appeared.

Many of these strategies are based on low temperature combustion (LTC) concepts, which achieve low NO_x and PM emission levels by reducing the combustion temperature. In Figure 1 below, the difference between the most important strategies in terms of start of ignition is shown, as well as the conventional controlled compression ignition (CI). In addition, NO_x and HC levels for each combustion process are shown.

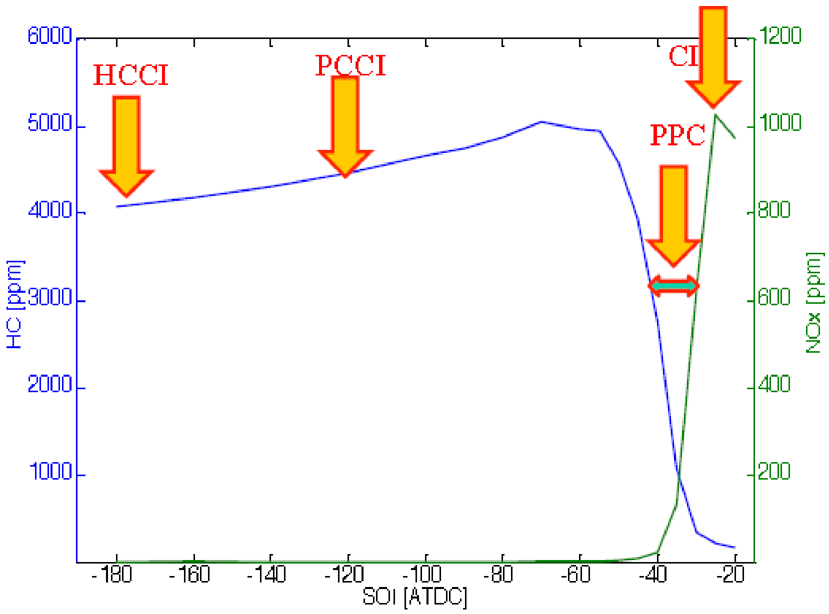

Figure 1. *Different combustion strategies, as well as their corresponding HC and NO_x emission levels [3].*

One of the first LTC technique was Homogeneous Charge Compression Ignition, HCCI. It was first invented by Onishi for 2-stroke engines in 1979 [16] and, in 1983, this concept got a renewed importance when Foster studied it in a 4-stroke cycle [17] [1]. HCCI is a combustion process where the fuel is injected in the cylinder during an early phase of the compression stroke, which allows to reach a homogenous mixture before the auto-ignition happens. In this way, a lean homogenous mixture of fuel and air is compressed until auto-ignition occurs, near top dead centre.

The most important reasons that make known the HCCI concept are the efficiencies and the emission levels. Regarding the efficiencies, values comparable to diesel engines can be achieved, due to the high thermodynamic efficiency, which can be even 50% higher [1]. With respect to the emission levels, they are in the range of spark ignition engines when three-way catalyst is used. This is because peak temperatures are significantly lower than in typical SI engines, which make NO_x levels almost negligible. In addition, the temperature becomes too low for the soot chemistry to become activate, therefore, no soot is produced.

However, several disadvantages are found regarding HCCI. One of the most important and limiting is the control of the combustion. Both in SI and CI engines, the combustion timing can be controlled. A spark to ignite the premixed fuel and air is used in SI engines and the injection of fuel into pre-compressed air controls the combustion in Diesel engines. Nonetheless, there is no direct control in HCCI, since the homogenous mixture of fuel and air is compressed and the combustion begins when enough pressure and temperature are reached. Several control approaches such as the compression ratio or the fuel-air ratio regulation are used to control the combustion timing in HCCI. In addition, there are other drawbacks with this combustion strategy. Some of them are the high in-cylinder peak pressures, which may damage the engine; the high heat release and pressure rise rates, which contribute to engine wear; and the HC and CO emission levels, which are higher than SI conventional engines for this combustion process [3]. Furthermore, despite the higher thermodynamic efficiency of this process, there are still some issues with the combustion, such as gas exchange and mechanical losses. As in most operational points the combustion efficiency is around 90% and the load applicability range is low, both the gas exchange and the mechanical efficiencies are low [1].

Premixed Charge Compression Ignition, PCCI, is other of the combustion strategies shown in Figure 1. In the PCCI combustion process, injected fuel is dispersed into the combustion chamber and is mixed with intake air before combustion starts [18]. This is a more proper method in regards of low emissions as a combustion procedure. The very advanced injection timing applied in this method produces lower amounts of NO_x and soot emissions because of providing a better vaporised air-fuel mixture. The mixture conditions approach to the homogenous charge at low temperature combustion conditions [10].

The control of the combustion and reduction of pollutant emissions can be improved using PCCI, but one of the problems with this combustion strategy is its sudden combustion under high load conditions. Increase of the fuel consumption results in knock occurrence, and hence, the operation range of the PCCI engines is limited to partial load conditions [10] [18].

Partially Premixed Combustion, PPC, is an alternative combustion process which can be considered as an intermediate process between HCCI and the conventional CI combustion. The main difference between these combustion processes is the start of ignition. In addition, PPC strategy is able to combine low smoke and NO_x emissions while having a higher combustion controllability than HCCI [10].

2.3 Partially Premixed Combustion

As shown in Figure 1, fuel injection in PCC mode happens during the compression stroke, before Top Dead Centre (TDC), but the fuel is not injected at a specific crank angle [9]. Therefore, the separation between the end of injection (EOI) and the start of combustion (SOC) makes possible a larger degree of premixing at the start of combustion. The benefit of PPC combustion compared to HCCI combustion is that the fuel injection timing can be used as a control parameter for the combustion timing [3].

Combustion temperature can also be reduced by using a high level of cooled EGR, resulting in lower levels of NOx emissions and lower heat losses. However, the problem of using EGR in diesel PPC is the fact that it is necessary to use 80% of EGR to achieve both low NOx levels and low soot levels at high load. Using such a high EGR levels leads to a decrease in the combustion efficiency and it also elevates the emission levels of CO and HC due to the lower oxygen content in the mixture.

Therefore, the aim of PPC is to achieve a long ignition delay, which allows air and fuel to be mixed before ignition, without using high levels of EGR.

2.3.1 High Efficiency and Low Emission Levels

In order to obtain high efficiency and low emissions, different tools and methods, which are explained below, can be applied.

High Efficiency

It is proved, using the first law of the thermodynamics, that the output work can be increased by increasing the internal energy of the system (i.e. higher inlet pressure). It means that higher boost can result in higher efficiency for a given fuel energy per cycle.

On the other hand, the efficiency of the system can be increased by controlling the combustion phasing and the combustion duration. Earlier combustion phasing and shorter combustion duration lead to higher temperatures during the combustion process and hence, higher heat transfer. However, late combustion phasing and long combustion duration result in a decrease in effective compression ratio and, therefore more exhaust losses.

The third method to increase the efficiency is the squish as thermal insulator. As it is known, the combustion volume is divided in two regions: the bowl and the squish volume. The first one is appreciably hotter than the second one. When most of the reactions take place into the bowl volume, the squish volume acts like a thermal insulator, resulting in a higher efficiency due to a reduction in heat transfer.

Low emission levels

One of the most important ways to decrease the CO, unburned HC and NO_x emissions is to combine properly lambda and EGR. As it is shown in Figure 2, in order to reduce this emission levels, the temperature into the combustion chamber throughout the combustion should be between 1500 and 2000 K. For temperatures higher than 1500 K, the CO and unburned HC emissions are oxidised and for temperatures lower than 2000 K, NO_x formation is avoided.

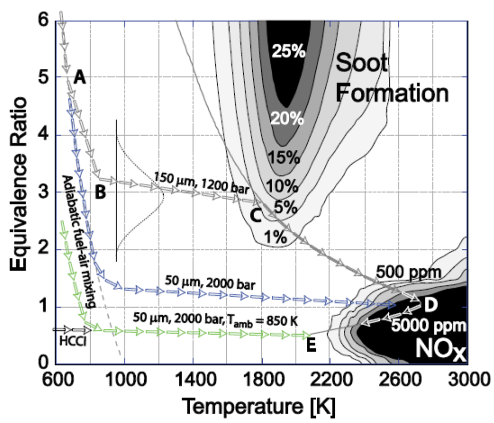

Figure 2. *Φ -T map where the soot and* NO_x *formation regions are shown [1].*

It was proved that if the engine is run with lambda between 1.3 and 1.6 and ERG between 45% and 55%, the maximum cycle temperature is within the mentioned range hence, it should be possible to obtain low CO, unburned HC and NOx [1]. Increasing the EGR, the soot emissions are increased since the temperature is not high enough to oxidise PM.

Other method to obtain low emissions is to modify the injector system. Smaller nozzle diameters and higher injection pressure decrease the soot formation in LTC.

It was also discovered that the fuel molecule plays an important role in the soot formation process. It is explained below.

2.3.2 Fuel in PPC Engines

Gasoline PPC

This concept was introduced by Kalghatgi in 2006 and afterwards it was studied at Lund University and University of Wisconsin.

The load range in which a compression ignition engine running in PPC mode with diesel fuel, having a compression ratio of 15-16, is 5 or 6 bar gross IMEP. If this IMEPg increases, it would need unacceptable amount of EGR and lower compression ratio in order to keep separated the end of injection and the start of combustion (low stratification when ignition occurs) [1].

It should be avoided operating with low compression ratio and high EGR in order to keep the mixing period at high load. Therefore, the engine can be run using gasoline fuel, since it is more resistant to ignition compared to diesel. In this way, as gasoline is more difficult to ignite, it exists more time between the end of the injection EOI and the start of the combustion SOC.

In this case, the fuel-air stratification is very important since, for the same fuel amount, when injection occurs very early in the cycle, the combustion can be very unstable and misfire can occur. However, if injection occurs around TDC, the more stratified mixture will result in a more stable combustion [1].

In terms of emissions, low NO_x and soot levels can be achieved when combustion takes place under homogeneous or very low stratified conditions. NO_x can be controlled by amount of EGR whereas soot produced is proportional to the ignite properties of the fuel [9].

Octane number indicates the tendency of fuels to knock. There are two ways of defining the octane number: Research Octane Number (RON) and Motor Octane number (MON). RON simulates fuel performance under low severity engine operation whereas MON simulates more severe operation that might be incurred at high speed or high load. In practice, the octane of a gasoline is reported as the average of RON and MON. Engine speed is normally set at 600 rpm to define RON and 900 rpm to define MON. In general, RON values are never less than MON, although exceptions to this rule exist. For pure compounds, the differences between RON and MON range from 0 to more than 15 numbers.

The higher octane number the more difficult the auto-ignition will be since higher RON results in longer ignition delay. Below can be found some fuels and theirs corresponding octane numbers.

- n-Heptane (C_7H_{16}) has an octane number of 0.
- iso-octane (C_8H_{18}) has an octane number of 100.
- Gasoline has an octane number between 93 and 97.

An important interaction between RON and the load range exists, since it was proved that fuels with lower RON values can be operated at lower loads.

Cetane number is a measure of the ignition quality of a diesel fuel based on ignition delay. A higher cetane number gives shorter ignition delay [7].

It denotes the ignition delay time (the start of the injection to the onset of the auto-ignition). The cetane number ranks the fuels and the higher the cetane number the faster the auto-ignition.

- Isooctane has a cetane number of 15.
- Diesel has a cetane number of about 37.
- Cetane ($C_{16}H_{34}$) has a cetane number of 100 [8].

For instance, gasoil (RON 84 (RON can be taken for the diesel fuel to be zero since its cetane number is very similar to that of n-heptane)) produces seven times more soot than gasoline (ON 95). Thus, it was shown that a gasoil engine can run at 3000 rpm in PPC mode while it is impossible with gasoline fuel because ignition delay is too long and misfire occurs [2].

It was also shown that, using gasoline with lower octane number, an increment in soot occurs when EGR was increased, but not as much as for diesel. Therefore, Kalghatgi concluded that the best fuel for gasoline PPC should have an octane number between 75 and 85 if the engine layout is kept constant [2].

Another of Kalghatgi's results was that increasing the aromatic percentage in the fuel, will help to increase the gasoline PPC upper load limit. Aromatic fuels become relatively more resistant to auto ignition compared to paraffin fuels as the pressure increases while the temperature is held constant [6]. Aromatics are hydrocarbons with alternating single and double bonds between carbon atoms forming rings. If the number of bonds increases to two and three double bonds, the knocking tendency decreases.

However, there is a problem with aromatic fuels since, as it is known, aromatics are potentially hazardous to health. Aromatics are based on benzene rings and benzene works by causing human cells not to work correctly. For instance, it can cause the bone marrow not to produce enough red blood cells, which can lead to anaemia. Benzene can also damage the immune system by changing blood levels of antibodies and causing the loss of white blood cells. Therefore, amounts of aromatics have to be controlled.

Dual fuel PPC

This concept was introduced by Besonette, who stated that the HCCI load range can be extended by varying the fuel composition. In addition, it was shown at University of Wisconsin that for a given load and engine layout, the efficiency is not maximised with either pure gasoline or pure gasoil [1].

However, different load speed points require different fuel reactivity and the optimal option is port injecting gasoline and direct injection of diesel. The reactivity of these mixture is controlled adjusting the diesel-gasoline ratio. Working with dual fuel PPC, combustion phasing is controlled by varying the fuel reactivity (ON) whereas the maximum pressure rise is controlled by modifying the stratification level of the fuel (start of fuel injection) [1].

As it was commented previously, combustion should start when the injection event is over. Two different stages exist:

- Low temperature reactions (LTR). Using diesel, low temperature reactions are followed by a high temperature heat release.
- High temperature reactions (HTR). Gasoline does not ignite until diesel transitions to thermal ignition.

Therefore, the most reactive fuel globally initiates the combustion process (reactions occur from the most to the less reactive fuel, which means that the combustion steadily progresses from LTR to HTR).

As it was explained, fuel reactivity gradient in the combustion volume can be used to increase the delay from the most to the less reactive fuel regions and hence, to extend the duration of the heat release rate.

2.4 Optical Engines

The aim of the optical engines is to gain visual access to the combustion chamber by manufacturing parts of the wall in transparent material. Optical property considerations like minimal birefringence or no UV fluorescence, often dictate that the windows are made from Fused Silica FS (quartz) which is a brittle material. The window can also be made of sapphire.

The experimental engine is usually modified to single cylinder operation to provide optical access into the combustion chamber and equipped with a fully variable valve train system [5].The remaining pistons are equipped with counter weights to compensate for the extra mass of the piston elongation.

One of the most important optical engine is the Bowditch design.

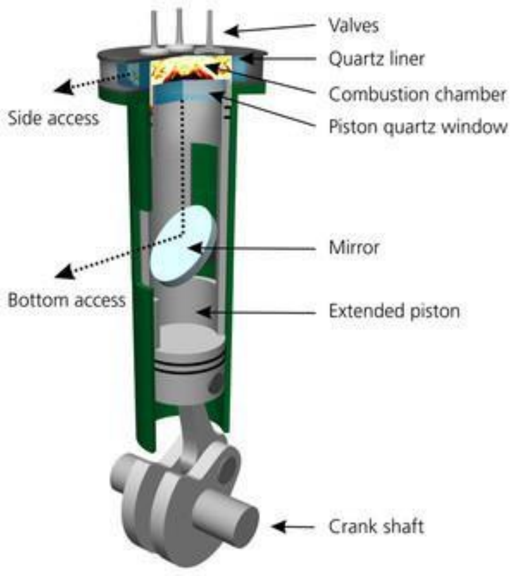

Figure 3. *Three-dimensional view of an engine equipped with optical access according to the Bowditch design.*

As can be observed in Figure 3, some parts of the combustion chamber are manufactured in quartz and an angled mirror (45º) is introduced in the bottom of the hollow piston extension. In this way, the combustion process can be observed from the side through the cylinder line and from below through the piston crown [5].

The use of optical engines often implies simplifications to the combustion chamber geometry in order to simplify the application of optical diagnostic techniques. These differences between optical and metal configuration engines affect the mixture preparation, combustion and emissions characteristics. Geometrical differences may also arise as a result of static and dynamic effects since the large optical piston may cause dynamic variations in the combustion chamber geometry [4]. In optical engines, a side-view allows for observing the flow structure and mixture distribution in a vertical plane into the piston bowl, therefore the upper compression rings must be located below the piston bowl floor. This results in large top ring-land crevice, which yields a lower compression ratio for the optical engine, compared to the same setup with metal pistons [15].Others geometric modifications may also be caused by installation of a window in one of the exhaust valve channels, removal of valve cut-outs from the piston top or compressive stresses of the extended piston assembly at high cylinder pressures.

The optical access impairs the heat transfer in the engine because glass is worse heat conductor than metal and because it is impossible to provide the glass parts with water cooling. Significant design effort is invested to avoid failure of the windows at high loads and boosted conditions while minimising piston mass. In order to reduce the risk of window failure maintaining moderate temperatures, optical engines are usually skip-fired, which means that only one injection occurs every few cycles. This approach decreases thermal and mechanical stresses. The combustion chamber surface temperatures are significantly higher in optical engines due to the low thermal conductivity of the optical windows. This leads to reduce head flux, resulting in higher combustion chamber surface and bulk gas temperatures. Aggravating the influence of low window thermal conductivity is the reduction in combustion chamber cooling capacity, caused by the surface area occupied by the windows and the necessity to restrict cooling passages to enable window installation.

The higher combustion temperatures will have a significant effect on the fuel oxidation reactions and the subsequent formation of CO, HC and NO_X [4] [5]. Therefore, it is necessary to carry out some modifications to the engine, such as moving the piston rings in order to avoid them passing the joint between glass and steel in the liner [4] [5].

2.5 Optical Diagnostics

Optical diagnostics are based on the utilization of electromagnetic radiation for the purpose of measuring or visualizing certain properties of the engine. Different diagnostic techniques are used depending on the aim of the optical engine investigation. These techniques can be classified into passive and active techniques.

2.5.1 Passive Optical Measurement Techniques

When using passive techniques, the combustion is usually imaged with a camera and the process is carried out without interference. Natural combustion radiation of soot luminosity and chemiluminescence from different gas molecules are part of passive techniques. Soot luminosity is normally more common, emitting radiation over the whole spectrum as a black body radiation [13]. Chemiluminescence is based on excitation of combustion radicals and it is explained in more detail below, since it is the main technique used in this project.

Passive techniques are commonly used to image hydroxyl radicals (OH). This species emit light in the Ultraviolet (UV) wavelength domain and the images provide important information about where the high temperature reactions occur.

However, the problem of passive optical measurement techniques is the fact that all of them give a line-of-sight perspective of the combustion chamber, since electromagnetic radiation includes light emission which travel in a straight line. This makes it impossible to capture the image inside of the reacting diesel flame [13]. In addition, another drawback of passive techniques is that species which are going to be analyse must radiate naturally.

Chemiluminescence

One source of optical emissions from combustion flames is chemiluminescence. In order to properly understand the chemiluminescence process, excitation events must be explained.

As it is known, an atom consists of neutrons, protons and electrons. Neutrons and protons together are called nucleons and they are forming the nucleus. Surrounding the nucleus, electrons can be found in a region called electron cloud. Within this cloud, electrons behaviour is defined by mathematical functions called atomic orbitals. Each atomic orbital corresponds to a particular energy level of the electron. The state of lowest energy is the one in which an atom is normally found and it is called the ground state. When the atom possesses more energy than its ground state energy, the atom is said to be in an excited state. However, the atom cannot remain in an excited stated permanently. In this way, the electron decays to one or another of the states at lower energy, returning finally to the ground state.

When de-excitation happens, a photon is emitted by the atom with an energy equal to the difference between both states. This energy corresponds to a specific wavelength [11, 12].

Once excitation process has been explained, chemiluminescence process can be described. This is the process whereby an electromagnetic radiation is emitted from the de-excitation of electronically excited species which are formed by chemical reactions in the combustion reaction zones. Thus, chemiluminescence can provide information about conditions in the reaction zone due to the visible and ultraviolet chemiluminescence of CH*, OH*, C_2* and CO_2* [14]. As said before, chemiluminescence signals have to be interpreted with caution due to their line of sight nature.

In this project, chemiluminescence is going to be used to determine how homogeneous the mixture is. Chemiluminescence can also be helpful in heat release calculations. Due to the short exposure time of these events, a high speed camera is required to capture the processes in the combustion chamber.

A high speed camera is a device which is capable of capture fast events and record them as images, which can be played back slowly to study a certain phenomenon. Depending on the species which want to be studied, the camera can also be equipped with a band-pass spectral filter that separates a particular wavelength. These cameras use nowadays electronic image sensors to record these high-speed events, such as CCD and CMOS, which can record over 1000 frames per second.

2.5.2 Active Optical Measurement Techniques

In active techniques the radiation from the measurement volume is generated by an external source of radiation. The benefit of active techniques compared to passive techniques is that using active techniques the interior of the flame can be analysed and also more species can be studied.

Active optical measurement techniques can be used to measure in a point, along a line, in a plane or in three dimensions [13]. In combustion engine diagnostics the measurements are carried out with lasers as radiation source. Some of these techniques are Laser-Induced Fluorescence (LIF) and Laser-Induced Incandescence (LII).

Laser-induced fluorescence

Laser Induced Fluorescence is the optical radiation emitted by laser excited molecules when de-exciting from a higher to a lower energy state. The laser needs to be tuned to a specific wavelength and this chosen wavelength depends on the studied molecule, since the laser has to excited electrons in a certain molecule. This phenomenon is usually detected at a longer wavelength than the laser and it can be imaged with a camera or spectrally resolved. LIF provides high signal and also minor species can be imaged [13].

This method is used to see certain components in the combustion chamber and allows the study of different species, giving different information about the combustion.

Laser-induced incandescence

Laser Induced Incandescence is created when a laser pulse heat soot particles to a higher temperature than the surrounding medium. Soot particles emit thereby a blue light-spectra, compared to the surrounding, which must be collected at short wavelengths, where the flame background luminosity is insignificant [13]. LII can be used to measure both soot volume fraction and soot particle size. The decay time of the LII signal is related to the soot particle size and the signal strength is related to the soot volume fraction.

3. EXPERIMENTAL APPARATUS

3.1 Engine Setup

The engine used in this master thesis is based on a Volvo D5, which is a five cylinder compression ignition engine. This engine has been modified to obtain an optical configuration in such a way that the engine was converted into a single cylinder operation engine, with a Bowditch piston extension. In Figure 4 below shows this engine.

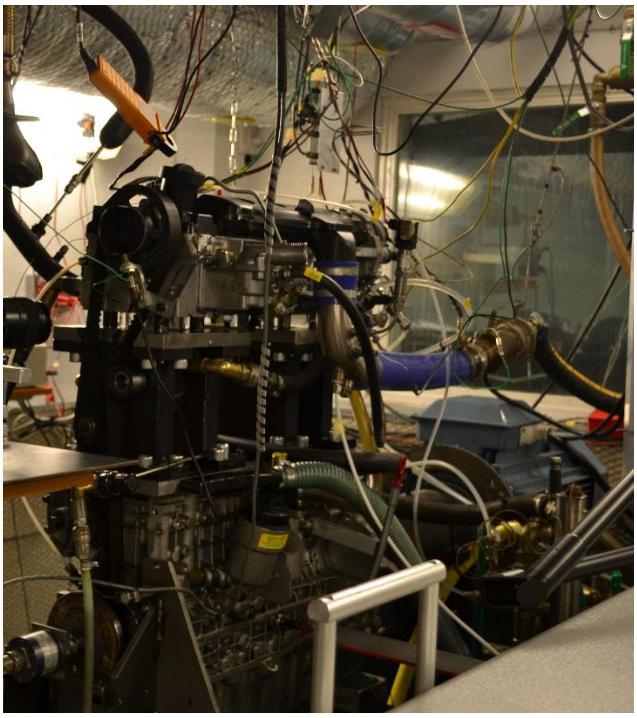

Figure 4. *Volvo D5 modified to be run in an optical setup.*

As the engine has been modified to run on a single cylinder, the remaining four cylinder are motored and equipped with weights to compensate for the extra mass of the modified piston. A fuel-silica (F-S) piston is used as a substitute for the conventional piston and it allows an image to be seen throughout the combustion process. This is possible through the use of a 45 degree mirror which is placed in the slot of the piston extender. In Figure 5 and Figure 6 below, the optical configuration in detail can be observed.

***Figure** 5. Detail of the optical configuration of the engine, showing the Bowditch piston extension as well as the combustion chamber.*

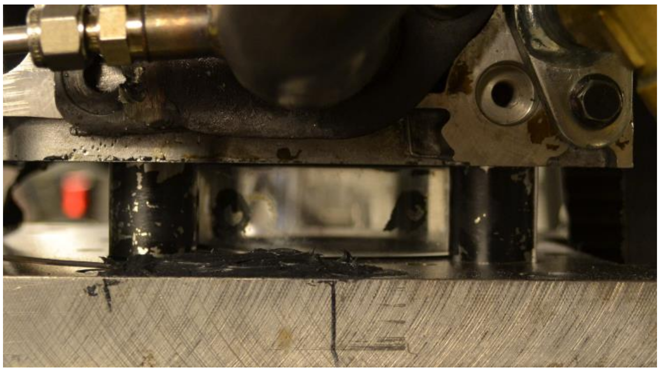

***Figure 6.** Detail of the window that allows to see the combustion chamber when the engine is running.*

The engine was equipped with a fully valve train system which had the characteristics of fully flexible valve lift, duration and timing. It also can control each valve individually.

The engine parameters are shown in Table 1 below.

***Table 1**. Engine parameters*

Engine Parameters	
Engine speed	800 rpm
Stroke	93.2 mm
Bore	81 mm
Compression ratio(metal configuration)	16.5:1
Compression ratio(optical configuration)	11.3:1
Number of valves	4
Fuel	PRF 70
Valve timings	Fully flexible

A Phantom PIV (Particle Imaging Velocimetry) camera is placed in front of the bottom access to focus the image reflected by the mirror. The camera setup used during the experiments is shown in Table 2 below.

***Table** 2. Camera data*

Camera Data	
Frame rate	9367 pps
Chip resolution	368x600
Exposure time	50 microseconds
OH interference filter	310 nm
FWHM	10 nm
f-number	5.6
Number de images per cycle	100

3.2 Engine Control

In order to accomplish the experimental work properly, the engine is controlled by a system which consists of a host PC, target PC and a logger. This system is shown in Figure 7 below.

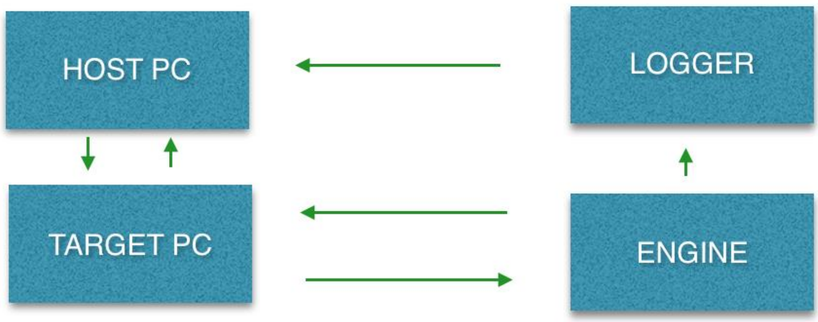

***Figure** 7. Sketch of the engine control system.*

Each one of the elements that are part of the controlling system are explained below.

3.2.1 Host PC

It is located in the control room. The aim of the host PC is to control the different parameters of the combustion, such as injection timing, injection duration, etc.; using LabVIEW.

This modifications are sent to the Target PC and a TCP/IP updates the values between host and target PCs. TCP/IP is a code protocol of the Internet Protocol Suite which derives from the initial network implementation in which it complements the Internet Protocol (IP). Therefore, TCP/IP is a way of sending and receiving information reliably over the network. TCP/IP functions are built into LabVIEW and these functions make the transmission across the network possible and reliable.

When some data is sent over the net, it is subdivided into packets. These packets can take different routes from a computer to the other over the net. Hence, the packets arrive at different times and are out of order. When that happens, TCP requests a re-send to be sure that it has all of the packets.

3.2.2 Target PC

The Target PC is located in the engine room and it has a double function.

On the one hand, it sends the information from the Host PC to the engine and, on the other hand, it collects the data from the engine and transfers it to the Host PC.

The Target PC has a RT Launcher that tells the field-programmable gate array (FPGA) when to do something. The FPGA is an integrated circuit designed to be configured by the customer. Its configuration is generally specified by using a hardware description language (HDL). In this case, the FPGA is used for measuring high resolution data, such as the in cylinder pressure, since these measurements are needed every 0.2 CAD. It is able to both sample information from sensors in the engine and be used to send commands to the actuators such as injection timing, injection duration, laser-triggering, etc.

The RT Launcher is a virtual instrument (VI) that includes the TCP/IP. It is able to transfer data between the host and the target so that the commands can be transferred to the engine every cycle as well as read data from sensors to the host PC.

3.2.3 Logger

The logger is an electronic device that records data over the time or in relation to the location. It is generally small, battery powered, portable and equipped with a microprocessor, internal memory for data storage and sensors.

The logger is used for measurements that are not needed that often (low resolution data).

3.3 Operating Conditions

The experimental study of this master thesis is focused on finding the homogeneity level of the combustion. In order to perform this experimental work, the engine was run at low load and using negative valve overlap (NVO) and different injection strategies. The homogeneity will be determined thus for a given setting of NVO and for a specific fuel injection strategy. The different injection strategies chosen were single, double and triple injection, and the negative valve overlapping was set to 10 CAD for all the experiments.

Primary reference fuel composed of 70% iso-octane and 30% n-heptane (PRF70) was used as fuel during the experiments. The engine was run at 800 rpm using a rail pressure of 500bar. An alternating current (AC) dynamometer controlled the engine speed. All the engine parameters used during the experiments are shown in Table 3 below.

Table 3. *Operating Conditions*

Operating Conditions	
Engine speed (rpm)	800
Injection pressure (bar)	500
Intake pressure (bar)	1.14
Intake temperature (ºC)	73
Swirl ratio	2.6
Lambda	1.8
Oxygen	17.5%
Cooling water temperature (ºC)	65
Liner wall temperature (ºC)	80
NVO (CAD)	10

In order to control the intake temperature around 73 ºC, as shown in Table 1, an electrical heater was used during the experiments. During the experiments, lambda was approximately 1.8. The oxygen level also had to be controlled around the set value since if the oxygen level is lower than required, it is more difficult to get the combustion. The temperature of the cooling water had to be around 65ºC, therefore it took some time to reach this temperature.

Whenever the combustion is occurring, high temperature values are reached by the glass parts, causing the failure of the glass. Hence, it was necessary to control this increased temperature, to such an extent that the experiment had to be stopped when the liner wall temperature reached values around 80ºC. The control of the liner wall temperature was made by a thermocouple mounted on the glass ring. In addition, skip-fired mode was not used during the experiments.

The NVO was used as a control of the combustion stability. When using this strategy, the hot residual gases (combustion products from the previous cycle) are trapped and recompressed early in the engine cycle, in such a way that a fraction of the fuel of that cycle can be injected during this period. The NVO strategy was used including early exhaust valve closing (EVC) and late intake valve opening (IVO) for the purpose of retaining large amount of residuals.

For the engine parameters described before, the different injection strategies chosen as well as the specifications for each one of them are shown in Table 4 below.

Table 4. *Injection strategies*

Injection Strategy	Case	Start of Injection (BTDC)	Injection Duration (μs)
Single	S16	16	600
Single	S24	24	600
Double	D52-17	52/17	600/390
Double	D35-17	35/17	600/390
Double	D45-24	45/24	600/390
Double	D54-20	54/20	600/390
Triple	T62-28-18	63/30/17	470/360/350
Triple	T62-28-11	63/30/12	470/360/350

As shown in Table 2, three different injection strategies were used during the experimental work. At first, two cases of single injection were run. In the first one, the start of ignition happens at 16 crank angle degrees (CAD) before top dead centre (BTDC). In the second case of single injection, combustion starts at 24 crank angle degrees before top dead centre. The injection duration was 600 μs for both experiments.

Next, four different double injection cases were carried out, using different starts of ignition. In the first two cases, the first injection was at 52 CAD before TDC and at 35 CAD before TDC respectively, being the second injection at 17 CAD before TDC. In the third case, the first injection was at 45 CAD before TDC and the second one at 24 CAD before TDC. In the fourth case, the first injection happened at 54 CAD before TDC and the second one at 20 CAD before TDC. Regarding the duration of each injection, it was the same for all the double injection cases. It was 600 μs for the first injection and 390 μs for the second injection.

Finally, two cases of triple injection were run. Both first and second injection happened at the same time for both cases. An early injection strategy at 62 CAD before TDC was chosen for the first injection, taking part the second injection at 28 CAD before TDC. The third injection was set at 18 CAD before TDC for the first case and at 11 CAD before TDC for the second case. Injection duration was the same in both cases, being 470 μs for the first injection, 360 μs for the second one and 350 μs for the last one.

4. METHOD

4.1 Theoretical Background

The aim of this project is to obtain an index which is able to measure how stratified the combustion is or, in other words, how homogeneous the combustion is. Chemiluminescence imaging is carried out to obtain this index, which will be obtain at the end of the post-processing and will be called "Stratification Number" (SS). This stratification level will allow to compare the different injection strategies studied in this work.

The post-processing is based on a frequency analysis, performed through the Fast Fourier Transform (FFT). The FFT is an algorithm to compute the Discrete Fourier Transform (DFT). Fourier analysis allows to convert time or space to frequency or wave number. In this project, a space to wave number conversion is used, since the FFT is applied to an intensity versus angle function. The procedure followed is explained in detail below.

4.2 Image Processing

For each injection strategy, a total of 3000 images are collected. The measurement interval reaches from -10 to 30 CAD after top dead centre (ATDC) and thirty cycles are studied for each injection strategy. Therefore, one hundred images are obtained per cycle and one image is taken every 0.4 CAD.

The frequency analysis performed on Matlab in order to post-process all the images and to obtain the final stratification number is explained below.

First of all, two for loops are used to read the 3000 images, so that an average of the 30 cycles measured for each injection strategy is obtained. The analysis is made now for one hundred images. When reading the images, figures such as Figure 8 are obtained, in which different colours are assigned to the different intensity levels within the combustion chamber.

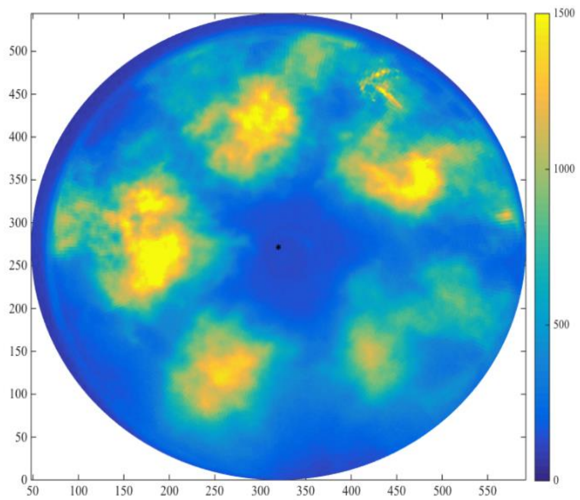

Figure 8. *Image showing the different intensity level of the different parts in the combustion chamber.*

A coordinate transformation to polar coordinates is done after to obtain a figure which represents the radius of the circle corresponding to the combustion chamber as a function of the angle theta. This is shown in Figure 9 below, where five spots corresponding to the five plumes of the injector can be observed.

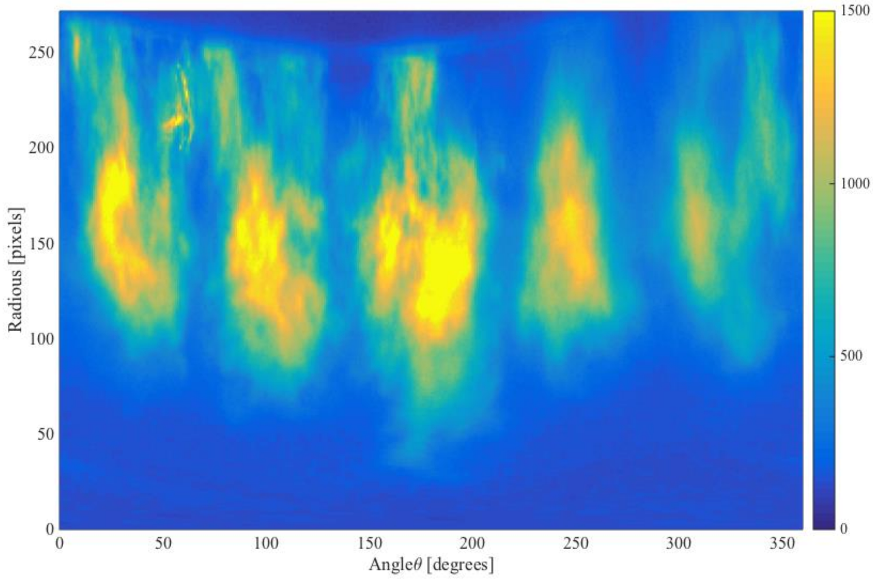

Figure 9. *Radius as a function of theta.*

A representative band from Figure 9 is selected to carry out the frequency analysis. This region, shown in Figure 10, goes from 125 to 175 pixels, and it is averaged for each angle. Using this band, a one dimensional graph is obtained, where the intensity level is represented as a function of the angle, theta. This graph is shown in Figure 10 and it can be seen the five peaks obtained, corresponding each one of them to each one of the five sprays of the injector.

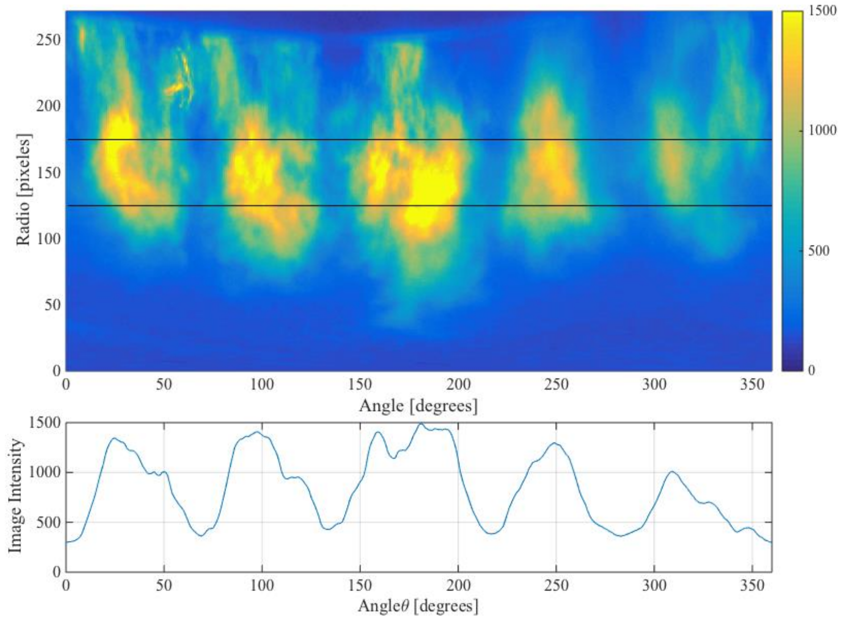

Figure 10. *A two-dimensional graph showing the radius as a function of theta and, below, a one-dimensional graph shows the intensity level of the averaged band as a function of theta.*

Finally, the Fast Fourier Transform (fft function on Matlab) is applied to this curve to obtain Figure 11. It shows a spectrum of frequency components or, in other words, the energy level as a function of the wave number. As one hundred images has been processed so far, this curve in based on the average of each one of this images, obtaining therefore an averaged spectrum of one hundred images.

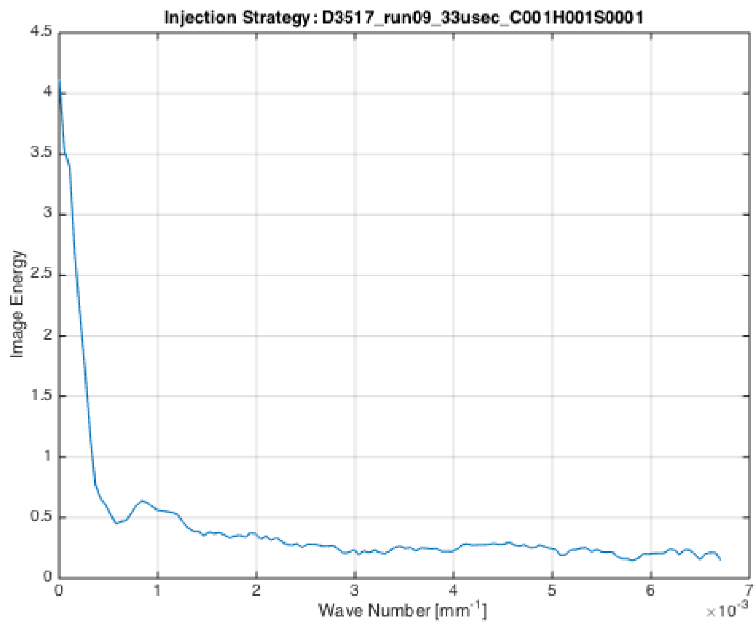

Figure 11. *Spectrum showing the Fourier Transform applied to graph of intensity as a function of theta.*

In addition, in order to get a better understanding of the combustion process, a three-dimensional graph which shows the energy as a function of the wave number and CAD (working with the average of each CAD for the 30 cycles) is also included in the results section.

4.3 Stratification Number

As said before, the aim of the frequency analysis is to obtain the stratification number, which allows to study the combustion homogeneity or stratification level. In order to obtain this index, the graph obtained in Figure 11 is used. The stratification number is a relation between the red area observed in Figure 12 and the total area enclosed by this curve. The red area is placed at a certain representative range of wave number and is the one which is going to be used to define the stratification number. This region is situated around one fifth of the total wave number scale.

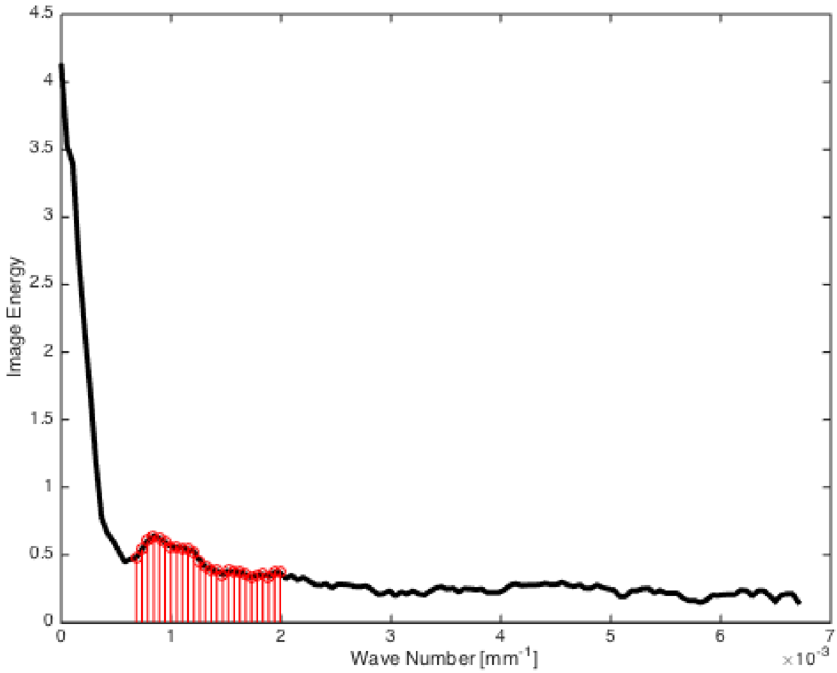

Figure 12. *Graph showing the selected area to calculate the stratification number, SS.*

This index makes it possible to compare the stratification of the different combustion strategies. A higher stratification number means a more stratified combustion or, in other words, a less homogenous combustion. Likewise, a lower stratification number means a less stratified combustion and, therefore, a more homogenous combustion.

5. RESULTS AND DISCUSSION

In this section, results and graphs obtained after performing the post-processing are shown. The results will be shown for one case of each different injection strategies. Therefore, three different cases will be commented below, one case for single injection, one case for double injection and one case for triple injection. The results for the rest of the experiments are included at the end of this thesis as an appendix (appendix 1).

For each discussed case, two graphs are shown. The first one shows the Fast Fourier Transform corresponding to the Figure 11 explained in the method section. The second one is a three-dimensional graph, also explained before, showing the combustion process.

5.1 Single Injection Strategy, S16

Figure 13 below shows a graph that is obtained by applying the Fast Fourier Transform (fft function) to graph showing in Figure 10. As it can be observed in Figure 13, a peak appears along the abscissa axis, at low frequencies, corresponding to the intensity of the five plumes of the injector.

The stratification number, calculated as explained previously, is SS=0.1119.

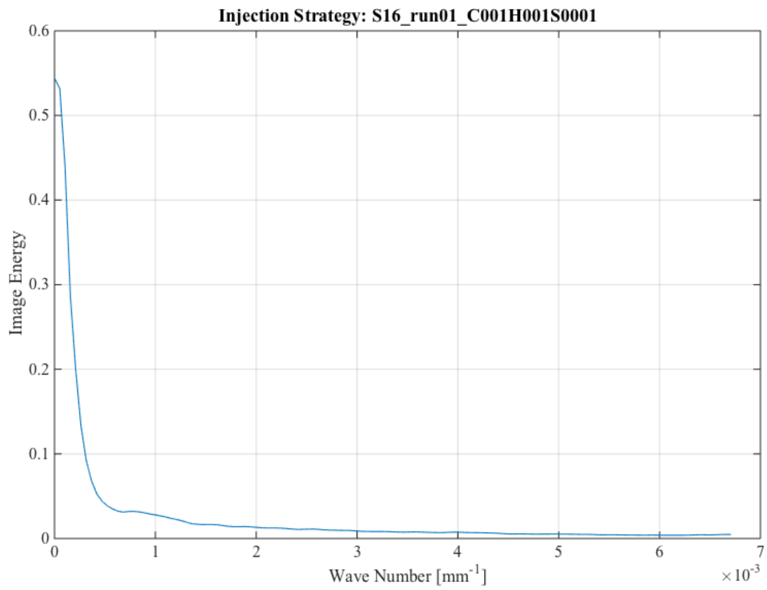

Figure 13. *Spectrum showing the Fourier Transform for single injection strategy, S16.*

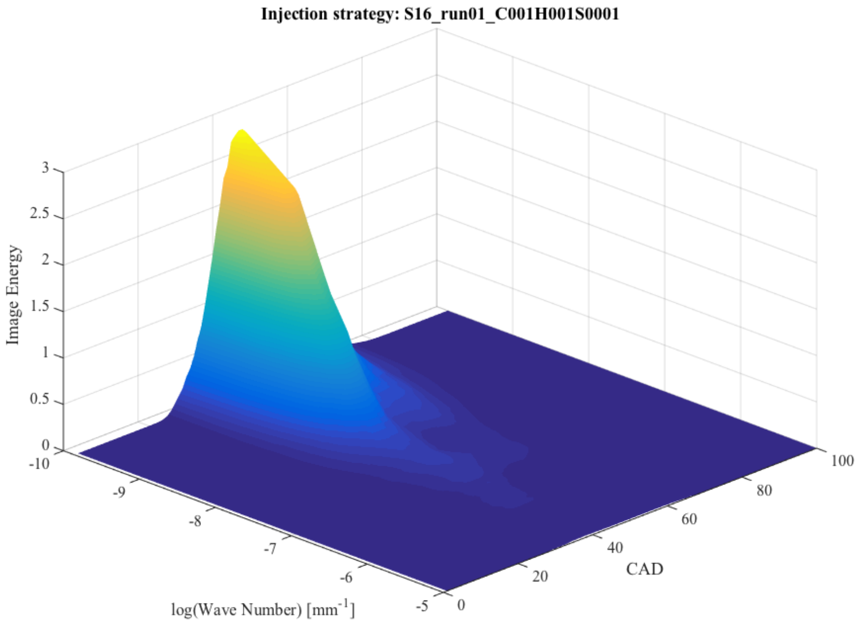

Figure 14. *Three-Dimensional Energy for single injection strategy, S16.*

Graph shown in Figure 14 above provides a better understanding of the combustion process for the injection strategy studied since energy is represented as a function of wave number and CAD. Therefore, energy as a function of length for each image taken (average of the same image for the 30 cycles) is shown. The combustion progress is observed, from the beginning to the end.

5.2 Double Injection Strategy, D35/17

As in the case mentioned above, in Figure 15 below can be seen a main peak for low frequencies and how this peak decreases as frequency increases.

The stratification number obtained in this case is SS=0.1657.

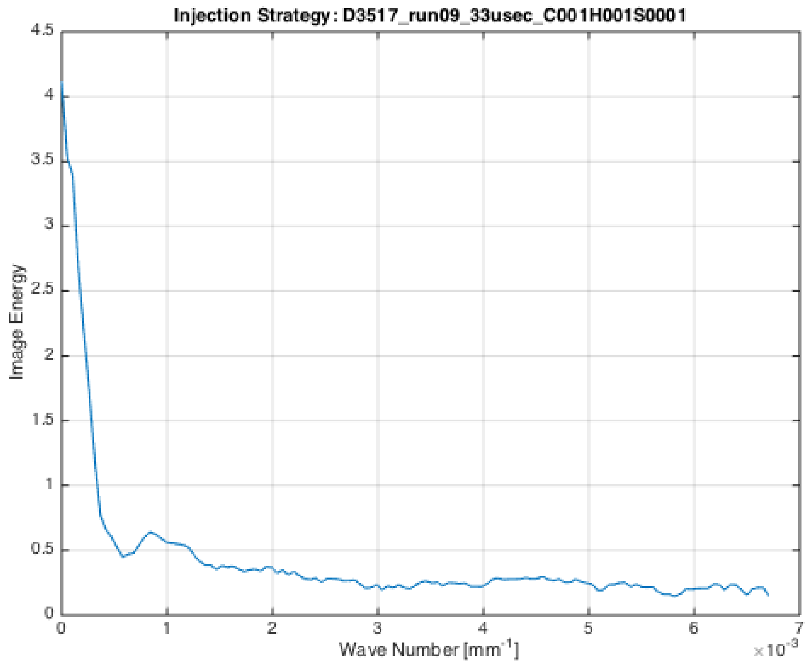

Figure 15. *Spectrum showing the Fourier Transform for double injection strategy, D35/17.*

Figure 16 below shows how the combustion occurs between CAD corresponding to images between 20 and 60. It also can be seen, as one would expect, how the energy decreases as wave number increases.

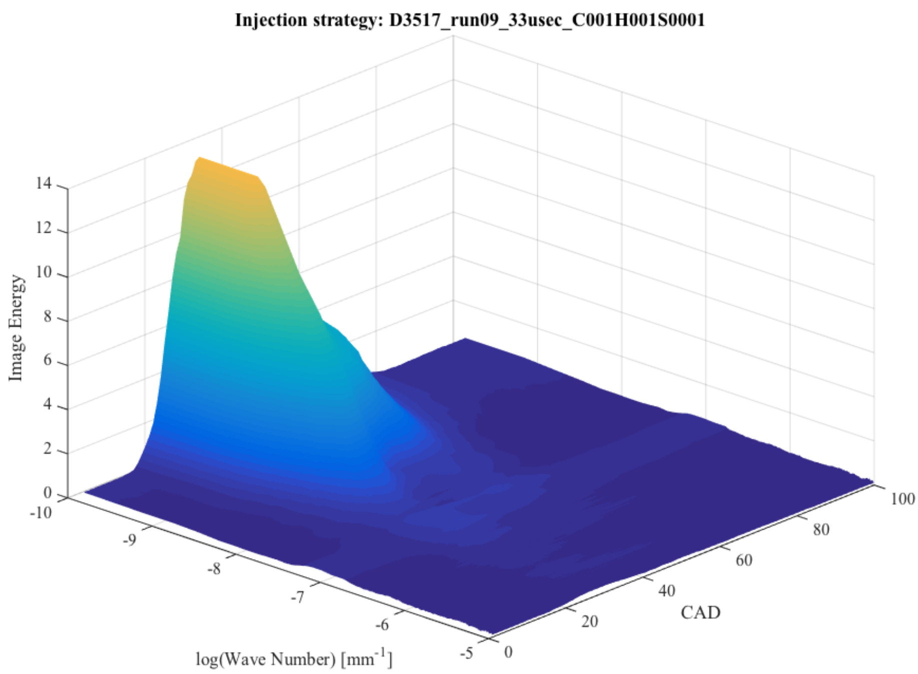

Figure 16. *Three-Dimensional Energy for double injection strategy, D35/17.*

5.3 Triple Injection Strategy, T62/28/11

As shown in the previous injection strategies, Figure 17 shows a plot of the energy as a function the wave number. The stratification number calculated for this injection strategy is SS=0.1039.

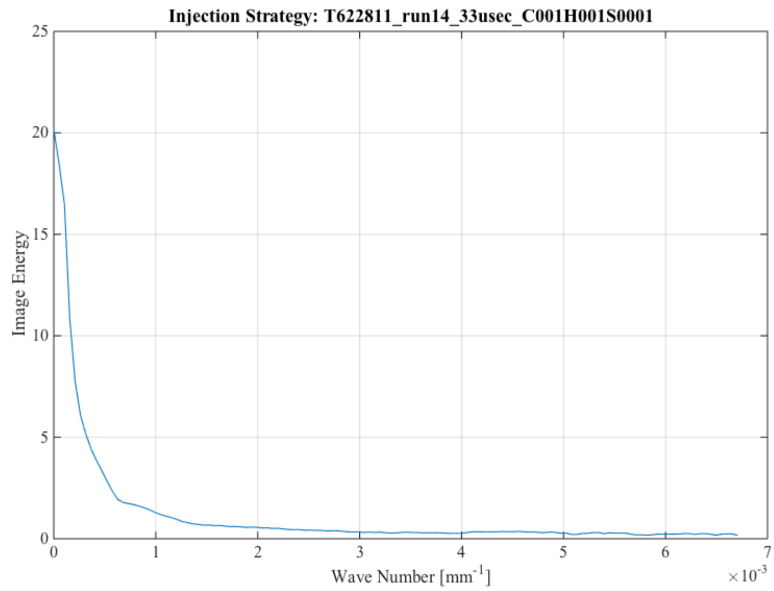

Figure 17. *Spectrum showing the Fourier Transform for triple injection strategy, T62/28/11.*

In Figure 18 below, the combustion progress, from start of combustion to the end of the combustion, is shown by plotting the energy as a function of wave number and CAD. Same behaviour as in previous injection strategies is obtained.

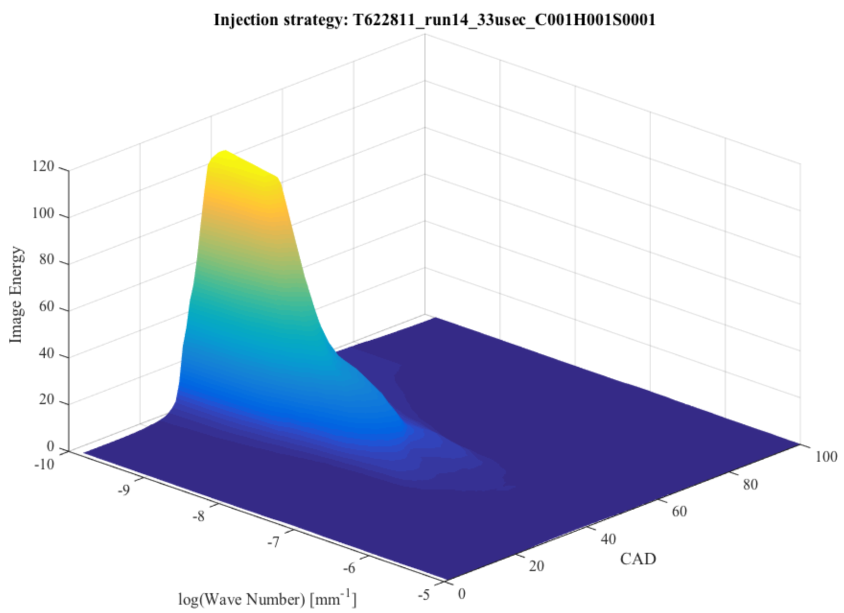

Figure 18. *Three-Dimensional Energy for triple injection strategy, T62/28/11.*

6. CONCLUSIONS

The goal of this study is to calculate a stratification level of the combustion for low load engine conditions using 10 CAD negative valve overlapping and different injections strategies. OH Chemiluminescence measurements were carry out in order to analyse the partially premixed combustion in a light duty optical setup engine using primary reference fuel, PRF70.

The stratification numbers obtained for each injection strategy are shown in Table 5 below, and they make it possible the comparison between the different injection strategies.

Table 5. *Stratification Number for each injection strategy.*

Injection Strategy	Stratification Number, SS
S16	0.1119
S24	0.2599
D35-17	0.1657
D45-24	0.1702
D52-17	0.1857
D54-20	0.1894
T62-28-11	0.1039
T62-28-18	0.1413

The average of this stratification numbers for the three different injection strategies can be seen below:

- SS_single = 0.24185
- SS_double = 0.1778
- SS_triple = 0.1226

The aim of the obtained stratification number is to measure how stratified or homogenous is the combustion. A high stratification number ought to correspond to a high stratified combustion, whereas a low stratification number should correspond to a more homogenous combustion. The averaged stratified numbers are used to compare the injection strategies.

As it can be seen in Table 5, the highest stratification number, SS=0.24185, corresponds to single injection strategy, meaning that this injection strategy is the most stratified. Likewise, the lowest stratification number, SS=0.1226, corresponds to the triple injection strategy. These results are consistent with the expected theoretical results, since the triple injection strategy is expected to be the most homogenous combustion. This is due to the fact that, in the triple injection strategy, the first injection is chosen 62 degrees before the top dead centre, the earliest, therefore the charge is well premixed before the start of combustion. The second injection controls the combustion phasing and, finally, zones with higher reactivity which will be burn firstly appear when the third injection occurs. On the other hand, single injection strategy is expected to be the more stratified, as it is obtained, owing to the charge is not well premixed before the start of combustion.

However, some problems with this method can be found when analysing the results obtained.

In figure 9 it can be observed how the coordinate transformation introduces a small distortion in the image since the five spots corresponding to the five plumes of the injector appear with a modified shape.

In addition, as it has been explained before, the study is focus on the range of radius selected since it is the most representative area in the figure. This means that not all the information that can be obtained from the image has been used.

Nonetheless, it can be concluded that the frequency analysis is a satisfactory method to study the combustion homogeneity since it provides consistent results as well as a comparison among different injection strategies. Chemiluminescence imaging is also a useful diagnostic to see what happens during the combustion process and, in this specific case, study the homogeneity of the combustion.

7. FUTURE WORK

As the time to carry out a master thesis is limited, it is convenient to propose some future work that can be performed after this project.

At first, this method can be apply to a heavy duty engine in order to analyse and compare the results obtained with the ones obtained in this study. In addition, it would be also interesting to apply this method to other injection strategies and analyse the obtained results.

As there are also other methods to analyse the homogeneity of the combustion, the results obtained with this method should be compared to the results obtained with the previously mentioned methods to prove that this method is satisfactory.

Finally, as it has been stated in the conclusions section, since this method can introduce some errors in the obtained results, a possible future work can be to quantify this error and modify the method to obtain a better result.

ACKNOWLEDGEMENTS

We would like to thank the department of Energy Sciences and especially the Division of Combustion Engines for giving us the opportunity to develop this study.

We would like, in particular, to thank our supervisor, Bengt Johansson, for his guidance and thesis motivation.

Furthermore, we would also like to thank the technicians for their efforts, which have made the development of our thesis possible.

We would like to thank our families for giving us the opportunity to study this year in Sweden as well as our home universities.

Finally we would like to thank each other for the enormous support and for all the help we got from each other. Thanks to Lund University for facilitating this, we have found a true friendship in each other.

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APPENDIX 1. EXTRA RESULTS FROM SINGLE, DOUBLE AND TRIPLE INJECTION (FREQUENCY ANALYSIS)

The rest of the results obtained for single, double and triple injection are shown in this appendix.

Single Injection Strategy, S24, SS=0.2599.

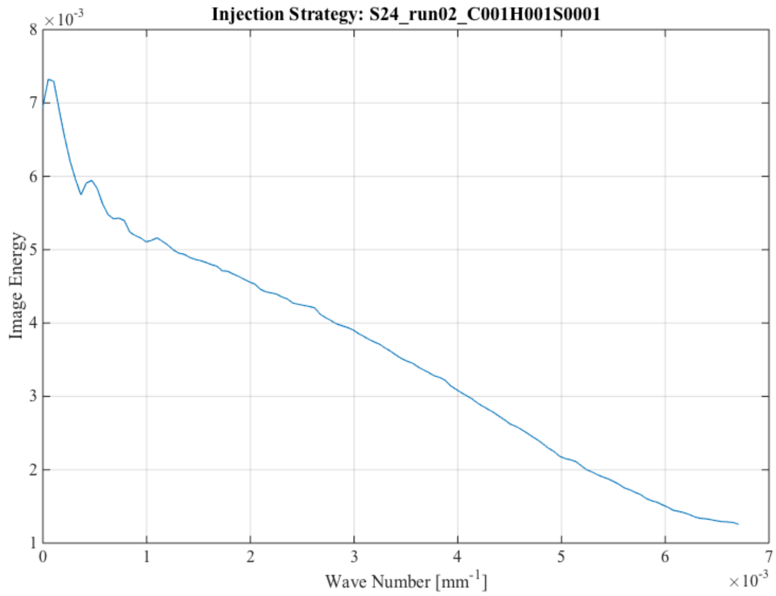

Figure 19. *Spectrum showing the Fourier Transform for single injection strategy, S24.*

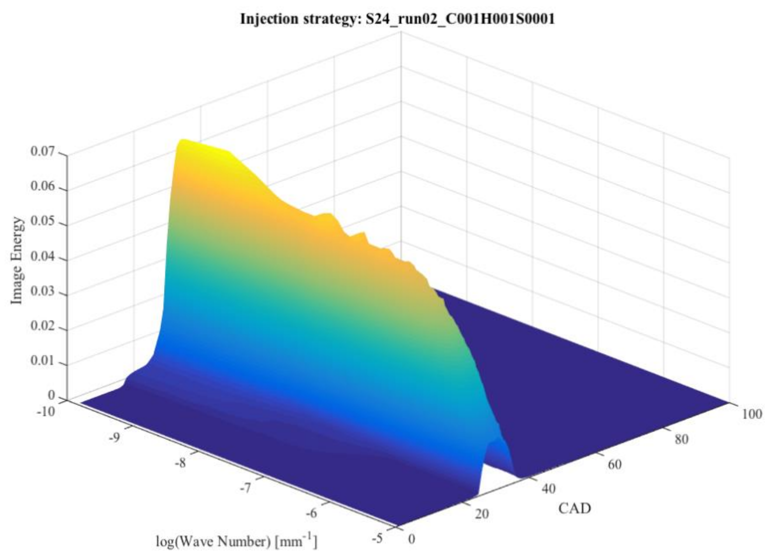

Figure 20. *Three-Dimensional Energy for single injection strategy, S24.*

Double Injection Strategy

Double Injection Strategy, D45/24, SS=0.1702.

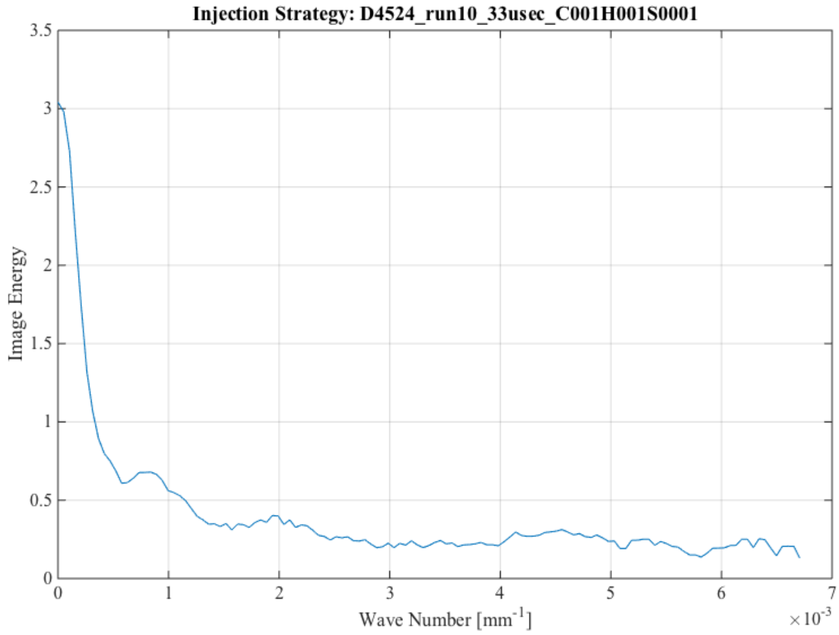

Figure 21. *Spectrum showing the Fourier Transform for double injection strategy, D45/24.*

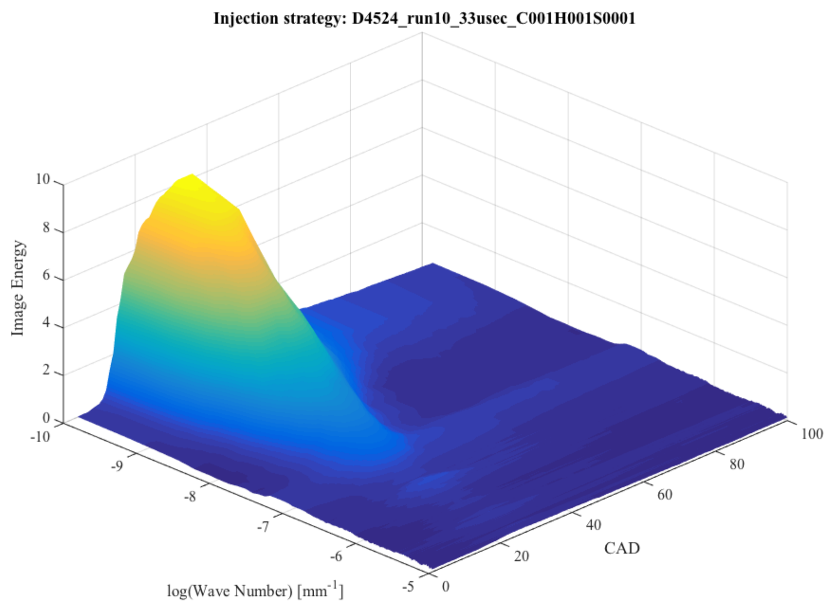

Figure 22. *Three-Dimensional Energy for double injection strategy, D45/24.*

Double Injection Strategy, D52/17, SS=0.1857.

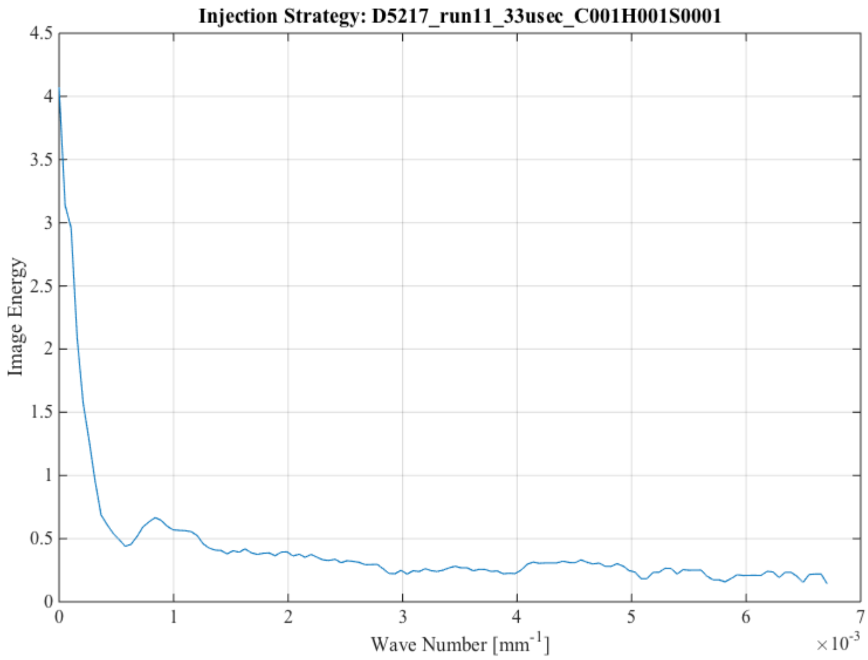

Figure 23. *Spectrum showing the Fourier Transform for double injection strategy, D52/17.*

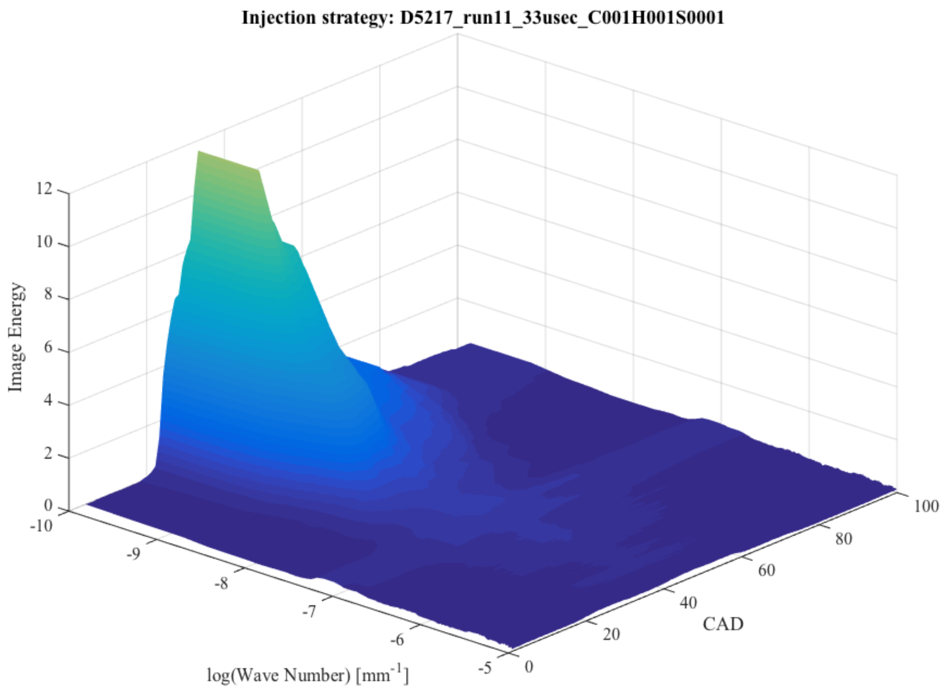

Figure 24. *Three-Dimensional Energy for double injection strategy, D52/17.*

Double Injection Strategy, D54/20, SS=0.1894.

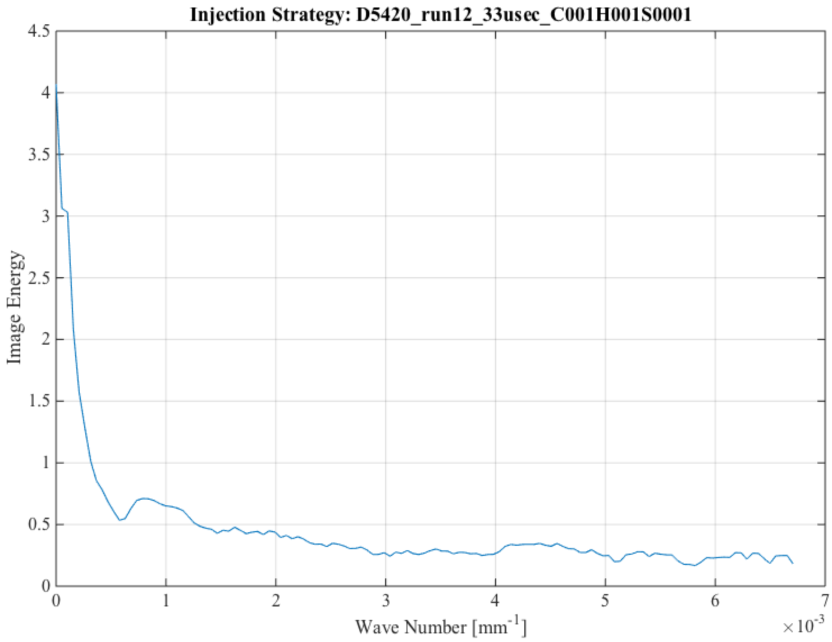

Figure 25. *Spectrum showing the Fourier Transform for double injection strategy, D54/20*

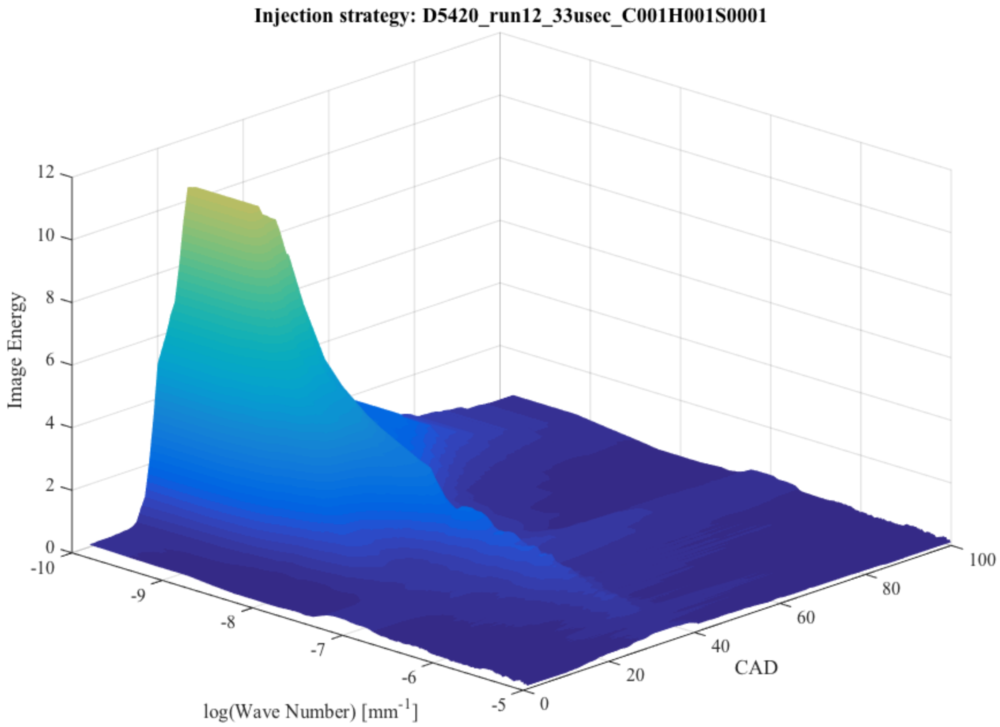

Figure 26. *Three-Dimensional Energy for double injection strategy, D54/20.*

Triple Injection Strategy, T62-28-18, SS=0.1413.

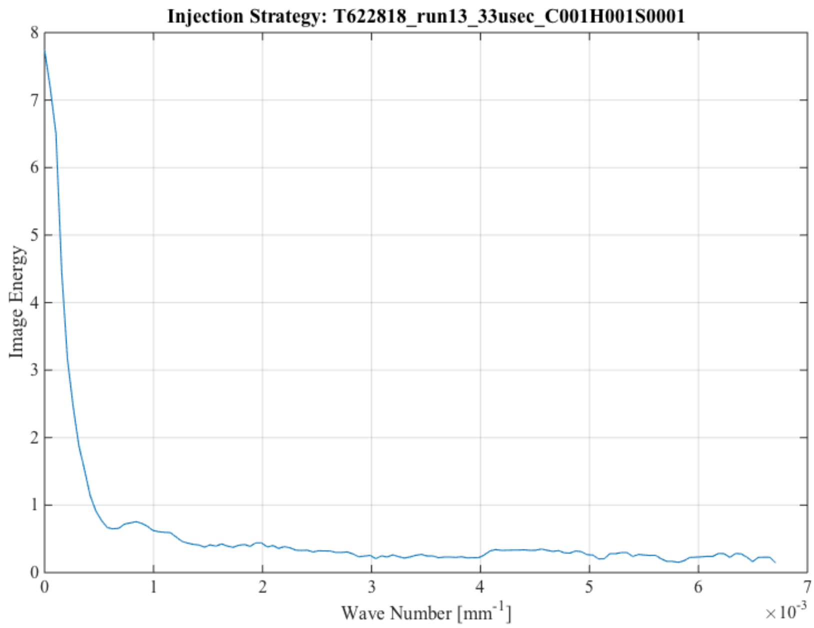

Figure 27. *Spectrum showing the Fourier Transform for triple injection strategy, T62/28/18.*

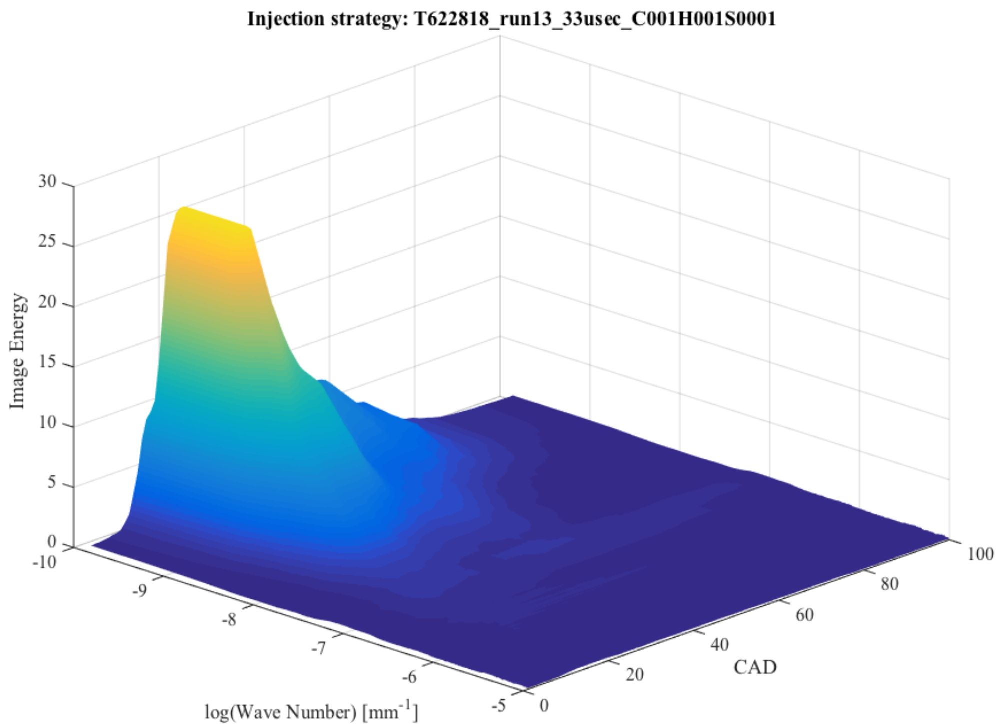

Figure 28. *Three-Dimensional Energy for triple injection, T62-28-18.*

APPENDIX 2. ALTERNATIVE METHOD TO OBTAIN THE STRATIFICATION INDEX

A different method has been developed in this master thesis in order to study the combustion homogeneity. This new method is based on the analysis of the images pixel by pixel and all the data has also been processed by this method. The obtained results are also included in this appendix, and they will be presented in terms of stratification.

In this method, a circle centred on each picture, corresponding to the combustion chamber, is selected and divided into five regions. Each of these regions correspond to the five plumes of the injector. The intensity is analysed using a polar coordinate system and the code created to facilitate this is explained below.

The first part of the code aims to read the 3000 images. Two for loops and the "imread" function are used to do this, since 100 images were collected per cycle, and 30 cycle were measured. Five 1x3000 are obtained and to summarise the information of the 30 cycles, "reshape" function is used, resulting in five 1x100 matrixes. Each one of these matrixes corresponds to the averaged intensity of the region over the 30 cycles.

Once the images are read, several graphs and results are generated. At first, two plots of the intensity level against the CAD are obtained. The first one, in Figure 29, shows five curves, corresponding to the five sprays of the injector, during the 30 measured cycles. It can be seen that combustion occurs in all the cycles, since continuous firing mode was used during the experiments.

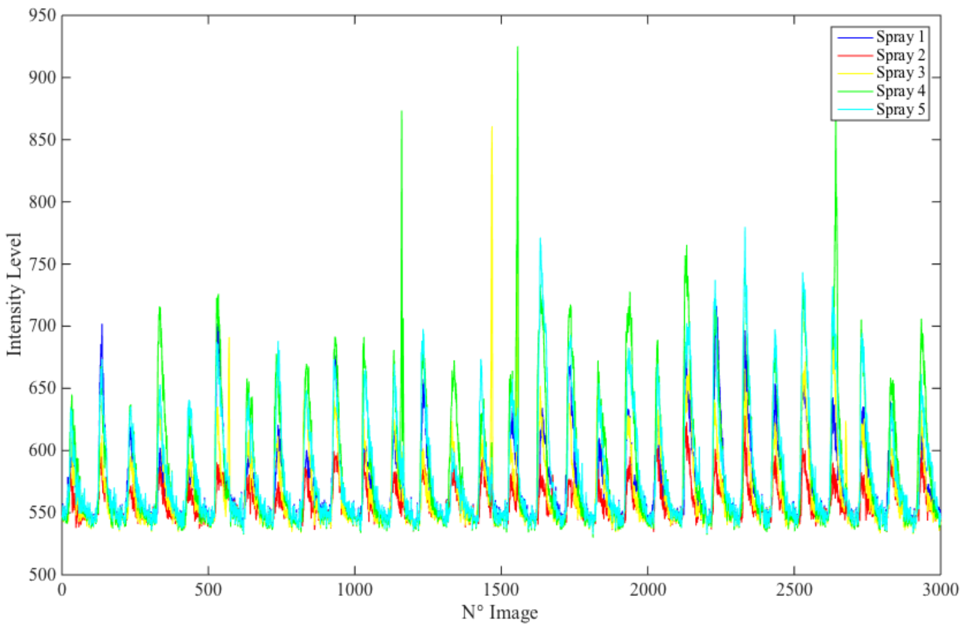

Figure 29. *Intensity level as a function of the total number of images for each spray.*

In Figure 30, the intensity level is represented as a function of CAD for an average of the 30 is represented.

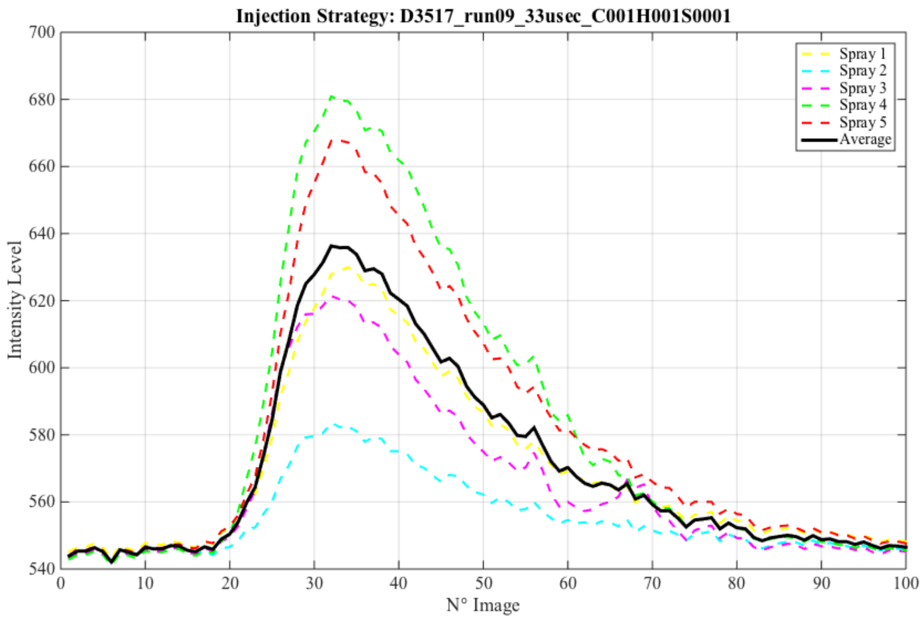

Figure 30. *Plot showing the intensity level for each spray, as well as an average of them, as a function of the average of the cycles.*

The following generated graph shows the intensity level as a function of the angle. This plot is shown in Figure 31 and an interval from image number 20 to image 60 is averaged to get it, since the combustion for all injection strategies occurs between -2 CAD (image 20) and 14 CAD (image 60).

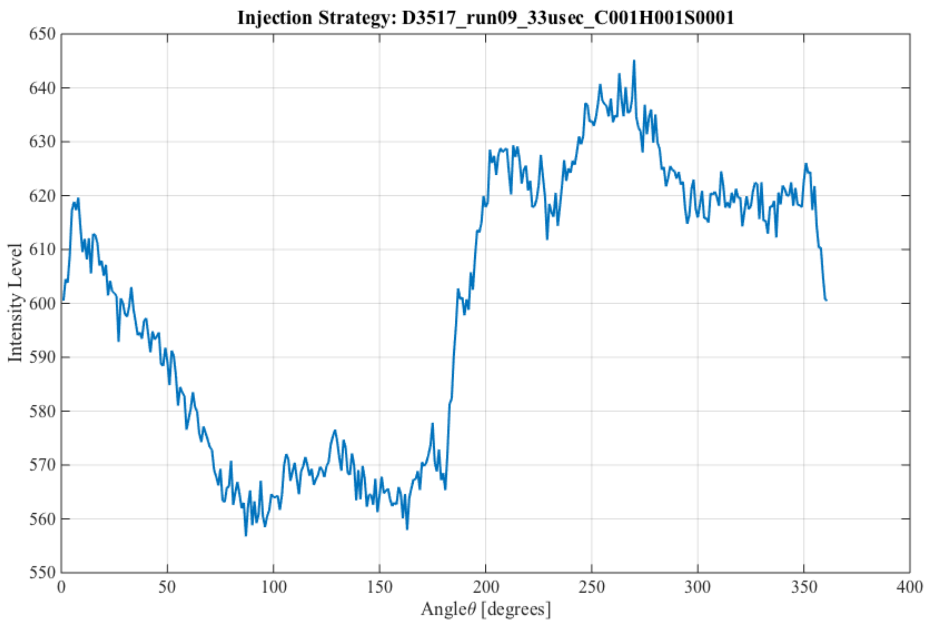

Figure 31. *Intensity level against angle is represented, showing five peaks, corresponding to five sprays in the injector.*

Eventually, two more graphs are obtained. The first one is a three-dimensional graph combining graphs in Figure 30 and Figure 31. Hence, the intensity level as a function of the angle as well as the CAD is shown, providing a better understanding of the combustion process.

The second graph represents the stratification index versus CAD. The stratification index is defined first for each spray and finally, a total stratification index is obtained as an average of the stratification level of the five sprays. The stratification index for each spray is defined by Equation 1 below.

$$\text{Stratification Index} = \frac{I_{average} - tmp2}{tmp1 - tmp2} \qquad (1)$$

In Equation 1, I_average represents the mean intensity for each spray and tmp1 and tmp2 represent the maximum and the minimum value of the intensity respectively. The total stratification index is an average of the stratification index of each of the five sprays.

Results

Four graphs are shown for each injection strategy. At the end of the results, a comparison of the three stratification index is also shown.

Single Injection Strategy, S16

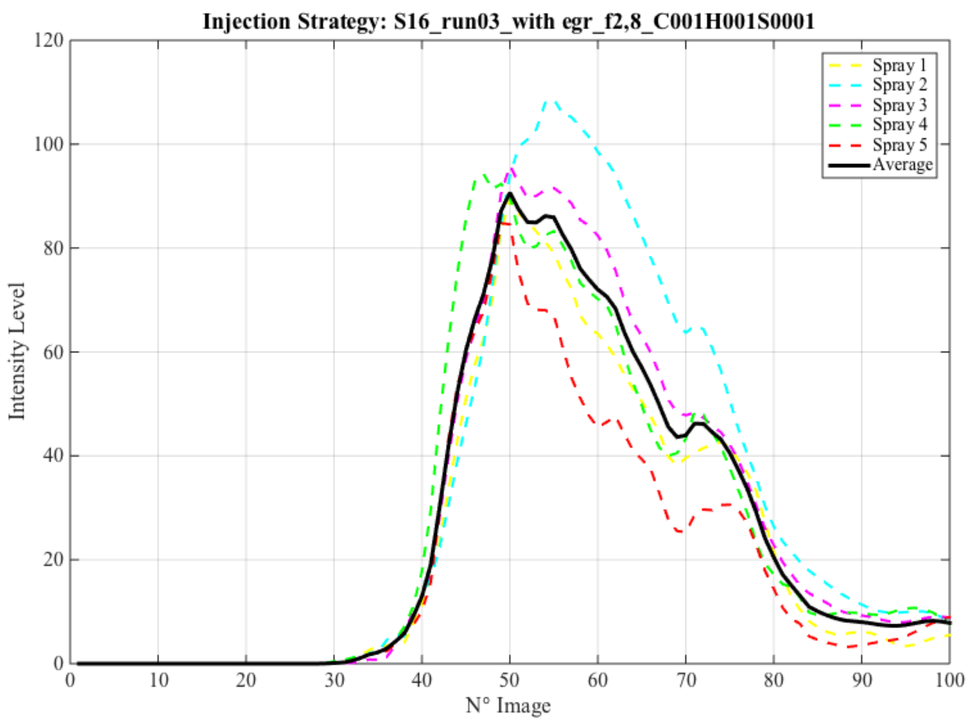

Figure 32. *Intensity level as CAD for single injection strategy, S16.*

Figure 32 shows a peak around image 50, both for each spray and for the average of them. This means that the peak appears around 10 CAD since the measurements are taken from -10 CAD to 30 CAD (maximum intensity activity). The SOC takes place around image number 30, which means 2 CAD.

It can be observed that the intensity level is different for different sprays at a given CAD because of different local equivalence ratio.

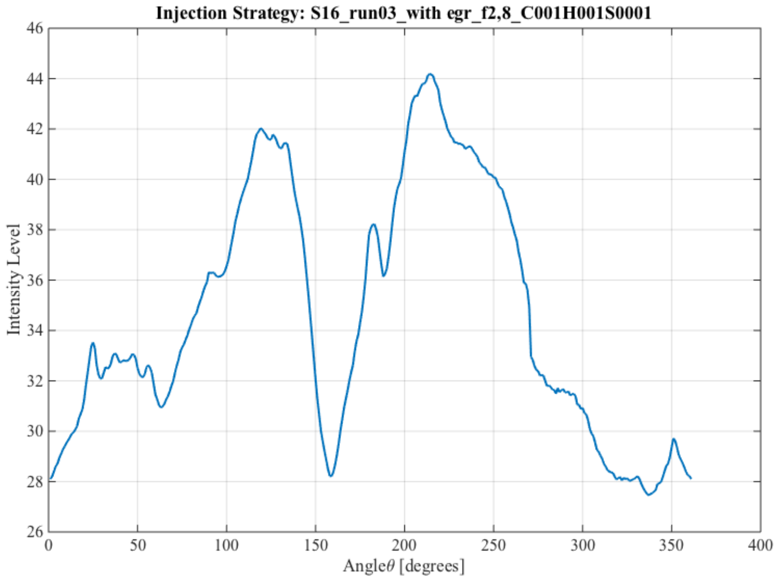

Figure 33. *Intensity level versus angle for single injection strategy, S16.*

In Figure 33, the intensity level is represented as a function of the angle, showing the five peaks of the five sprays of the injector.

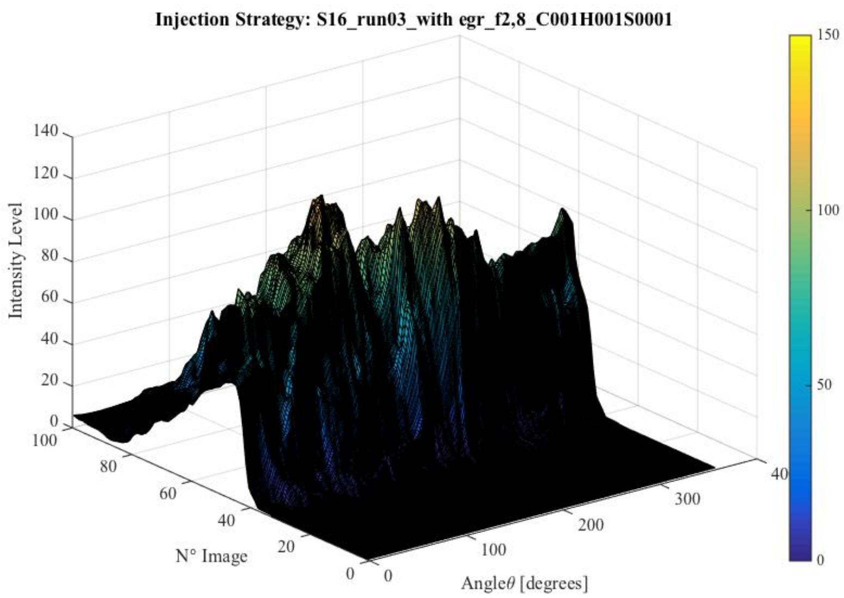

Figure 34. *Intensity level as a function of CAD and angle for single injection strategy, S16.*

Figure 34 consists of a three-dimensional graph which represents the intensity level as a function of angle and CAD. It is a combination of the two previous, figures which provides a better understanding of the combustion process, showing the progress of the combustion, from SOC to the end of the combustion.

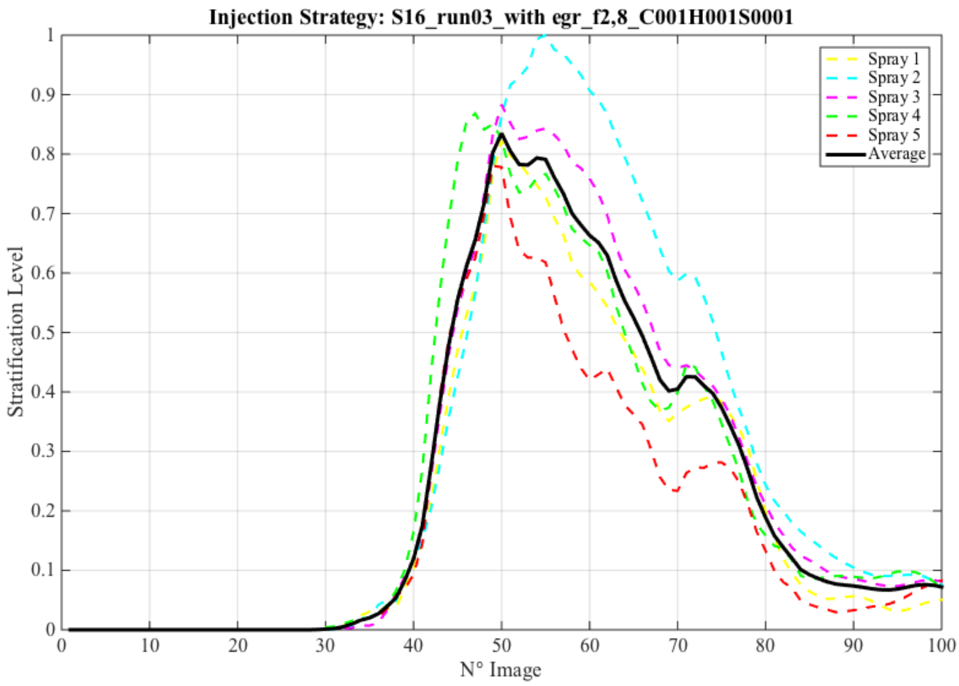

Figure 35. *Stratification index as a function of CAD for single injection strategy, S16.*

Figure 35 shows an averaged stratification index of 0.82 for the single injection strategy.

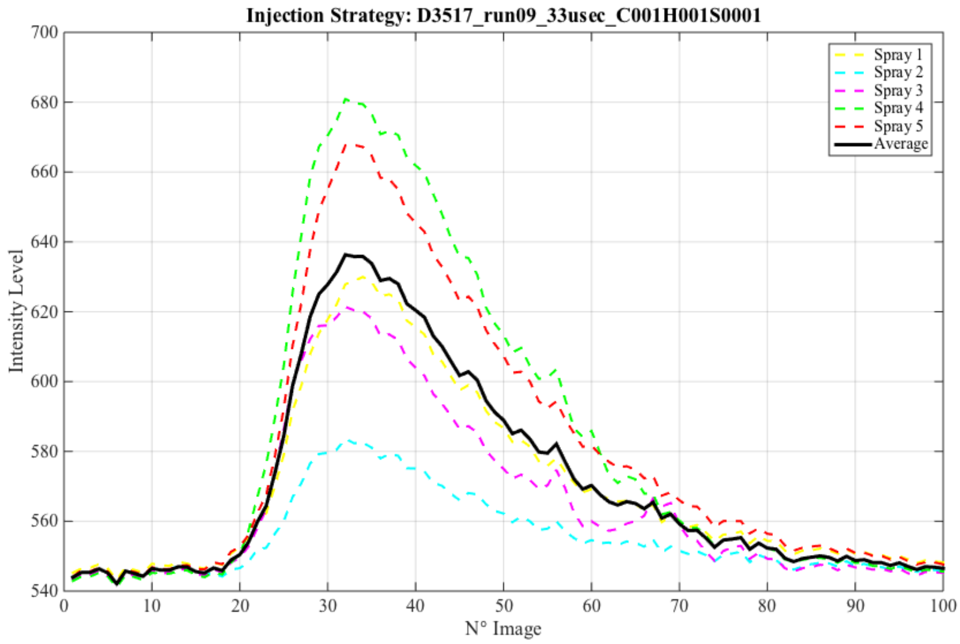

Figure 36. *Intensity level as a function of CAD for double injection strategy, D35/17.*

Figure 36 shows a peak around image number 33, which means 3.2 CAD. The start of combustion occurs around image number 20, -2 CAD. The start of combustion occurs early since the fuel is injected earlier than the single strategy injection case and therefore the mixture is better premixed.

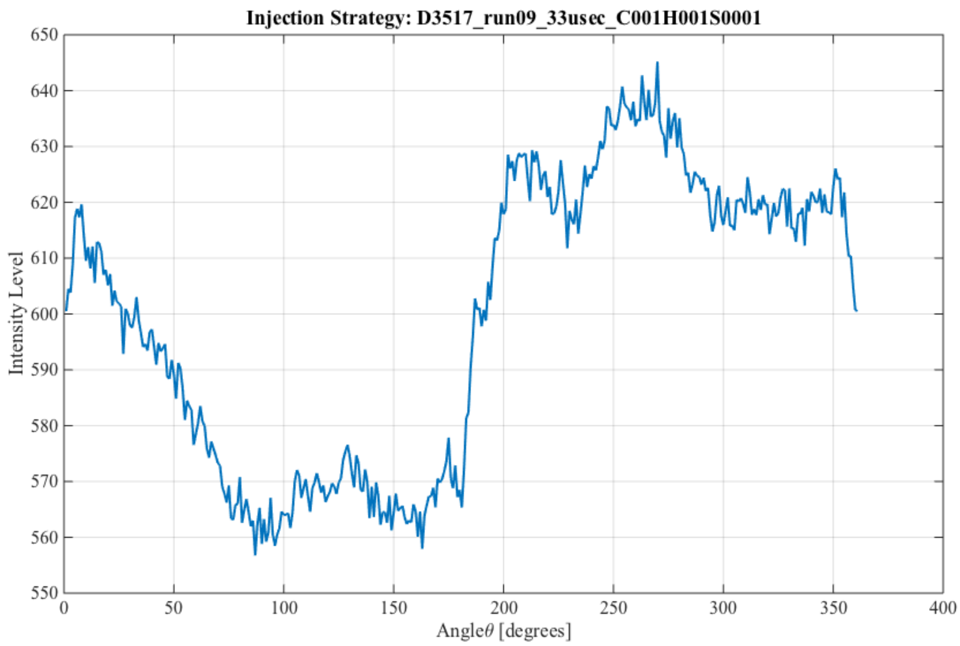

Figure 37. *Intensity level versus angle for double injection strategy, D35/17.*

Five peaks can be observed in Figure 37 as a result of the five sprays of the injector. Different intensity levels are shown for each spray, as also can be seen in Figure 36.

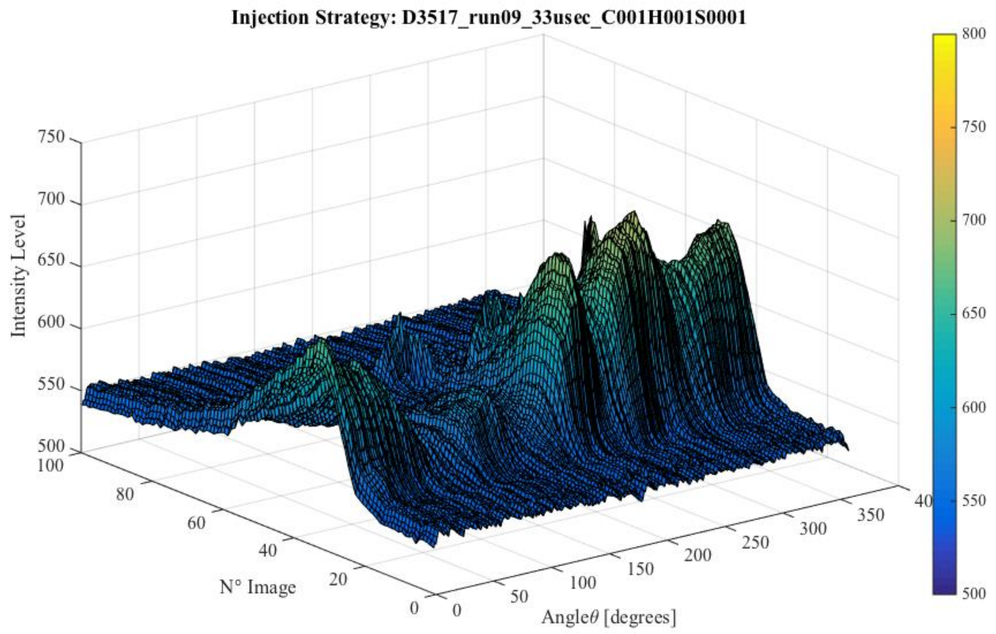

Figure 38. *Intensity level as a function of CAD and angle for double injection strategy, D35/17.*

The 3D graph in Figure 38 shows five peaks corresponding to the five plumes of the injection. The intensity level varies as a function of angle and CAD as the combustion occurs.

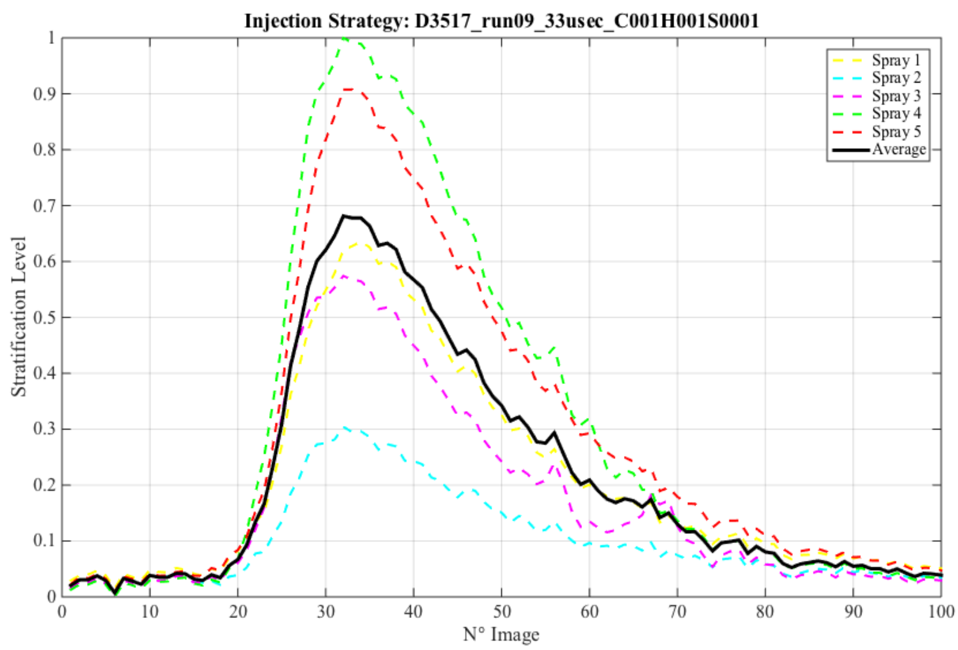

Figure 39. *Stratification index as a function of CAD for double injection, D35/17.*

Figure 39 shows an averaged stratification index of 0.68 for the double injection strategy.

Triple Injection Strategy T62/28/11

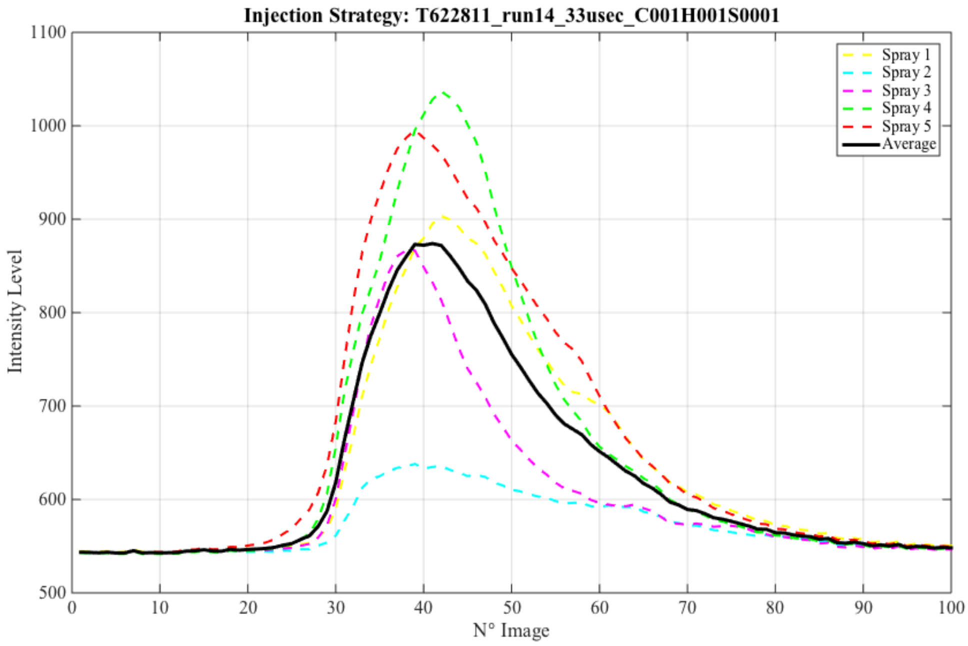

***Figure 40**. Intensity level against CAD for triple injection strategy, T62/28/11.*

In Figure 40, a peak of the averaged intensity is observed around image number 40, which means around 6 CAD. SOC occurs around image number 28, 1.2 CAD. In this case, an early injection strategy at 62 crank angle degrees (CAD) before TDC provides a well premixed charge.

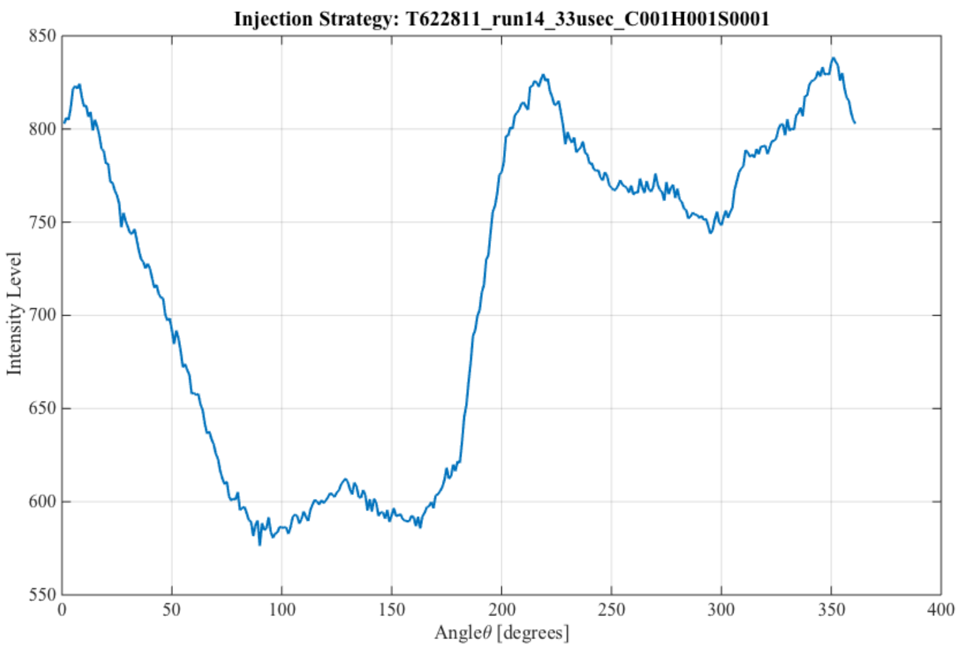

***Figure 41.** Intensity level as a function of the angle for triple injection strategy, T62/28/11.*

As stated before, five peaks corresponding to five sprays are shown in Figure 41 above.

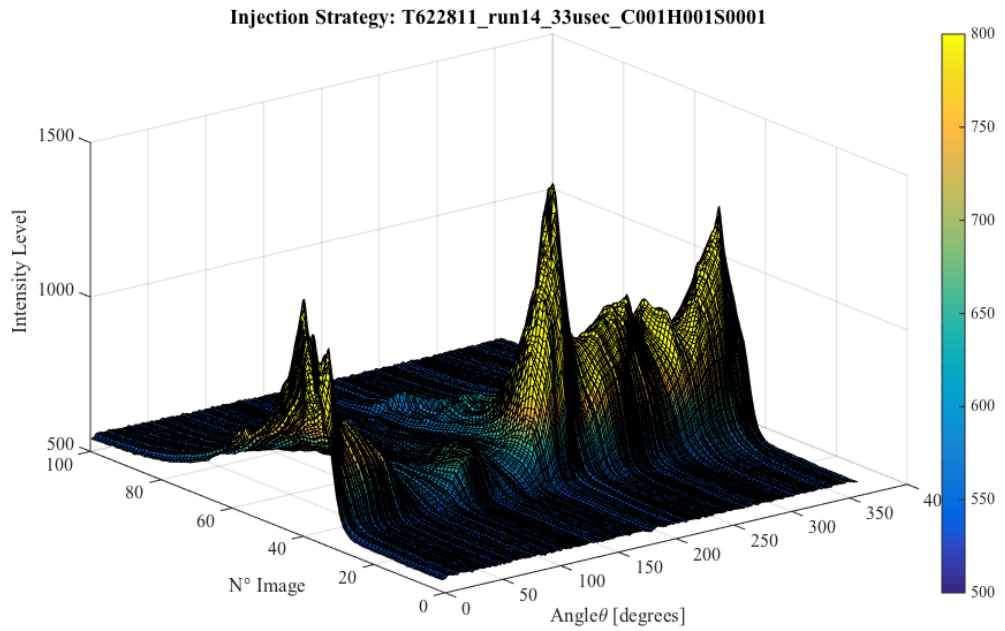

Figure 42. *Intensity level as a function of CAD and angle for triple injection strategy, T62/28/11.*

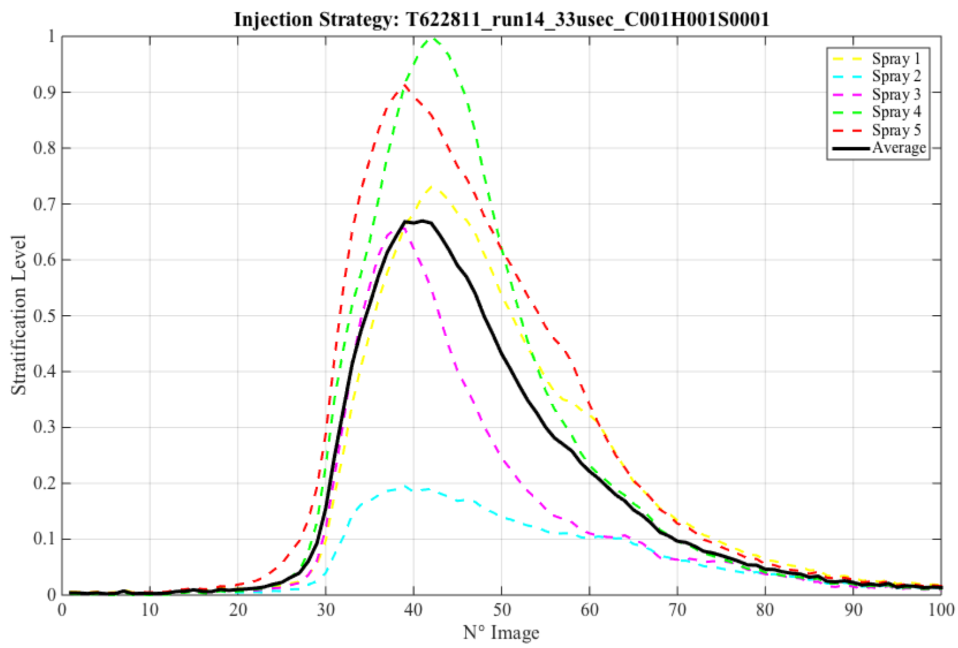

Figure 43. *Stratification index against CAD for triple injection strategy, T62/28/11.*

From Figure 43 is obtained an averaged stratification index of 0.68 for triple injection strategy.

Comparison and Conclusions.

Figure 44 below represents the stratification level for each type of injection strategy as a function of CAD. It can be observed that the most stratification level corresponds to single injection, and the lowest value correspond to triple injection strategy, which means that the most homogeneous combustion corresponds to the triple injection.

This obtained result is expected since, in triple injection strategy the first injection occurs 62 degrees before top dead centre resulting in a very well mixed charge before the combustion occurs. With the second injection, richer zones are created, and finally when the third injection occurs, this areas are burnt at first, and the reaction is extended to the leaner regions resulting in a more homogeneous combustion.

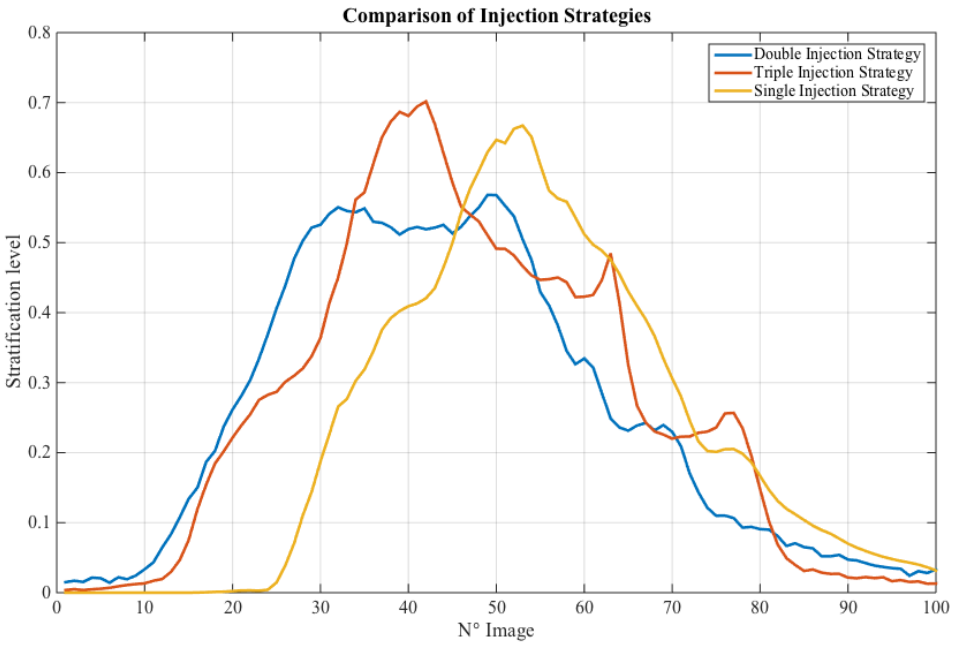

Figure 44. *Averaged stratification level for each injection strategy.*