Application and Development of Optical Soot Diagnostic Techniques

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Application and Development of Optical Soot Diagnostic Techniques

TED LIND | DIVISION OF COMBUSTION ENGINES
DEPARTMENT OF ENERGY SCIENCES | LUND UNIVERSITY | 2018
Application and development of optical soot diagnostic techniques

Ted Lind
Internal combustion engines (ICE) have been a vital part of society ever since their inception more than a hundred years ago. While initially it seemed as if the replacement of horse and carriage had solved the issue with pollutant emissions, it became evident in the 60’s that emission from ICEs is a major concern. The first emissions in focus were the nitrogen oxides (NO\textsubscript{x}). Lately, however, focus has shifted towards emissions which affect the global warming trends. The two worst pollutants, with respect to global warming, are carbon dioxide and soot.

The main focus of this thesis is the study of soot processes in optical diesel engines as well as development of optical soot diagnostics. While the diesel engine is favoured due to its high fuel efficiency, and therefore low CO\textsubscript{2} emissions, it does suffer from higher soot emissions than the spark ignition engine. Soot emission is the net result of two competing processes; soot formation and soot oxidation. Soot oxidation processes have previously been shown to determine the trends of soot emissions for conventional diesel combustion and for that reason this thesis puts more focus on these.

Another known fact is that injections of fuel after the main injection, so called post injections, have been shown to reduce soot emissions. However, exactly how this works is not clear. In this thesis we elucidate the mechanisms of post injection soot reduction with the use of a novel soot diagnostic technique called diffuse back-illumination extinction imaging. Using this technique it is revealed that one of the reasons behind the soot reduction of post injections is that most or all of the soot that is formed by a short post injection is also oxidized, thus leading to no net emissions. The oxidation process is especially enhanced due to the increased mixing which occurs in the jet as the injector closes.

Lastly, a new soot thermometry technique based on the DBI technique is developed. By directly measuring the amount of soot within a flame with an active technique such as DBI, many of the uncertainties associated with conventional optical thermometry techniques such as two color pyrometry can be avoided.
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Application and Development of Optical Soot Diagnostic Techniques

Ted Lind
Cover image: KL distribution, Planck radiation curves, DBI-T temperature distribution

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Fakultet Lunds Tekniska Högskola
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Abstract

Internal combustion engines (ICE) have been a vital part of society ever since their inception more than a hundred years ago. While initially it seemed as if the replacement of horse and carriage had solved the issue with pollutant emissions, it became evident in the 60’s that emission from ICEs is a major concern. The first emissions in focus were the nitrogen oxides (NOx). Lately, however, focus has shifted towards emissions which affect the global warming trends. The two worst pollutants, with respect to global warming, are carbon dioxide and soot.

The main focus of this thesis is the study of soot processes in optical diesel engines as well as development of optical soot diagnostics. While the diesel engine is favoured due to its high fuel efficiency, and therefore low CO2 emissions, it does suffer from higher soot emissions than the spark ignition engine. Soot emission is the net result of two competing processes; soot formation and soot oxidation. Soot oxidation processes have previously been shown to determine the trends of soot emissions for conventional diesel combustion and for that reason this thesis puts more focus on these.

Another known fact is that injections of fuel after the main injection, so called post injections, have been shown to reduce soot emissions. However, exactly how this works is not clear. In this thesis we elucidate the mechanisms of post injection soot reduction with the use of a novel soot diagnostic technique called diffuse back-illumination extinction imaging. Using this technique it is revealed that one of the reasons behind the soot reduction of post injections is that most or all of the soot that is formed by a short post injection is also oxidized, thus leading to no net emissions. The oxidation process is especially enhanced due to the increased mixing which occurs in the jet as the injector closes.
Lastly, a new soot thermometry technique based on the DBI technique is developed. By directly measuring the amount of soot within a flame with an active technique such as DBI, many of the uncertainties associated with conventional optical thermometry techniques such as two color pyrometry can be avoided.
Populärvetenskaplig Sammanfattning

Förbränningsmotorn har i över hundra år underlättat vardagen för människan. Fordon drivna med förbränningsmotorer har lagt grunden till det ekonomiska välstånd som vi i dag har i världen, men det är inte utan att det har orsakat några problem. Ett av de största orosmolnen just nu är den globala uppvärmningen orsakad av människans utsläpp av växthusgaser. Tack var sin höga verkningsgrad är diselmotorn en mycket lämplig motor i detta avseende då den släpper ut betydligt mindre CO₂ per kWh än en liknande bensinmotor. En nackdel med diselmotorn jämfört med bensinmotorn är dock dess högre sotutsläpp. Sot är enligt FN:s Intergovernmental Panel on Climate Change (IPCC), näst efter CO₂, den största orsaken till den antropogena delen av den globala uppvärmningen. Även om elektrifiering av en del av fordonsklotet kan hjälpa till att minska de globala CO₂-utsläppen så beräknas den totala mängden fordon med konventionella motorer öka i antal inom överskådlig framtid. Det beräknas finnas ungefär 1 miljard fordon idag och det antalet kommer med stor sannolikhet att fördobblas inom en 30-årsperiod. Således finns det till dags dato ingen enskild teknisk lösning som kan klara av IPCCs utsläpssmål och samtidigt bibehålla det ekonomiska välstånd som människor, i framförallt västvärlden, har vant sig vid.

Denna avhandling fokuserar på hur man kan minska sotutsläpp från just dieselmoter samt hur man kan utveckla nya och mer precisa mätmetoder för att studera sot under hela förbränningsprocessen i en optisk motor. Genom användning av laserbaserade mätmetoder finner vi i denna avhandling att det viktigaste för att minska sotutsläppen inte är att minimera sotproduktionen utan att förbränningen sker under förhållanden där sot lättare kan oxideras. En annan metod för minskning av sotutsläppen som testas och verifieras i denna avhandling är användandet av små postinsprutningar (bränsle insprutat efter den huvudsakliga bränsleinsprutningen). Med hjälp av en ny optisk mätmetod som för första gången appliceras i en tung dieselmotor visar vi i avhandlingen att postinsprutningarna minskar sotutsläppen genom att allt sot
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I am truly glad to have had so many great co-workers. Unfortunately, since the cost of printing the thesis increases per page, I cannot mention everyone of you individually. This division is truly a great place to work at!


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Last but certainly not least, Emelie you are truly my rock and together with Selma, my greatest source of joy!
List of Papers

This thesis is based on the following publications, referred to by their Roman numerals. The papers are appended to the thesis.


V. Lind, T., Roberts, G., Li, Z., Andersson, Ö., Musculus, M.P.B., “DBI-T, a novel soot thermometry technique” Manuscript to be submitted
Other related work:

Nomenclature

\textbf{aHRR} apparent Heat Release Rate  
\textbf{ATDC} After Top Dead Centre  
\textbf{CA50} Crank Angle at 50 \% of total heat release  
\textbf{CAD} Crank Angle Degree  
\textbf{CCD} Charge Coupled Device  
\textbf{CFD} Computational Fluid Dynamics  
\textbf{CMOS} Complimentary Metal-Oxide-Semiconductor  
\textbf{CO} Carbon monoxide  
\textbf{CO}_2 Carbon dioxide  
\textbf{CI} Compression Ignition  
\textbf{DBI} Diffused Back-illumination Imaging  
\textbf{DBI-T} Diffuse Back-illumination Temperature Imaging  
\textbf{ESE} End of Solenoid Energizing  
\textbf{EoI} End of Injection  
\textbf{EV} Electric Vehicles  
\textbf{HC} Hydrocarbons  
\textbf{HSV} High Speed Video  
\textbf{ICE} Internal Combustion Engine  
\textbf{ID} Ignition Delay  
\textbf{IEA} International Energy Agency  
\textbf{IMEP} Indicated Mean Effective Pressure  
\textbf{IPCC} Intergovernmental Panel on Climate Change
KL Optical thickness
LEM Laser Extinction Measurement
LTC Low Temperature Combustion
MK Modulated Kinetics
Nd:YAG Neodymium-doped Yttrium Aluminium Garnet
NL Natural Luminosity
NOx Nitrogen Oxide
O Oxygen atom
O2 Oxygen molecule
OH Hyroxyl
OPO Optical Parametric Oscillators
PAH Poly-cyclic Aromatic Hydrocarbons
PPS Pegasor Particle Sensor
PLIF Planar Laser Induced Fluorescence
PLII Planar Laser Induced Incandescence
PM Particulate Matter
SoC Start of Combustion
SSE Start of Solenoid Energizing
SI Spark Ignition
SINL Spatially Integrated Natural Luminosity
TCP Two Color Pyrometry
TDC Top Dead Centre
1. Introduction

1.1. Background

1.1.1 History of the internal combustion engine

Ingenuity and fire has been two of the backbones of human societies ever since man first learned to tame the fire. While fire has long been used for such things as cooking, metallurgy, and lighting, the realization that fire could be used to power machines is truly a stroke of human ingenuity.

While the cannon can be regarded as the first internal combustion engine (ICE), it had mostly malevolent uses. However, the fact that fire could potentially be used to power machines which could potentially be used for transportation has been known for some time. In 1673 Christiaan Huygens designed the first engine with a working piston powered by heat [1]. The use of the combustion engine was still fairly limited up until 1712 when Thomas Newcomen released his external combustion engine which was used to pump flood water from mines. Things really took off for the external combustion engine in 1781 when James Watt patented his steam engine, which could produce continuous rotary motion. These two engines played a paramount part in the industrial revolution. However, the steam engines of Newcomen and Watt had a low power output per unit of mass and were not always very practical. They could be used for locomotives but had very limited use for smaller transportation.

In 1876, human ingenuity and fire once again propelled society forward. This was the year Nicolas Otto presented his four-stroke gas engine [1]. Otto’s ICE had a much larger power output per unit of mass than the steam engines. Otto’s engine used a spark to ignite the fuel within the engine and have
therefore been aptly classified as a spark ignited (SI) engine. In 1892, Rudolf Diesel presented his compression ignition (CI) engine [1]. The working principles of these ICEs are the same as for all the ICEs still used today.

### 1.1.2 Characteristics of the CI and SI engines

While a lot of refinement and progress have been made with the CI engine the principle is, as previously mentioned, still the same.

The highest theoretical, and practically unattainable, thermal efficiency of any heat engine is given by the Carnot cycle

\[
\eta_{th} \leq 1 - \frac{T_C}{T_H},
\]

where \( \eta_{th} \) is the thermal efficiency, \( T_C \) the temperature of the surrounding medium, and \( T_H \) the temperature of the working medium. To achieve such efficiency, it is necessary to extract all work at \( T_C \) and add all heat to the working medium at \( T_H \).

While the Carnot cycle is the most ideal cycle, some more realistic, but still idealized, engine cycles can be used to pinpoint some of the most important characteristics of what makes an engine efficient. One of the most common ways of displaying this is by the use of a so called isochoric engine cycle. Isochoric implies that the volume is constant during the period when the heat is added to the system as well as when it is extracted. The isochoric engine cycle also assumes that the working fluid is described by an ideal gas and that compression and expansion are isentropic. As shown in [2] the thermal efficiency for such a process is determined by

\[
\eta_{th} = 1 - \frac{1}{r_c^{\gamma-1}},
\]

where the compression ratio, \( r_c \), is defined as the fraction of the maximum volume divided by the minimum volume during the engine cycle and \( \gamma \) is the heat capacity ratio. As can be seen in Equation 2, the theoretical efficiency increases with increasing compression ratio and heat capacity ratio.
The heat capacity ratio varies for different gases and while air has a value of 1.4 at 20 °C, conventional fuels have a lower value. Therefore, a mixture having a high fuel to air ratio will have a lower thermal efficiency than a mixture with lower a fuel to air ratio, all other things being equal. CI engines are generally more fuel efficient than their SI counterparts, which is largely due to the fact that CI engines generally use a higher compression ratio and that they are run with a fuel lean mixture, thus increasing both $r_e$ and $\gamma$ of Equation 2 compared to an SI engine. SI engines cannot use too high compression ratios or they risk knock, a form of unwanted autoignition which can severely damage the engine, and they are typically operated at stoichiometric conditions to facilitate the exhaust gas aftertreatment. At stoichiometric conditions, the exhaust gases can be treated with a three-way catalyst, which simultaneously oxidizes unburned components (hydrocarbons and carbon monoxide) and reduces NOx at the same time.

As stoichiometry will be discussed repeatedly in this thesis, we will introduce the equivalence ratio,

$$\phi = \frac{(F/A)}{(F/A)_{Stoichiometric}}$$

where $(F/A)$ is the actual fuel air ratio and $(F/A)_{Stoichiometric}$ the stoichiometric fuel air ratio. $\phi > 1$ thus indicates a fuel-rich mixture, $\phi < 1$ a fuel-lean mixture, and $\phi = 1$ refers to stoichiometric conditions.

Another advantage of the CI engine over the SI engine is the fact that load is controlled by adjusting the amount of fuel injected into the engine; therefore, unlike for the SI engine, there is no need to throttle the engine, leading to less losses in the form of pumping work.

However, since a CI engine cannot be operated under stoichiometric conditions due to the risk of incomplete combustion, a three-way catalyst is not applicable, which results in higher NOx emissions. An additional drawback with the CI engine is that it emits more particulate matter (PM) and soot. Soot is both a local pollutant that harms the human health [3-4] as well as a global pollutant that serves to increase the greenhouse effect through radiative forcing and by changing albedos of glaciers and snow covered regions such as the Antarctic [5-8], leading to increased global warming.
1.1.3 Future outlook of the ICE

Electric vehicles (EV) are becoming a more common sight within the transportation sector. EVs have no, or close to no, local emissions and can therefore drastically decrease issues with air quality in cities. However, no realistic projections predict that the ICE will be completely replaced by EVs within the foreseeable future. In fact, most projections point towards the ICE having a larger market share for personal transportation than EVs for several decades to come. For heavy freight traffic the market share will likely be in favour of the ICEs for the foreseeable future [9]. Figure 1 displays the current and estimated electricity production mix, according to the world energy outlook of the International Energy Agency (IEA) [9]. The projected mix is based on the new policies scenario, which assumes that the current and proposed environmental policies, are fulfilled. As can be seen from that graph it is clear that the world’s electricity needs are predicted to be provided, to a large degree, by a growing supply of fossil sources by the year 2040. Renewable sources will, according to this outlook, make up roughly 40% at that time. Furthermore, the total oil use of passenger cars will remain largely unaffected by 2040 compared to now. The road freight sector is even expected to increase its oil use by 2040. With this information in mind it is clear that the ICE will play a large part in forming society for the foreseeable future. With the projected amount of more than 2 billion vehicles, even in IEA’s most optimistic projections, the market share of EV’s for personal transportation makes up for less than 40% of the total market cap by 2040. In the new policies scenario, the IEA estimates that they will make up roughly 15% of the total market cap by 2040. The two projections are shown in Figure 2.
Figure 1 Estimation of the energy outlook, with currently active and proposed policies taken into account [9].

Figure 2 Estimated number of EVs. Green line shows the estimation of EVs if IEA’s sustainable development scenario is achieved and teal line indicates the estimated number of EVs with the current and proposed policies in place [9].
1.2. Research Scope

The objective of this thesis has been twofold; to study in-cylinder soot processes and to develop optical soot diagnostic techniques. As will be further discussed later in this thesis, previous studies have shown that soot oxidation is more important for engine out soot emissions and, for that reason, the focus was kept mostly on soot oxidation.

Post injection strategies have also been studied in order to better understand why they sometimes yield very beneficial soot emission behaviour while at other times being detrimental.

Development of new optical techniques to better elucidate soot processes is also of interest. As will be detailed later in this thesis, diffuse back-illumination extinction imaging (DBI) allows for instantaneous 2D soot concentration measurements with much higher accuracy and precision than the widely used two colour pyrometry technique, thus enabling better understanding of in cylinder soot processes.

1.3 Thesis contribution

The measurements covered within this thesis all involve optical engine studies. Various optical techniques have been utilized. Planar laser induced incandescence (PLII) was used to perform qualitative studies of soot. Planar laser induced fluorescence (PLIF) was used simultaneously with the aforementioned PLII technique. This allowed for studies of how the soot oxidizer OH was distributed with respect to the in cylinder soot which could then be correlated to the engine out soot emissions.

Findings using laser extinction measurements covered within this thesis support the previous position that soot formation rate is not the dominant process in determining trends in engine out soot emissions. Soot oxidation appears to play a more important role.
It is also made clear that spatially integrated natural luminosity (SINL) is not always a reliable measurement technique. For post injection strategies, SINL does not correlate with the engine out emissions.

The thesis also covers the implementation of DBI in an optical heavy duty engine. This is the first time the method has been successfully employed in such an environment.

Using DBI to study soot during a complete cycle, it is also revealed that one of the reasons why post injections can be used to reduce engine out soot emissions is that, while much soot is formed in the post injection this soot is later fully oxidized, granted that the post injection is sufficiently short. The entrainment wave, which will be discussed more in detail in section 2.3, is believed to be the main reason behind this increased oxidation rate in the post injection. As long as the entrainment wave reaches the head of the jet before it reaches the piston bowl wall, oxidation will be very efficient.

A new soot temperature measurement technique called diffuse back-illumination temperature imaging (DBI-T) was also developed. By directly measuring the soot extinction signal using DBI and at the same time measuring the spectral radiance it is possible to more accurately determine the mass averaged soot radiation temperature compared to previous methods such as two color pyrometry (TCP)
2. DI Diesel combustion

2.1 Conventional single injection Diesel combustion

As mentioned in the introduction, two main types of engines exist: the SI and the CI engine. The scope of this thesis will focus on the CI engine. The CI engine is probably more commonly known as the diesel engine named after Rudolf Diesel, but the names are interchangeable. As the name alludes to, the combustion processes in an CI engine is initiated by compressing the air in the cylinder, thereby increasing the pressure and temperature. When the fuel is injected into this hot air, it autoignites. The heat release in a CI engine can usually be divided into four stages – one stage before combustion and three stages during combustion.

The stage before combustion occurs between the start of fuel injection (SoI) and the start of combustion (SoC). SoI usually occurs close to top dead centre (TDC). The fuel does not start to burn as soon as it enters the cylinder. There is need for vaporization and mixing between the fuel and the air to reach temperatures of typically 800 K before auto ignition occurs. The time between SoI and SoC is called the ignition delay (ID) and is largely dependent on the chemical properties of the fuel [2]. The ignition quality of a fuel is characterized by its cetane number.

After SoC, energy is released in the portions of the fuel that have been premixed with air into a combustible mixture. While the premixed combustion phase is relatively short, the amount of energy released per unit of time is usually high. This rapid energy release per crank angle degree (CAD) leads to large in cylinder pressure derivative (dp/dCAD) which in turn causes the relatively loud and characteristic sound of a CI engine.
The stage after the premixed combustion is sometimes called the main mixing-controlled combustion stage. During this time, assuming it is long enough, a quasi-steady jet is established. During this stage the combustion processes and rates are largely driven by physical properties such as mixing. Most of the energy during a cycle is usually released in this stage or during the last stage of the combustion and it is therefore of great interest. Greater attention will be paid to this stage in section 2.2.

The last stage of combustion is the late mixing-controlled stage. After end of injection (EoI) the remaining kinetic energy from the spray dissipates and the turbulence from this helps with mixing the remaining fuel with the air. Even though the temperatures are decreasing in this stage, chemical reactions, such as soot oxidation, occur and energy is released. Previously, most research has been focused the earliest stages of combustion but, since studies suggests [10-12] that both engine out emissions and fuel efficiency are largely dependent on late cycle mixing behaviour, research focus is nowadays more evenly distributed between the various combustion stages.

In Figure 3, the heat release during a typical single injection cycle is shown and the three aforementioned combustion stages are marked out.

![Figure 3 A typical heat release rate with the three main stages of combustion indicated.](image)
2.2 The quasi-steady diesel jet

During medium and high load operation, much of the energy is usually released during the quasi-steady jet phase. For this reason, and the fact that this stage is relatively easy to study in optical engines and high pressure vessels, this stage has been of special interest and research into it has led to, perhaps, one of the most iconic models within the engine research community [13]. The model, proposed by Dec in 1997, established several distinct zones within the quasi-steady jet by the use of various optical measurement techniques. These zones are of key interest, especially with regard to soot and nitrogen oxide (NOx) emissions. In Figure 4, a schematic image of this model is shown. As the fuel leaves the nozzle, atomization of the liquid fuel is instantly initiated thus creating a fuel rich mixture with $\phi$ between 2 and 5, where $\phi$ is defined according to equation 3.

This fuel rich mixture then ignites creating a standing premixed flame. Soot production starts in the product gas from this reaction step. As the soot travels downstream in the jet, soot growth occurs. Soot formation is discussed in more detail in section 2.4.1. At the periphery of the jet, the product gas from the first step is mixed with surrounding air, forming a second reaction zone in the form of a diffusion flame. This is evident by a thin sheet of OH around the jet. OH is a soot oxidizer and therefore most of the soot leaving the flame is oxidized. Soot oxidation is discussed in little more detail in section 2.4.2. The diffusion flame is a high temperature region where most of the thermal NOx is believed to be formed.

It is worth noting that the model was developed using a fairly limited set of operating conditions and, perhaps more importantly, oxygenated fuels for the higher load cases. This might alter the behaviour of the quasi-steady jet studied compared to when using normal diesel fuel [13]. Nevertheless, this model has served to greatly further the understanding of diesel combustion.
2.3 The entrainment wave

The entrainment wave is a fluid dynamic phenomenon which occurs due to the conservation of momentum as the injector is closing. During the quasi steady jet phase the air entrainment into the jet is constant. However, as the injector needle begins to close, the entrainment rate of air increases and this enhancement of entrainment is what defines the region of the so called entrainment wave. The entrainment wave spreads through the jet at speeds up to twice as high as those of the initial jet propagation rate and increase mixing by up to a factor of three[14,15]. The strength of the entrainment wave is affected by, among other things, injection pressure and ramp down time of the injector. With a higher injection pressure the entrainment wave will propagate faster and with a quick ramp down the entrainment wave will also propagate faster.
2.4 Soot processes

Soot emission is the net result of the two competing processes of soot formation and soot oxidation. In sections 2.4.1 and 2.4.2, brief introductions to these processes will be given.

2.4.1 Soot formation

Soot formation is a complex process but it can be simplified and classified into a few separate steps. In the first step, pyrolysis of the fuel leads to the fuel breaking down into smaller molecules. These smaller molecules then merge to form soot precursors such as poly-cyclic aromatic hydrocarbons (PAH). Nucleation will start once the soot precursors are formed, as long as the concentrations are sufficiently high and the temperature is above 1300 K [16]. In the nucleation step, small hydrocarbon chains attach to the soot precursors leading to the formation of a soot nuclei. When soot nuclei have been established, mass is added to the nuclei through coalescence, surface growth, and agglomeration. While the nucleation is temperature dependent, these latter steps are more influenced by fuel concentration and, for this reason, soot growth can occur relatively far from the flame front [17]. The various stages are graphically represented in Figure 5.

![Figure 5 Progression from fuel to soot. Reprinted from [17].](image-url)
It is possible to qualitatively predict the soot formation in a diagram with $\phi$ and $T$ as variables. This was first done by Kammimoto [18] and popularized by Akihama [19]. In these diagrams, homogeneous reactor simulations are used to map out the $\phi$ and $T$ regions where soot and NO$_x$ are formed. In Figure 6, an example of a $\phi$ and $T$ diagram is seen. In this diagram, the pathway of a fuel parcel during conventional diesel combustion is displayed using open arrows. It is important to note that the displayed pathway is just one out of many possible pathways. Global parameters, like exhaust gas recirculation (EGR) levels, inlet temperature, total fuel mass, and fuel composition will alter the pathway [20]. Conventional diesel combustion is also highly heterogeneous and different fuel parcels will therefore find themselves in different $\phi$ and $T$ environments. However, $\phi$ and $T$ diagrams are still useful and the possible soot and NO$_x$ formation rates can be bounded by the adiabatic flame temperature, the highest possible temperature for a given fuel at a specific O$_2$ concentration.

As seen in Figure 6 it is possible to reduce the soot and NO$_x$ formation rates by employing low temperature combustion (LTC) concepts such as modulated kinetics (MK). The grey arrows indicate a misfire event and the black arrows a successfully fired cycle. Different LTC strategies exist and have their own drawbacks and advantages but are outside the scope of this thesis.

![Figure 6 $\phi$-T Diagram with pathways of various engine concepts as well as adiabatic flame temperatures at 21% and 15% O$_2$. Reprinted with permission from [20].](image)

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2.4.2 Soot oxidation

Soot oxidation in a diesel engine involves carbon (C) reacting with oxygen molecules (O$_2$), oxygen atoms (O), hydroxyl (OH), or other oxidizing species. Oxidation can occur during any stage of the soot formation processes as long as the local temperatures are sufficiently high. The oxidation pathways differ depending on the oxidizer. OH is very reactive and therefore reacts with the surface of the soot [21]. O$_2$ on the other hand is less reactive but due to this it can penetrate further into the soot particle where it will cause internal burning, fracturing the soot particle into several smaller particles [22,23]. Figure 7 shows a schematic of the various soot oxidation pathways.

![Figure 7 Soot oxidation pathways as suggested in [22].](image)

The oxidation rate by O$_2$ is usually described by the Nagle Strickland-Constable (NSC) reaction rate [24],

$$W_{O2} = \left( \frac{k_A p_{O2}}{1 + k_x p_{O2}} \right) x + k_B p_{O2} (1 - x)$$

(4)

Here, $W_{O2}$ is the soot oxidation rate due to O$_2$, $k_A$, $k_B$, and $k_x$ are rate constants for oxidation at A and B sites, and $p_{O2}$ the partial pressure of oxygen. $x$ is defined by

$$x = \frac{1}{1 + (k_T / k_B) p_{O2}},$$

(5)
where, \( k_T \) is another rate constant. The \( k_A \) and \( k_B \) rate constants are related to the rate at which oxidation occurs at so-called A and B sites. While A sites are more reactive than B sites, thermal rearrangement due to increased temperature will decrease the number of available A sites, therefore decreasing the overall oxidation rate. Eventually all A sites will be converted into B sites upon which the oxidation rate will once again start to rise as temperature increases even more.

Likewise, oxidation via OH is usually described by Neoh’s OH oxidation model [25],

\[
W_{OH} = \gamma_{OH} \frac{3n_{OH}}{N_A} \left( \frac{8RT}{\pi M_{OH}} \right)^{1/2}
\]

where \( W_{OH} \) is the soot oxidation rate of OH, \( n_{OH} \) the number density of OH, \( M_{OH} \) the molar mass of OH, \( R \) the general gas constant, \( N_A \) Avogadro’s constant, and \( \gamma_{OH} \) the collisional frequency of OH and soot. As can be seen in equation 6, \( W_{OH} \) will increase monotonically with temperature. There is also a strictly linear correlation between the number of available OH molecules and the oxidation rate.

While useful, these models do not fully account for variations of oxidation pathways as described in the first paragraph of this section, and there is therefore still plenty of research dedicated to improving our understanding of soot chemistry. This is, however, out of the scope of the thesis.

### 2.5 Post injection strategies

#### 2.5.1 Post injection classification

Post injections can be used for various reasons, such as management of after-treatment systems and reduction of hydrocarbon (HC) emissions. However, the studies of post injections covered within this thesis are limited to those where the intent of the post injection is to reduce the engine out soot emissions.
While no precise definition has been established within the scientific community, injections after the main injection are usually classified as post injections if they comprise roughly 20% or less of the total amount of fuel injected during a cycle. If the injection after the main injection contains more fuel, it is often classified as a split injection schedule [26].

Additionally post injection strategies are often also divided into close-coupled and non-close-coupled post injections. The close coupled post injections are defined as such if the fuel is injected within a few CADs after the main injection.

2.5.2 Proposed post injection soot reduction effects

Even though post injections have been used commercially for soot reduction for quite some time, exactly how or even when post injections are effective for reducing the soot emissions is unclear and still the topic of much research. There are a few leading hypotheses as to why it works. The three leading ones are; enhanced mixing, increased temperature, and injection duration effects.

Enhanced mixing is perhaps the leading hypothesis and works in two proposed ways; either by enhancing soot oxidation rates [27-30], where the enhanced mixing could lead to increased availability of important oxidizers such as OH, or by suppressing soot formation [31] by lowering the local $\phi$ values to levels where soot formation rates are reduced or even completely stopped. There have been several studies that suggest enhanced mixing as the leading cause of engine out soot reduction for post injections but, as with most optical engine studies, it is very difficult to isolate a single parameter due to the chaotic nature of in cylinder combustion. However, in [32] normal post injection of fuel is replaced with a post injection of inert combustion gases, thereby making sure that the temperature will not increase when injecting this gas, as opposed to what would be the case if fuel was injected. That study finds that soot is reduced with the addition of the post injection and that a gas injection with higher momentum leads to lower soot emissions, thus supporting the hypothesis that increased mixing reduces the engine out soot emissions.
Increased temperature is another proposed hypothesis where the addition of a fairly late post injection serves to increase the temperature of the soot, thereby enhancing the oxidation rate. This is however not straightforward to experimentally verify since it is not easy to determine whether or not the increased temperature is an effect of increased oxidation. In addition to this, optical temperature measurements are currently not very precise or accurate. Nevertheless, this idea of soot reduction has been proposed in several studies [33-35]

Injection duration effects are another fairly common explanation but it is once again difficult to decouple and experimentally measure. However, computational fluid dynamic (CFD) studies have found that a single main injection will produce more soot than two split injections even though the amount of fuel injected is the same [36]. The proposed reason for this is that with a single long injection a quasi-steady jet is established for a longer time and the head of the quasi-steady jet is continuously replenished with new fuel. Therefore, according to John Dec’s conceptual model, more soot will be formed since the head of the jet is one of the regions with the highest soot formation rates.
3. Experimental Equipment

3.1 Optical Engines

Most engine research is performed on full metal engines. During this type of research the engine is used as somewhat of a black box. You can control what goes into the engine and measure what comes out of the engine but exactly what happens during the combustions is not easily determined, since usually the only data collected from the cylinder is the pressure trace during the cycle. Optical engines are used to elucidate the fundamental processes within the cylinder. The most common optical engine design is the so-called Bowditch design [37]. In this design, the cylinder head is lifted from the engine block using an extension. A hollow piston extension is then connected to the original cylinder in the block. By putting a transparent piston (usually quartz or sapphire) at the top of the extension and placing a 45° mirror below it, optical access can be gained from below. In Figure 8, a schematic drawing of an optical engine with a, for this thesis, typical optical setup can be seen.
As seen, side windows have also been installed in this engine. This allows for active optical techniques such as laser diagnostics to be utilized. Furthermore, one of the exhaust valves have been replaced with an additional window in this engine, allowing for vertical optical access throughout the whole cycle. While removing the exhaust valve will affect the residual gas composition in the cylinder, this engine (and most optical engines) is operated in skip fire mode. When running in skip fire mode, one fired cycle is followed by a fixed number of non-fired/motored cycles (for example, one fired and nine motored cycles). Therefore it is reasonable to assume that the removal of a single exhaust valve will not have any effect on the gas composition of the fired cycles.

*Figure 8 Optical engine schematic.*
While optical engines have often been limited to measurements at low and medium loads, newer engine designs have made it possible to utilize Bowditch-type optical engines at as heavy loads as 21 bar IMEP [38].

3.2 Lasers

Various laser systems are frequently used within optical engine research. Lasers emit light through the use of stimulated emission of electromagnetic radiation. The biggest advantage of light emitted by lasers compared to other light sources is that the light is coherent, both temporally and spatially. This is a fundamental property of lasers [39]. The spatial and temporal coherence makes collimation of the laser beam possible with high spectral flux, which is crucial for many of the applications used in optical engines.

The first prerequisite for laser radiation is that the atoms/molecules in the laser’s active medium is in an excited state. A photon entering the medium can then trigger de-excitation of an atom in the excited medium, stimulating emission of a new photon that has exactly the same properties as the original photon. Those properties include polarization, direction, and wavelength. This leads to an avalanche effect as the two photons will stimulate emission of two additional photons from two other excited atoms/molecules and so on. To enable this avalanche effect, it is necessary that there is a so-called population inversion, that is, that there are more atoms/molecules in the higher energy state than in the lower. This is normally not the case as the energy levels under equilibrium conditions in a given medium are distributed according to the Boltzmann distribution,

$$\frac{N_{i+1}}{N_i} = e^{\left(\frac{E_{i+1}-E_i}{kT}\right)},$$  \hspace{1cm} (7)

where $N_i$ is the fraction of atoms in energy state $E_i$ and $N_{i+1}$ the fraction of atoms in the energy state above, $E_{i+1}$. As can be seen from equation 7, the energy state $N_{i+1}$ becomes completely depopulated as the temperature $T$ approaches 0, and as the temperature approaches infinity the fraction of atoms in energy state $N_{i+1}$ approaches (but never reaches) that of $N_i$. In order to reach a population inversion, pumping is necessary. In short, the idea
behind pumping is to transfer the atoms to an energy state from which they can only decay through a so-called “forbidden transition”. In practice, this is done via three or four stage pumping schemes, which are necessary to achieve a steady-state population inversion. In such schemes, the atoms are excited to a higher energy state that feeds into the state from which the forbidden transition occurs. If the forbidden transition takes place to the ground state, it is a three-level pumping scheme. If it takes place to a fourth energy level, it is a four-level scheme. “Forbidden transitions” cannot occur through electric dipole transitions and are thus quantum-mechanically unfavoured. For this reason, the lifetime in this state will on average be much longer, making population inversion possible [40].

In Figure 9, a schematic example of a four-level pumping scheme is shown. For all four level pumping schemes, the lasing occurs between levels 3 and 2 whereas for a three-level scheme, the lasing occurs between level 2 and 1. The wavelength of the laser from the four levels pumping scheme is then given by

$$\lambda = \frac{hc}{E3 - E2}.$$  \hspace{1cm} (8)

One of the more commonly used lasers within the engine community is the neodymium-doped yttrium aluminium garnet (Nd:YAG) laser. This laser employs a four-level pumping scheme and achieves lasing at the fundamental wavelength of 1064 nm [39]. Using this fundamental wavelength it is possible to obtain other lasing wavelengths through various optical processes such as frequency doubling or through the use of optical parametric oscillators (OPO) and various dyes. However, the theories behind these processes are out of the scope of this thesis.

![Figure 9 Schematic of a four level pumping scheme. Lasing achieved between E3 and E2.](image-url)
3.3 LEDs

Another light source which is seeing increased use within the engine community is the light emitting diode (LED). LEDs are semi-conductors with a so-called positive-negative (p-n) junction. As a current is applied over the semi-conductor the electron holes and electrons will recombine and, when this happens, energy is released in the form of photons. The wavelength of the photons is determined by the so called band-gap, which is the energy difference between the valence band and the conduction band of the semi-conductor. Since the possible transitions are relatively plentiful for a LED at normal temperatures, the wavelength of the emitted photons will vary more in a LED than in a laser. In addition to this, unlike the photons emitted by a laser, the photons emitted by a LED will not be spatially or temporally coherent. However, if extremely narrow bandwidth of the emitted light is not crucial, LEDs can be a great source of luminosity due to its relatively high radiant energy and low cost.

3.3 CCD/CMOS cameras

The cameras used for image acquisition are typically cameras that employ a complimentary metal-oxide-semiconductor (CMOS) image sensor or a charge coupled device (CCD). CMOS cameras are preferred for high speed cameras, as they enable quicker re-exposure of the image sensor [41]. When operating at 10 Hz, which is often the case for laser based studies, CCDs can be re-exposed quickly enough. For that reason, cameras of that type were used for all the laser based imaging techniques covered within this thesis.

When performing measurements with cameras, it is necessary that the signal response of the camera is carefully measured if one wants to do a quantitative analysis of the images. The signal response is often not a linear function of the irradiance. Another, maybe less known fact is that CMOS cameras suffer from image lag. This is an effect where the preceding image affects the subsequent image due to an incomplete reset of the CMOS. A dim negative image of the previous image is then superimposed onto the newly acquired
image. The spatial extent and amplitude of this effect varies from camera to camera and should be therefore always be investigated [42, 43].

3.4 Soot Detectors

Engine out soot emission measurements were performed with two different sorts of instruments; the Pegasor particle sensor (PPS) and the AVL 415 S smoke meter.

In short, the PPS works by sampling the exhaust air and charging the particles therein. As the now charged particles leave the sensor this creates a current which is proportional to the amount of particles in the sampled air. The sampling rate of the PPS used in this thesis was 100 Hz. It could thus be used to measure emissions variations from cycle to cycle [44].

The AVL 415s works by drawing the emissions into the instrument and depositing it on white paper. The paper blackening is then measured in a reflectometer and correlated to the soot in the emissions. The AVL 415s samples the emissions during a longer time than the PPS and does not have the capability of cycle resolved measurements [45].
4. Experimental Methods

4.1 Natural luminosity

Passive imaging techniques such as high speed video (HSV) imaging are frequently used within the optical engine research community. For conventional diesel combustion, the vast majority of the radiance is originating from thermal radiation of soot particles. This radiation is broadband and often assumed to follow the Max Planck blackbody radiation law,

\[ B_\lambda(\lambda, T) = \frac{2hc^2}{\lambda^5} \left( e^{\frac{hc}{\lambda k_B T}} - 1 \right)^{-1}. \]  

(9)

Here, \( B(\lambda, T) \) is the spectral radiance, \( h \) the Planck constant, \( c \) the speed of light in the medium, \( \lambda \) the wavelength, \( k_B \) the Boltzmann constant, and \( T \) the temperature. Since \( 2hc^2 \) and \( hc/k_B \) are physical constants, they are often simplified into \( C1 \) and \( C2 \) and called Planck’s first and second radiation constants. Figure 10 shows examples of the characteristic intensity distributions for various temperatures. A higher temperature will always yield a shorter wavelength for the peak intensity of the distribution. It is worth noting that there is no single known physical entity that is a perfect blackbody radiator. For this reason, even in the best case, soot radiation will deviate slightly from the Planck radiation law [40].
4.1.1 Two color pyrometry

A technique based on natural luminosity is the two color pyrometry technique, which utilizes Planck’s equation and detected natural luminosity at two (or more) discrete wavelengths, in order to find information about both the soot temperature and the soot optical thickness [46].

Defining the monochromatic emissivity of a black-body according to,

$$
\varepsilon_\lambda = \frac{I_\lambda(T)}{I_{b,\lambda}(T)},
$$

(10)

where $\varepsilon_\lambda$ is the monochromatic emissivity, $I_{b,\lambda}$ is the emissivity of the blackbody radiator and $I_\lambda$ the emissivity of the non-blackbody, which in our

Figure 10 Spectral radiance from a black-body radiator at 2000 K, 3000 K, and 4000 K.
case is the soot. As can be seen by this definition, the monochromatic emissivity of a non-blackbody has a value ranging between zero and smaller than one, since a blackbody is defined as an object whose emissivity is strictly equal to one.

We will now introduce the concept of the apparent temperature, \( T_a \). This is the temperature at which a blackbody radiates with the same intensity as a non-blackbody at temperature \( T \). It is defined by

\[
I_{b,\lambda}(T_a) = I_\lambda(T).
\]  

(11)

Using the definition of apparent temperature and combining it with equation 9 and 11, a theoretical expression of the emissivity of the soot is given by,

\[
\varepsilon_\lambda = \frac{e^{C_2/\lambda T} - 1}{e^{C_2/\lambda T_a} - 1}
\]

(12)

However, since the quantity \( T \) cannot be experimentally measured, equation 12 is left with two unknowns (\( \varepsilon_\lambda \) and \( T \)). To solve this, the empirical relationship of Hottel and Broughton [47] is often used:

\[
\varepsilon_\lambda = 1 - e^{-KL/\lambda^2}.
\]

(13)

Here, \( KL \) is the optical thickness and \( \alpha \) is the dispersion coefficient. According to Rayleigh theory, \( \alpha \) should be equal to unity but this is often not the case [46-48]. Combining equation 12 and 13, the unknown emissivity can be substituted using

\[
1 - e^{-KL/\lambda^2} = \frac{C_2}{e^{C_2/\lambda T} - 1},
\]

(14)
which can further be re-written as

\[ KL = -\lambda^\alpha \ln \left( 1 - \frac{C_2}{e^{C_2a_T - 1}} \right) \]. \tag{15} 

Finally, the unknown \( KL \) can be substituted by using two different wavelengths in equation 15, yielding the final expression

\[ \left( 1 - \frac{e^{C_2/a_{T1} - 1}}{e^{C_2/a_{T2} - 1}} \right) \lambda_1^\alpha = \left( 1 - \frac{e^{C_2/a_{T1} - 1}}{e^{C_2/a_{T2} - 1}} \right) \lambda_2^\alpha \]. \tag{16} 

This method does have some uncertainties. The value of \( \alpha \) is dependent on both the soot optical properties and the wavelength at which one is detecting the light. Another uncertainty is the fact that the detected light is susceptible to temperature gradient and soot gradient effects along the line of sight [49]. A third issue is the so-called beam steering effects. Due to density gradients in the medium, light will refract differently for two different wavelengths and this will lead to inaccuracies in both \( T \) and \( KL \) when using the TCP method [50].

4.2 Laser Induced Fluorescence

Laser induced fluorescence (LIF) is a common measurement technique within various fields of research [51, 52]. The principle behind it is to use a laser to excite an atom or molecule and then study the fluorescence as the atom or molecule de-excites. Since fluorescence, by definition, is light emitted when an excited state is relaxed to a lower energy state through a so-called allowed (electric dipole) transition, the lifetime of fluorescence is relatively short, usually ranging between 0.1 and 20 ns [39]. By using a suitable wavelength, that is, a wavelength with the same photon energy as the
required excitation energy of the relevant atom or molecule, species-specific fluorescence can be obtained.

Two of the most common naturally occurring species of study within the engine community is OH [53-55] and PAHs [56-58]. One of the reasons why OH is interesting is that it is, as discussed in section 2.4.2, an important oxidizer. PAHs, on the other hand, are important soot precursors and are therefore especially important when analysing soot formation. LIF studies are also performed where a fluorophore has been added to the fuel as a tracer in order to study, for example, fuel distributions within the cylinder [59]. One of the main issues with quantitative LIF measurements is that, even though the lifetime of the excited state is on the order of nanoseconds, collision rates between particles in a dense gas, such as those found within an engine, are so high that de-excitation through collisions have a similar or even higher chance of occurring as compared to de-excitation through an electric dipole transition. De-excitation through collisions do not produce any emission of light and the amplitude LIF signal thereby does not correlate linearly with the concentration of species studied with LIF. This effect is called collisional quenching and its effect is heavily dependent on pressure and temperature [60].

The LIF experiments covered within this thesis were all qualitative and, for this reason, no major precautions were taken to minimize the effects of collisional quenching.

4.3 LII

Laser induced incandescence (LII) uses short laser pulses to heat soot particles up to the point of sublimation. While the temperature of soot found in flames is normally around 2000 K, soot heated through the use of LII is often heated up to more than 4000 K [60]. Since soot behaves similarly to a blackbody radiator, the total radiated power will increase in accordance with Stefan Boltzmann’s law,

\[ I = \sigma T^4 \]  

(17)
Here, \( I \) is the intensity, \( \sigma \) the Stefan Boltzmann constant, and \( T \) the temperature of the soot particle. This means that, while the LII signal is broadband just like the natural luminosity of a normal flame, the LII signal is still fairly easy to distinguish since it is much brighter than the background. When considering that, according to Planck’s law (equation 9), the peak intensity will be blue-shifted compared to the natural luminosity, the LII signal will be even easier to detect if one employs a shortpass filter or a bandpass filter with transmission in the UV, where intensity from LII signal will be several orders of magnitude larger than the natural luminosity.

While the LII experiments covered within this thesis were only qualitative, it is possible to use LII in a quantitative manner as well, since the LII signal is proportional to the soot volume fraction as long as the laser fluences are sufficiently high and the signal is calibrated [61]. It can even be possible to determine the size distribution of soot particles using LII [62]. A simplified description of the principle is as follows; as soon as the laser pulse ends, the soot will begin to cool down through radiative (emitting light) and conductive heat transfer. This heat transfer is proportional to the surface area of the soot and the decay rate of the LII signal is therefore proportional to the soot particle size. In order to accurately predict the particle size it is necessary to know the initial temperature of the surrounding gases as well as that of the soot. As discussed in section 4.1, optical thermometry techniques such as TCP have uncertainties and this will affect the accuracy and precision of LII-based particle size measurements. Additionally, the optical properties of soot, such as the emissivity and the complex part of the refractive index, are not always known, leading to further uncertainties [63].

A general issue with LII is that the signal might be affected by so-called signal trapping. This means that LII signal is absorbed by soot between the measurement region and the detector, making the absolute LII signal uncertain. This is especially prevalent under heavily sooting conditions such as those found during normal diesel operation. Another potential issue is unwanted excitation and subsequent fluorescence of arbitrary species. Especially PAHs are known to both absorb and fluoresce when using a laser wavelength of 532 nm [57]. For this reason, LII studies covered within this thesis were performed using the fundamental wavelength of the Nd:YAG which is 1064 nm. While LII is an optical technique it is still a somewhat intrusive technique since. It has been shown that, since LII heats the soot to
temperatures where the soot is rapidly decomposed, measurements in the order of kHz will affect the soot distributions and also affect the bath gas temperature which, in turn affects the LII signal [64].

In this thesis, LII has only been used as a qualitative measurement technique used to detect the spatial extent of soot clouds and not the soot volume fraction.

4.4 LEM

Laser extinction measurements (LEM) uses lasers to probe the optical absorption along the line of sight of a medium. The principle behind LEM is given by Beer Lambert’s law

\[ \frac{I}{I_0} = e^{-(K_{abs}L + K_{sca}L)}, \]  

(18)

where \( I_0 \) the incident laser intensity, measured before the absorbing medium, \( I \) is the measured intensity after the absorbing medium, \( K_{abs} \) the extinction coefficient due to absorption, \( K_{sca} \) the extinction coefficient due to scattering, and \( L \) the optical path length. Assuming that the particles are smaller than the laser wavelength, the scattering part will be negligible and equation 18 will therefore only be a function of \( K_{abs} \) and \( L \). Under diesel-like conditions, soot particles are often smaller than 100 nm [17] and the laser wavelength used in the experiments covered herein was always longer than 500 nm. A visualization of the principle of Beer Lambert’s law is shown in Figure 11.

Since the absolute values of \( L \) and \( K_{abs} \) are often unknown in a non-controlled flame, such as those found in diesel engines, the product \( K_{abs}L \) is often used to evaluate the total optical thickness along the line of sight.

LEM is a quantitative technique with a very good temporal resolution, often used with a sampling rate of close to a 100 kHz.
If $L$ can be estimated, it is possible to determine the value of $K_{abs}$. Knowing this, it is possible to obtain an expression describing the soot volume fraction $f_v$ using

$$f_v = \frac{K_{abs} \lambda}{6\pi E(m)}.$$  

(19)

Here, $E(m)$ is the imaginary part of the complex refractive index of the soot absorption function, and $\lambda$ is the wavelength. $E(m)$ is a source of fairly large uncertainty [63] due to both wavelength effects and soot morphology effects. With this and the difficulty to accurately determine the value of $K_{abs}$ in mind, all extinction measurements performed within this thesis have been evaluated based on the total optical thickness ($KL$) alone and no conversion from $KL$ to soot volume fraction has been performed.

One issue with LEM is that it is susceptible to beam steering. For quantitative experiments, it is necessary to know if the light was absorbed or merely steered off the detector. Studies have been done in optical diesel engines to estimate the amount of light being steered. It was found that, as long as a diverging angle of roughly $4^\circ$ is accounted for then 95% of the light should be captured under typical diesel conditions [65]. Another issue with LEM is that it is a point source measurement and thereby carries no spatial information. It is therefore best used when evaluating relatively homogenous environments such as the late-cycle stages of the expansion stroke.
While soot is usually the medium one wants to determine the absorption of, it is important to keep in mind that for instance PAH will also absorb light, especially if the wavelength is short [48]. For this reason, it is generally better to use long wavelengths whenever using absorption-based techniques, even if such wavelengths can be more cumbersome to work with.

4.5 DBI

DBI is similar to LEM in being a line of sight extinction technique relying on Beer Lambert’s law to determine the absorption. The main advantages of DBI compared to LEM is that it is a 2D technique and, assuming that certain criteria are fulfilled, it can compensate for beam steering. Using state of the art LEDs like the Sandia Pulser [66], it is possible to achieve DBI imaging with frame rates of several tens of kHz. The DBI system developed and used throughout this thesis is based on the system developed in [67-69] which, in turn, was based on [70]. One of the main components of a DBI setup is the engineered diffuser which creates a Lambertian beam profile when illuminated by a collimated light source. A Lambertian beam profile has a constant radiance emittance at all forward angles and it is shown in [68] that, if the Lambertian emitter’s spatial extent and divergence angle are sufficiently large, any beam steered out of its original trajectory will be replaced by an additional ray of equal radiance. The first criterion is described by

$$\theta \geq \alpha + \omega, \quad (20)$$

where $\theta$ is the divergence angle of the engineered diffuser, $\alpha$ the anticipated beam steering angle, and $\omega$ the acceptance angle of the optics. The second criteria is given by

$$D \geq S + \tan(\alpha + \omega) L, \quad (21)$$

where $D$ is the size of the engineered diffuser, $S$ the extent of the studied object, and $L$ the distance between the engineered diffuser and the object. These criteria are visualized Figure 12.
4.6 DBI-T

A new thermometry technique has been developed within the work of this thesis that we have named Diffused back-illumination temperature imaging (DBI-T). Using measured $KL$ values, it is possible to extract soot temperatures from natural luminosity images that are bandpass filtered to contain only the same wavelength as the one used to determine the $KL$ value. This should be more precise and accurate than the common TCP method mentioned in a previous section, since it avoids the use of the Hottel and Broughton empirical relationship, with its fairly uncertain dispersion coefficient $a$. Instead, Kirchhoff’s law of radiating bodies can be used together with equation 12 to get an analytically solvable expression for the temperature,

$$T = \frac{C_2}{\ln\left(\frac{C_2}{\lambda T a} - 1\right)(1 - e^{-KL}) + 1}.\quad (22)$$

Here the variables and constants are the same as the ones described in the TCP chapter with the exception of $KL$, which is the, wavelength-specific,
optical thickness, measured using the DBI technique and the apparent temperature, $T_a$ is measured using a calibrated HSV camera. Another benefit of the DBI-T technique is that it does not suffer from the same issues with beam steering, both due to the beam steering compensation of the DBI technique and to the inherent need of only using a single wavelength for both absorption and radiance measurements.

4.7 Pressure Trace and Heat Release Analysis

While the focus of this thesis is on the application and development of optical techniques, the most common measurement technique employed within the optical engine community (as well as the engine community) is cylinder pressure and heat release analysis. Using a pressure sensor, it is possible to follow the pressure evolution within the cylinder at sub-CAD time resolution. Using the first law of thermodynamics along with some assumptions (for example that we are dealing with an ideal gas) it is possible to derive an expression for the heat released in the cylinder that is only a function of the pressure and the volume. A thorough derivation of this can be found in [2] but, for the sake of completeness, a derivation will be presented here as well.

The first law of thermodynamics gives that for a closed system, such as an engine cylinder during the closed part of the cycle, the heat release rate is given by

$$\frac{dQ}{dt} = \frac{dU}{dt} + \frac{dW}{dt} + \sum_i m_i h_i, \quad (23)$$

where $Q$ is the heat added to the system, $U$ is the change in internal energy, $W$ the work performed by the system, $m_i$ is the mass, and $h_i$ is the enthalpy of the $i$th element entering the system. The internal energy $U$ is described by

$$U = mC_v T, \quad (24)$$

where $m$ is the total mass of the system, $C_v$ the specific heat at constant volume and $T$ is the temperature. With the somewhat faulty assumption of a constant mass and the use of the ideal gas law, $dU/dt$ can be expressed as
\[ \frac{dU}{dt} = \frac{C_v}{R} \left( p \frac{dV}{dt} + V \frac{dp}{dt} \right), \]  \hspace{1cm} (25)

The pressure-volume work \( W \) can likewise be expressed as

\[ \frac{dW}{dt} = p \frac{dV}{dT}. \]  \hspace{1cm} (26)

Assuming constant mass, inserting equations 25 and 26 into equation 23 yields

\[ \frac{dQ}{dt} = \frac{C_v}{R} \left( p \frac{dV}{dt} + V \frac{dp}{dt} \right) + p \frac{dV}{dT}, \]  \hspace{1cm} (27)

where the heat release per unit time is a function of pressure and volume. Once again using the assumption of an ideal gas, \( R \) is given by

\[ R = C_p - C_v. \]  \hspace{1cm} (28)

Knowing that the heat capacity ratio \( \gamma \) is defined by

\[ \gamma = \frac{C_v}{C_p}, \]  \hspace{1cm} (29)

equation 27 yields the final expression for the heat released per unit time as function of only volume and pressure:

\[ \frac{dQ}{dt} = \frac{\gamma}{\gamma - 1} p \frac{dV}{dt} + \frac{1}{\gamma - 1} \frac{dp}{dt}. \]  \hspace{1cm} (30)

This expression is used for heat release calculations within this thesis.
5. Results and Discussion

5.1 Swirl, injection pressure, and engine out soot emissions

How the swirl level affects the engine out soot emissions is not trivial to understand and was studied in paper I. Intense, large scale motion will increase the kinetic energy of the in-cylinder gas and increase the mixing between fuel and air. It is believed that this will help to reduce engine out soot emissions by enhancing late cycle soot oxidation and by suppressing the occurrence of regions with high soot formation rates due to high local fuel equivalence ratios. Soot is typically formed in regions with $\phi$-values greater than two. However, excessive swirl levels can also lead to spray interactions which will create pockets of both low equivalence ratios as well as very high equivalence ratios. This was shown in [71] and led to elevated hydrocarbon, CO, and soot emissions.

Higher injection pressures introduce more kinetic energy into the combustion chamber, which could enhance the late cycle soot oxidation. Increasing the injection pressure will also increase the velocity of the fuel, increasing the lift-off length and thereby reducing the soot formation rate, as more oxygen is mixed into the jet before combustion starts [72-75].

In paper I, we employ a cylinder head that allows the swirl ratio to be set to 0.2, 1.2, and 2.2. The injection pressures are varied between 1500, 2000, and 2500 bar in the same experiment. As can be seen in Figure 14, there is no monotonous relationship between engine out soot emissions and the swirl level. The lowest soot emissions are found with the swirl level of 1.2. Soot emissions are monotonously decreasing with increasing injection pressure, with the exception of the case with a swirl level of 1.2, which has a slightly lower emission level at 2000 bar than at 2500 bar. While it is a common
conception that increased swirl will yield lower soot emissions, it is shown not to be the case here. This could potentially be explained by the complex interactions between flow structures set up in the cylinder by the swirling flow and the injection pressure, leading to the need for a proper balance between the spray momentum and the rotational velocity to effectively oxidize the soot late in the cycle [73].

This finding was further supported by additional (unpublished) experiments performed with the same engine configuration but a different cylinder head. As seen in Figure 14, we established that the cylinder head configuration with a swirl ratio of 5.6 produced higher soot emissions than the configuration with a swirl ratio of 1.6.

It was also revealed that while the high swirling head produced consistently more engine out soot, the high swirl also appeared to make the efficacy of the post injection less susceptible to injection timings, which is also shown in Figure 14.

Figure 13 Soot emissions as a function of injection pressure for three different swirl levels.
5.2 Soot oxidation studies by simultaneous OH-PLIF and PLII imaging

OH is, as was discussed in section 2.3.2, an important oxidizer. For this reason, it is of great interest to study the abundance of OH and the effect it might have on engine out soot emissions. This was investigated in paper I by the use of simultaneous OH-PLIF and PLII imaging for the nine different operating conditions found in Figure 13. For each operating condition, 50 images were captured and used for evaluation. Due to low signal to noise ratios in some images, 50 useful images were not found for all operating conditions but a slightly lower number of images is not considered to affect the statistical significance to any large degree.

Since the study focused on late cycle soot oxidation it is crucial to time the imaging optimally. It can be assumed that the rate of heat release after end of injection (EoI) is dominated by oxidation processes since no quasi steady jet exists and no new fuel enters the combustion chamber. The timing of the OH-PLIF and PLII was therefore determined by analysing the apparent heat release rate (aHRR). As shown in [76], an exponential decay function can be fitted to the part of the aHHR curve occurring after EoI. Computing the half-life of this curve yields a measure of the late cycle oxidation rate. EoI was
determined through the use of HSV imaging of the injection, and not as the end of solenoid energizing (ESE). Using this method, we were able to capture images for the various operating conditions at set half-life intervals after 50% of the total energy had been released (CA50). Image analysis was performed for images acquired one half-life after CA50. Therefore, while the absolute soot levels are never known, we can be confident that the various image timings are equally far into their late cycle soot oxidation stages.

An example of the progression of the OH and soot abundance in the field of view can be seen in Figure 15, where the green regions represent OH and the red regions represent soot. In Figure 15 it is clear that there is initially very little OH in the laser sheet but, as combustion progresses, more and more OH is formed (or at least enters the plane of the laser sheet). The repetition rates of the lasers were 10 Hz and therefore only one image per cycle was captured.

![Figure 15 OH distributions in green and soot (LII signal) in red at four different timesteps](image)

At 12 CAD in Figure 15 there appears to be a clear interface between the soot and the region of OH, as could be expected since OH is formed in the diffusion flame where soot-rich regions mix with fresh air and react at stoichiometric conditions. This interface is even more evident in other cycles such as those shown in Figure 16. As discussed in section 2.4.2, the abundance of OH is not necessarily the only parameter of importance for OH oxidation; the proximity between the OH and soot is also likely to affect the efficacy of oxidation. To evaluate this, the amount of OH within proximity of soot is measured in all the images, and the mean value is plotted against the soot emissions in Figure 17a. A pixel containing OH was determined to be in proximity of the soot if a soot pixel was found ten or fewer pixels away. In
addition to this, the total amount of OH within each image was also measured and plotted versus the engine out soot emissions as shown in Figure 17b.

The measurements suggested a negative correlation between the amount OH in proximity to the soot and the engine out soot emissions. Furthermore, the total amount of OH within these images had a negative correlation to the engine out soot emissions. While the data is somewhat noisy, this relationship is statistically significant.

![Figure 16 Images of OH-LIF (green) and LII (red) showing a characteristic overlap/interaction between the two.](image-url)
The total amount of soot within the field of view was also analysed and correlated to the engine out soot emissions. This is shown in Figure 18 and there it can be seen that there appears to be no correlation between the amount of soot at the time of CA50 + one half-life and the engine out soot emissions. The fact that the amount of OH shows a negative correlation with soot emissions while the in-cylinder soot does not, supports the idea that soot oxidation rates are more important than soot formation rates for determining the trends of engine out soot emissions under normal diesel like conditions as found in, among other studies, [10-12,76].

Figure 17 Soot emissions as a function of the ensemble averaged proximity pixels to the right and as a function of the total LIF pixels within Field of view to the left.
5.3 LEM measurements

Laser extinction measurements have been a common technique for some time, in our lab as well as well as in others. For paper II, a LEM system was developed and implemented according to Figure 19. The optical access through the cylinder head was achieved by removing the exhaust valve and replacing it with a tilted window. The tilted window allowed for a completely vertical beam path despite the fact that the laser had to enter the cylinder head at an angle. With a vertical beam path, it is possible to study the soot evolution in a representative part of the cylinder during a complete engine stroke. The main focus of paper II was to study the late cycle soot oxidation rates. While the LEM technique only probes a one-dimensional projection along the cylinder axis, it is reasonable to assume that, in a swirling engine, the constituents of the cylinder have been well-mixed and are close to homogeneous late in the cycle. The intake oxygen concentrations were varied from 9-21 % by the use of an external EGR source, which dilutes the intake air with rest gases from a diesel furnace operated at stoichiometric conditions. The load was kept constant at 6 bar IMEPg and the injection pressure was set to 2000 bar. CA50 was kept constant at 369 CAD after top dead centre (ATDC).
Figure 20 shows HSV false color images of the combustion with the place where the laser beam passes through the piston indicated by a white dot.

Figure 19 Schematic setup of the LEM experiment.

Figure 20 NL images at CADs indicated by black lines on the x-axis. The white point displays the position of the laser point. Camera exposure times have been changed inbetween images to avoid saturation.
As can be seen from Figure 20, the laser is targeted between two sprays and therefore it takes a while for the soot to reach this region. Due to the limited measurement area, it is hard to draw any conclusions about the general combustion occurring in the cylinder, but since the focus of paper II was on late cycle trends, this is of limited concern.

*KL* curves for the various O₂ concentrations are shown in Figure 21. It is clear that while the 11 % O₂ conditions appear to form quite a bit less soot than the higher O₂ concentration cases, the deteriorating soot oxidation results in the highest engine out soot emissions of all cases (the exhaust port opens at 140 CAD ATDC). The maximum *KL* values are reached for the 15 % case, but the curves should not be trusted at the highest *KL*-values. This is because a *KL* value of 4 corresponds to a laser intensity decrease of more than 98 %. The relatively high background luminosity from the combustion at this stage of the cycle, combined with the poor signal-to-noise ratio due to the massive extinction, makes it difficult to tell which of the two highest oxygen concentrations produce most soot.

![Figure 21 *KL* as a function of CAD for various O₂ concentrations.](image-url)
By fitting an exponential decay function to the KL curves in Figure 21, it is possible to compute a half-life of the KL value. The result of this is shown in Figure 22 where the half-life is plotted against the inlet O₂ concentration. Here, it can be seen that a higher O₂ concentration yields shorter half-lives and thus more efficient soot oxidation, as could be expected. The deviation from this trend seen at 9 % O₂ is most certainly due to the very poor signal to noise ratio at this operating condition.

![Figure 22 Half-life of KL as a function of O₂. Evaluation of single shots indicated by black and averaged values in red.](image)

In paper III an algorithm used to compensate for window fouling is implemented. After the implementation of this algorithm the background natural luminosity, arising from broadband emission of soot particles, is compared to the KL values. Such a comparison is shown in Figure 23. Looking at the right plot it is clear that the laser is attenuated before any natural luminosity is detected. This might be counter intuitive since the LEM only measures the extinction in a small spot size whereas the natural luminosity could arise from a much larger region and thus one could expect that the natural luminosity should be detected first. However, injections in to inert conditions, shown in the left part of Figure 23 reveals that the rise time
of the KL during fired conditions curve correlates well with the rise time of KL during non-combusting operation. This suggests that the initial attenuation is caused by fuel droplets and not soot. Since fuel droplets are larger than the wavelength of the laser used, the scattering part of $K_{sc}$ cannot be ignored and therefore it is not possible to accurately determine the absorption of the liquid fuel. The total attenuation during non-combusting operation is lower than the attenuation of the second peak in the fired case. This is most likely due to the fact that under conditions where oxygen is present, soot precursors like PAH will form before the soot. Unlike soot, PAH is not emitting any broadband emission but it will still absorb light and thus attenuate the laser signal before natural luminosity from the soot is visible.

In paper II, by measuring the KL and establishing the decay of the KL value as a metric for the soot oxidation rate, we show that the oxidation rate is heavily dependent on the oxygen concentration and correlates well with the measured soot emissions. Furthermore, we establish that the initial amount of soot formed does not correlate with the amount of emitted soot. This supports previous studies which suggested that soot formation rates are not the dominant factor when determining the trends of soot emissions [10-12,76].

In paper III, an algorithm was developed for compensation of window fouling, an effect that occurs in optical engines due to soot deposits on the windows. After this algorithm had been developed the overlap between
natural luminosity and laser attenuation was also investigated. It is shown that natural luminosity does not appear at the same time as laser attenuation. While it could be expected that natural luminosity would be visible before laser attenuation, due to the fact that natural luminosity could arise anywhere within the cylinder whereas the laser attenuation can only occur in a very small region of the combustion chamber, this does not happen. It is likely that the laser attenuation arises due to absorption and scattering from liquid fuel as well as non-luminous soot precursors. This discrepancy emphasises the necessity of using complimentary optical techniques to gain as much knowledge as possible and to decrease the risks of drawing inaccurate conclusions.
5.4 DBI measurements

DBI was employed in paper IV to elucidate the mechanisms behind the soot reduction of small, closely-coupled post injections. Various post injection strategies were tested in a Cummins heavy-duty optical engine, operated on a single cylinder of 2.34 L. It is worth noting that a Delphi DFI 1.5 light-duty injector was used and therefore the injection durations were much longer than what would normally be the case for loads covered within this paper. Soot measurements were performed using an AVL 415s smoke meter and the results are shown in Figure 24. Here, it is revealed that a short post injection increases the load of the engine while it does not increase the soot emissions. However, for longer post injections, the soot emissions are increased above the single injection strategies at the corresponding loads. This behaviour can be seen for both the 18 % (left side) and 15 % (right side) O₂ concentrations. To better understand what underlies the efficacy of the post injections, DBI was, for the first time, employed in a heavy-duty optical engine. The optical setup can be seen in the top part of Figure 25 and the engineered diffuser had a divergence angle of 10° which, according to equation 20 and the findings in [65], should be enough to compensate for most, if not all, of the beam steering under these conditions.

![Figure 24 Left: Paper blackening as a function of load at 18 % O₂. Right Paper blackening as a function of load at 15 % O₂.](image-url)
Image acquisition for the DBI setup was done at 120 kHz using a Phantom 7.3 camera. The LED was pulsed at 40 kHz, that is, in every third image. The quick sampling rate allowed for background subtraction using the image preceding each LED pulse. The image following the LED pulse was used to reset the camera CMOS in order to avoid effects of negative image lag, as discussed in section 3.3. The DBI field of view is shown in relation to the combustion chamber in the bottom part of Figure 25. Natural luminosity imaging of a quadrant of the combustion chamber was performed using a Phantom 7.1 camera with a temporal resolution of 7.2 kHz, which corresponds to one image per CAD at 1200 rpm. This was used to determine the actual SoI of the post injections as well as the EoI of the main, post, and single injections.

Figure 25 Optical setup and field of view of the DBI setup.
The left part of Figure 26 shows spatial integration of the ensemble averaged KL and NL signals within the DBI field of view for all the single injection operating conditions at 18% O₂. It is revealed that, while increased injection duration increased the amount of soot within the DBI field of view, the NL value showed no such correlation. In addition to this, KL and NL images, normalized with respect to the maximum value during a cycle, revealed poor spatial correlation. An example of this can be seen in the left part of Figure 26. This suggests that natural luminosity might be a poor metric to use for quantitative soot measurements. This lack of correlation likely owes to the fact that the soot luminosity is dependent on both the total amount of soot and the temperature and, for this reason, regions such as the one in the recirculation zone between two jets (shown in the left part of the field of view images) will contain much soot at a low temperature and thereby not be particularly luminous. The NL images by themselves would rather suggest that there is less soot in this region, despite it being one of the sootiest regions.

Figure 26 Left: Ensamble averaged KL and NL values as a function of CAD for various single injection strategies. Right: Single cycle comparsion of KL and NL values.
Field of view averaged $KL$ and $NL$ curves for post injection strategies and a single injection case, which has the same duration as the main injection of the post injection strategy are shown in Figure 27. It can be seen that, for a short post injection ($<400 \mu s$), the average $KL$ and $NL$ values are unaffected by the post injection. For the $450 \mu s$ post injection there is a small bump on the $KL$ curve before it drops down to the same level as the single injection case at roughly 385 CAD. For post injections up to 600 $\mu s$, the late cycle (after 420 CAD) $KL$ values converge to the same levels as the single injection case. This is consistent with the engine out soot emissions shown in Figure 24, which show no increase for post injection strategies shorter than 600 $\mu s$. There is a linear correlation between the engine out soot emissions and the late cycle $KL$ values of Figure 26 and Figure 27. A linear regression model fitted to this data yields an $R^2$ value of 0.968.

Additionally, it can be seen that the $KL$ value averaged over the maximum field of view is much higher for the 800 $\mu s$ post injection than it is for the 2350 $\mu s$ single injection. On the other hand, the maximum field of view averaged $NL$ values is much lower for the 800 $\mu s$ post than it is for the 2350 $\mu s$ single injection. Remembering that the $NL$ signal is affected by both the amount of soot and the temperature of the soot, it is likely that the temperature of the soot found in the post injection is relatively much lower than the temperature of the soot in the main or the single injection. As discussed in section 2.4.2, a lower temperature will result in lower soot oxidation rates.

![Figure 27](image.png)

*Figure 27* Right: $KL$ values as a function of CAD for various post injection strategies compared to the single injection case. Left: $NL$ values as a function of CAD for various post injection strategies compared to the single injection case.
Special interest was taken in two regions within the DBI field of view. These regions are labelled jet region and recirculation region and are shown in Figure 28. The jet region represents the upstream region of the spray whereas the recirculation region is located in a downstream region where the jet has been in contact with the bowl wall and collided with the jet originating from another nozzle.

In Figure 29, the average $KL$ and $NL$ values of the respective regions are shown, the jet region in the left part of the figure and the recirculation region in the right part. Looking at the top row (showing $KL$ values) it can be seen that, with the 450 $\mu$s post injection, there is clear indications of soot entering the jet region at around 380 CAD, whereas no soot reaches the recirculation region. It can also be seen that, in the jet region, the peak $KL$ value of the 600 $\mu$s post injection is very similar to that of the 800 $\mu$s post injection. In the recirculation region, however, things are once again different. Here, the peak $KL$ value of the 600 $\mu$s post injection is much lower than the peak value of the 800 $\mu$s post injection. This suggests that the oxidation process for the post injections with durations lower than 800 $\mu$s are more efficient overall.

![Figure 28](image)

*Figure 28  Field of view of the DBI with the Recirculation Region indicated by a green rectangle and the Jet region as a red rectangle.*
By normalizing the \( KL \) and \( NL \) values with respect to the maximum value, an interesting feature is shown; the maximum \( NL \) value always occurs after the maximum \( KL \) value. This can be seen in Figure 30. Since, as discussed before, the \( NL \) signal is a function of the temperature and quantity of the soot, and the \( KL \) value is only a function of the quantity of soot, this suggests that the temperature of the soot must increase when the \( KL \) decreases and \( NL \) increases. This temperature increase is detected in the jet region a few CAD after EoI for all cases and it is therefore likely that the temperature increase is due to increased mixing, caused by the entrainment wave, as the injector is closing.

Figure 29 Upper part: \( KL \) as a function of CAD in the Jet region and the Recirculation region respectively. Lower part: \( NL \) as a function of CAD for Jet region and the Recirculation region respectively.
Knowing the SoI and EoI of the post injections and using the 1D jet model of Musculus and Kattke [14], it is possible to estimate the position of the entrainment wave. In Figure 31 and Figure 32 the estimated position of the entrainment wave is superimposed on the cycle resolved KL and NL images.

As can be seen in Figure 32, the entrainment wave reaches the head of the jet before the jet reaches the bowl wall whereas, in Figure 31, the head of the jet reaches the bowl wall before the entrainment wave reaches the head of the jet. The blue region in the topmost part of the image panel in Figure 31 shows a decrease of KL from 3 to 2.5 after the entrainment wave has passed. It can furthermore be seen that the spatial overlap between the 10 percent of the pixels that have the highest KL and NL values show a larger spatial overlap for the shorter post injection, suggesting that the regions with the most soot are also regions with high temperature, which would be expected to enhance the oxidation rate. In Figure 24 it is seen that the soot emissions increase slightly for the 600 µs post injection case and substantially for the 800 µs case, but not for the 450 µs case. Seeing this and how the position of the entrainment wave correlates well with an increase in soot temperature, it is possible that the efficacy of the post injection strategies are heavily affected by how large a fraction of the post injection that reaches the bowl wall before the entrainment wave catches up with the head of the jet. In Figure 33, the 400 µs post injection is seen and here it is evident that almost all of the soot has been oxidized well before the jet reaches the bowl wall.

Figure 30 Zoomed in and normalized KL and NL values of the Jet region in Figure 29.
Figure 31 KL (top) and NL (middle) images at 378-381 CAD for the 2350 µs + 600 µs injection strategy. Bottom part shows the location of the 10% pixels with the highest NL and KL values. Entrainment wave location indicated by yellow dashed line. Blue region in the top row indicates regions discussed in the text.

Figure 32 KL (top) and NL (middle) images at 377-380 CAD for the 2350 µs + 450 µs injection strategy. Bottom part shows the location of the 10% pixels with the highest NL and KL values. Entrainment wave location indicated by yellow dashed line.

Figure 33 KL (top) and NL (middle) images at 377-380 CAD for the 2350 µs + 450 µs injection strategy. Bottom part shows the location of the 2.5% pixels with the highest NL and KL values.
In paper IV, we show that a small closely-coupled post injection can be used to increase the work of the engine while keeping the soot emissions constant compared to operation without the post injection. While it is often unclear why post injections work, we can here attribute it to the total oxidation of soot formed in the post injections that are sufficiently short. Whether a post injection is sufficiently short or not appears to depend on whether the entrainment wave manages to catch up with the post injection before it reaches the bowl wall or not. The entrainment wave increases mixing and judging by the fact that the natural luminosity is higher in the tail of the jet, where the amount of soot is lower, the increased mixing appears to also increase temperature, further enhancing the soot oxidation processes.

5.5 DBI-T development and evaluation

In paper V, a new soot thermometry technique is developed. It utilizes the fact that by using conventional DBI to directly measure $KL$, many of the uncertainties associated with techniques such as TCP thermometry can be avoided. With the 2D $KL$ distribution known, one can, with a properly calibrated camera, use equation 22 to obtain 2D temperature maps of the DBI/DBI-T field of view.

To gauge whether the experimental DBI-T results seemed reasonable, a theoretical model was created and the values obtained from this model were used to compare the theoretical DBI-T temperature to the theoretical TCP temperatures obtained in [50,78].
For the theoretical evaluation of DBI-T presented here, the same theoretical flame structure was used as in [50]. Here, the flame is divided into 42 zones, with a KL and temperature distribution according to Figure 34. The virtual detector is located on the left hand side of the theoretical flame. The total KL of this flame is 2.4 and the mass averaged soot radiation temperature is 2127 K.

The total monochromatic radiant intensity of the flame is given by,

$$\frac{1}{e^{\left(\frac{C_2}{\lambda T_a}\right)} - 1} = \sum_{i=1}^{n} \frac{W_i}{e^{\left(\frac{C_2}{\lambda T_i}\right)} - 1}. \quad (31)$$

Here $T_i$ is the temperature of zone $i$, $T_a$ the apparent temperature, $\lambda$ the wavelength, $C_2$ Planck’s second radiation constant, and the weighting factor $W_i$ is defined as

$$W_i = \left(1 - e^{\frac{KL_i}{\lambda \sigma}}\right)e^{-\sum_{j=i+1}^{n} \frac{KL_j}{\lambda \sigma}}, \quad (32)$$
where $K_{Li,j}$ is the KL value of the $i$:th and $j$:th zone, and $\alpha$ the dispersion coefficient. Using $T_a$ computed from equation 31 and inserting it into equation 22, the temperature of the flame in Figure 34 is obtained. Using the DBI-T approach yields a temperature of 2082 K, which is quite close to the mass averaged radiation temperature of the flame which, as mentioned before, is 2127 K. By comparison, the temperature obtained using the TCP setup in yields a temperature of 2509 K. It is worth noting that the KL value theoretically measured by the TCP setup is 0.23 [50] – an underestimation by an order of magnitude.

An example of an experimental measurement using DBI-T is shown in Figure 35 together with KL and $T_a$ maps. A 15 % O$_2$ case is displayed to the left and an 18 % O$_2$ case to the right. Here it is seen that the lower oxygen concentration yields a lower in cylinder temperature, as can be expected. It is also revealed that the temperature of the soot in the leftmost area is relatively low. Here, two jets have merged and it appears as if this has caused a temperature decrease compared to many other parts of the flame. It is likely that this temperature reduction is due to the fact that the availability of oxygen decreases as the jets merge, thus lowering reaction rates and leading to a lower temperature, which will further reduce the soot oxidation rate.

![Figure 35 KL, Ta, and T maps for 2350 μs single injection strategy at 373 CAD at 15 and 18 % O2 respectively.](image-url)

Figure 35 KL, Ta, and T maps for 2350 μs single injection strategy at 373 CAD at 15 and 18 % O$_2$ respectively.
One of the sources of uncertainty in TCP measurements is the effects of beam steering. To the left in Figure 36, a comparison of the maximum temperature within a region where DBI-T can fully compensate for beam steering is compared to the maximum temperature of a region where beam steering is not compensated for. As can be seen, the DBI-T temperature is much less noisy. In regions where the beam steering is uncompensated for, the temperatures can vary by over 100 K from one CAD to another. On the right side of Figure 36, the mean temperature in the field of view is compared with and without beam steering compensation. Here it can be seen that the average temperature of the region without beam steering compensation is lower than for the region where beam steering is compensated for. While this at first might seem counter-intuitive, since the maximum temperature was higher without beam steering compensation, it is an effect of energy conservation and the $T^4$ dependence on radiation. Given a fixed amount of energy, the highest possible mean temperature is achieved when the intensity is uniform over all the pixels.

Figure 36 Maximum and mean temperature with beam steering (black) and without beam steering (red).
One additional benefit of the DBI-T techniques compared to the TCP technique is that, since it actively measures the $KL$ values, they make it possible to measure the window fouling and then compensate for it. A passive technique such as TCP will be affected by soot deposited on the window from previous fired cycles and therefore the piston window should ideally be cleaned after every fired cycle. In Figure 37 the mean temperature during CAD 365 - 370 are shown for 10 consecutive cycles with and without compensating for window fouling. While the cycle variations are fairly large it is clear that the uncompensated temperatures follow a decreasing trend whereas the compensated temperatures do not.

The uncertainty of the DBI-T technique was also assessed using Monte Carlo (MC) simulations. As mentioned before, by actively measuring the $KL$ it is possible to avoid theoretical uncertainties. The uncertainties of the DBI-T system are thereby governed only by camera and calibration uncertainties.

One of the main sources of uncertainty is the effect of the time shift between the images used to measure $T_a$ and the consecutive images used to measure $KL$. Since the environment of the ICE is highly turbulent, it is important to

![Figure 37 Average temperature during CAD 365 – 370, for 10 consecutive cycles with (black) and without window (red) fouling compensation.](image_url)
minimize the timestep between these images. In Paper V, a framerate of 120 kHz was used, corresponding to a delay of roughly 8 µs between the images. By computing the difference $I_{\text{difference}}$ between two consecutive images $I_j$ and $I_{j+1}$ according to

$$I_{\text{difference}} = I_j - I_{j+1},$$

the extent of this error can be determined. A typical $I_{\text{difference}}$ image is shown on the left side of Figure 38 and the right side displays the frequency distribution of the $I_{\text{difference}}$ values. No distinct features are seen and the distribution seems to follow a normal distribution. Using a similar approach, the error in $I_0$ and $KL$ can also be estimated using a random normal distribution. The error in the calibration of the camera appears to follow a uniform random distribution ranging from ±10 % at the lowest intensity down to roughly ±1 % at the highest. In the MC simulation a pessimistic stance is taken and a ±10 % uniform random distribution is used all the time.

Figure 38 The result of $I_{\text{difference}}$ during 373 CAD. To the left as an image and to the right as a histogram.
In the leftmost part of Figure 39, the distribution of possible temperatures in a single pixel is shown. The displayed values correspond to pixel 50,64 of the 18 % case shown in Figure 35. The standard deviation is 7 K for this pixel at this specific CAD and cycle. To show that this distribution is representative of the overall DBI-T temperature distributions, the middle part of Figure 39 shows the standard deviation of the 50,64 pixel during three randomly chosen cycles. Likewise, the rightmost part of Figure 39 shows the standard deviation during a single cycle, for three randomly chosen pixels.

![Figure 39](image.png)

*Figure 39 Left: Temperature distribution of pixel 50;64 in Figure 35 according to the MC simulation. Middle: Standard deviation of pixel 50;64 at three different cycles. Right: Standard deviation of three random pixels during the same cycle.*

In paper V we develop DBI-T, a new soot thermometry technique. We show that, according to theory, it should be a more accurate technique than the widely used two color pyrometry technique. Effects of previously unaccounted factors, such as beam steering and window fouling, are quantified. Especially beam steering is shown to have a large impact on the maximum temperature distributions. Additionally, a Monte Carlo simulation is used to evaluate the standard deviation of the DBI-T temperature. According to this simulation the standard deviation is roughly 10 K. This can be compared to the various error estimations of two color pyrometry found in the literature which reports uncertainties of ± 60 K [79], -50 K and + 150 K [50]. It should also be noted that errors reported in these publications do not take beam steering effects and image lag effects into account. Furthermore, [50] uses a three color camera and when evaluating the temperature with the red and green channels as opposed to the blue and red channels, the average temperature decreases by more than 100 K while the KL values double. This suggests that the error due to uncertainties in α might be even larger than
assumed, further emphasizing the advantage of using a technique like DBI-T, which does not rely on determining the value of $a$ in order to obtain accurate temperatures.
6. Summary and outlook

This thesis provides further evidence for the idea that soot oxidation, not soot formation, is the dominating processes for determining engine out soot emission trends under conventional diesel conditions. PLII measurements of the instantaneous amount of soot at CA50 shows no correlation with the engine out soot emissions. On the other hand, PLIF measurements of the important soot oxidizer OH do show a correlation with the engine out soot emissions. Furthermore, LEM measurements show a clear correlation between the engine out soot emissions and the soot oxidation rate, where the soot oxidation rate is measured as decay of the $KL$ signal.

DBI measurements of small, close-coupled post injections reveal that the efficacy of the post injections on engine out soot reduction is largely affected by the soot oxidation of the post injection. The oxidation rate of the post injection is enhanced by the increased mixing caused by the entrainment as the injector is ramping down. As long as the entrainment wave catches up with the head of the post injection jet before it reaches the bowl wall it appears as if whole post injection is completely oxidized, at least under the engine conditions covered within this thesis. Following these findings, it would be interesting to perform DBI measurements on injection strategies where more post injections than one are utilized. It is not unconceivable that this could further reduce the engine out soot emissions. It would also be interesting to compare the same injection strategies that are investigated in this thesis, but with varied ramp down times of the injector since the ramp down time will affect the entrainment wave.

Furthermore, it would be of interest to perform DBI measurements at various wavelengths combined with line of sight PAH fluorescence. Since PAH absorption is wavelength dependent it could, at least in theory, be possible to couple a discrepancy between the $KL$ values measured with DBI at two
different wavelengths to the total amount of PAH. It would also be possible to distinguish whether the absorption in the early stages of a cycle is due to PAH or soot that has not reached high enough temperatures to be detectable by a NL camera.

DBI-T is a novel thermometry technique that is developed in this thesis. Theoretical comparison with the widely used TCP thermometry technique reveals that the temperatures measured with DBI-T are closer to the soot mass averaged temperature than the TCP. Additionally, DBI-T avoids several uncertainties associated with techniques such as TCP. For example, beam steering is compensated for, and direct measurements of $KL$ enable temperature measurements without relying on the uncertainty of the value of the dispersion coefficient $a$. It would be very interesting to continue development of DBI-T. For instance, in this thesis DBI-T measurements were only performed at a wavelength of 630 nm. Conducting simultaneous measurements at a different wavelength would hopefully confirm that the technique is as wavelength independent in practice as it is in theory. Performing measurements in axis-symmetric flames could also allow for a complete temperature mapping of the interior of the flame if DBI-T is used in conjunction with Abel inversion in the post processing.

One simplification, which all soot thermometry techniques that utilize Planck emission are based on, is that it assumes that the detected spectral radiance should follow the distribution of a single black body radiator, since a blackbody is a good approximation of soot. However, in reality the soot cloud is made up of many soot particles, each radiating as a black body. Therefore, the detected spectral radiance should likely be a super-positioning of several soot particles at temperatures distributed according to a Boltzmann distribution. It would therefore be interesting to see how the TCP and DBI-T temperatures are affected by employing a statistical model of several black body radiators radiating at different temperatures, but with the same mean temperature, compared to the temperatures obtained with the current use of a single black body radiator.
7. Summary of Papers

7.1 Paper I

A Study of In-Cylinder Soot Oxidation by Laser Extinction Measurements During an EGR-Sweep in an Optical Diesel Engine

Gallo, Y., Simonsson, J., **Lind, T.**, Bengtsson, P., Bladh H., and Andersson Ö.


In this paper the effect of in-cylinder oxygen concentration on soot oxidation rates are studied using a laser extinction measurement setup. It is revealed that the oxygen concentration plays a paramount role for determining the soot oxidation rates. Soot emission measurements reveal that reducing the O₂ concentration increases the soot emissions until the O₂ concentration drops to 9 %, during these conditions virtually no soot is formed, so despite the very poor soot oxidation rate the engine out soot emissions remains low. This further strengthens the belief that suppression of soot formation is not the most important parameter for reducing engine out soot under normal diesel operating conditions, soot oxidation appears to be the dominant mechanism.

*All of the experimental work was carried out together with Johan Simonsson. Yann Gallo participated during many of the experiments. Johan Simonsson wrote the Lab view code and Yann Gallo analysed the data. Yann Gallo was responsible for writing the paper.*
7.2 Paper II

Comparison of Laser-Extinction and Natural Luminosity Measurements for Soot Probing in Diesel Optical Engines

Li, Z., Gallo, Y., Lind, T., Richter, M., and Andersson, Ö.


The second paper compares the results from laser extinction measurements with those of natural luminosity measurements. It is revealed that, with the cameras setting normally used for natural luminosity measurements, there is a mismatch between the timing of extinction detection and luminosity detection. Despite the fact that the laser extinction measurement is only a point source technique and thus only measures a small fraction of the cylinder volume, extinction is detected well before any natural luminosity is detected anywhere within the cylinder. It is likely that this extinction arises due to liquid fuel droplets and soot precursors such as poly aromatic hydrocarbons.

In addition to these measurements a post processing algorithm was developed to compensate for window fouling.

The experimental work was performed together with Zheming Li and Yann Gallo. Zheming Li analysed the data and was responsible for writing the paper

7.3 Paper III

Simultaneous PLIF imaging of OH and PLII imaging of Soot for studying the Late-Cycle Soot oxidation in an Optical Heavy-Duty Diesel Engine
Lind, T., Li, Z., Micó, C., Olofsson, N., Bengtsson, P.E., Richter, M., and Andersson, Ő.


The third paper studies how engine out soot emissions are affected by varying swirl and injection pressure by using simultaneous PLIF and PLII. It is revealed that the extent of the PLII signal, which is correlated to the instantaneous soot distribution, has no correlation with the engine out soot emissions. However, the extent of the PLIF signal, which is correlated to OH, an important soot oxidizer, does correlate with the engine out soot emissions. It is also revealed that there is a non-linear relationship between engine out soot emissions and swirl with the intermediate levels of swirl producing the least amount of engine out soot emissions.

The experiments were conducted together with Zheming Li and Carlos Micó. Nils-Erik Olofsson calibrated the PLII setup. I was responsible for analyzing the data and writing the paper.

7.4 Paper IV

Mechanisms of Post-Injection Soot-Reduction Revealed by Visible and Diffuse Back-Illumination Soot Extinction Imaging

Lind, T., Roberts, G., Eagle, W., Rousselle, C., Andersson, Ő., and Musculus, M.P.B.


In this paper diffuse back-illumination soot extinction imaging, a novel optical 2D measurement technique, is employed to elucidate the mechanisms behind beneficial behaviour of certain types of post injections. It is shown that short closely-coupled post injection can be used to increase the work of an engine while the soot emission remains constant. Despite the fact that
much soot is formed in the post injection, it is revealed that all of the soot is oxidized inside the cylinder as long as the post injection is sufficiently short. The reason for this enhanced oxidation rate is largely due to the increased mixing caused by the entrainment wave.

*Experiments were carried out together with Gregory Roberts and Walter E. Eagle. I was responsible for analysing the data and Gregory Roberts performed the 1D-simulations to determine the position of the entrainment wave. I was responsible for writing the paper.*

### 7.5 Paper V

**Diffuse back-illumination temperature imaging, a novel soot thermometry technique**

**Lind, T.,** Roberts, G., Eagle, W., Andersson, Ö., and Musculus, M.P.B.

To be submitted to Combustion and Flame

In this paper a new optical soot thermometry technique is developed and utilized in a heavy-duty optical engine. Actively measuring the soot extinction at the same wavelength as the soot luminosity is measured allows measurements with lower uncertainties than the conventional two color pyrometry technique. The inherent beam steering compensation of the diffuse back-illumination soot extinction imaging further decreases uncertainties associated with other optical thermometry techniques such as the aforementioned two color pyrometry technique as well as those of laser based absorption/emission measurements.

Monte Carlo simulations of the uncertainty of diffuse back-illumination temperature imaging show that the standard deviation of the temperature measurements are in the order 10 K.
I performed the experiments together with Gregory Roberts and Walter E. Eagle. I had the main responsibility for method development and analysis of the data. I was the lead author of the paper.
7. References


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