High-speed optical and laser diagnostics - Internal combustion engines and gas turbine applications

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DOCTORAL DISSERTATION

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Abstract:

Increasing demands to meet regulations on combustion emissions and their environmental impact, and the need to improve their efficiency in different applications, have been the centre of focus in research and industry for decades. Optical and laser diagnostics have been proven to be amongst the best available tools due to their remote nature and non-intrusiveness, high spatial and temporal resolution, and their ability to investigate combustion processes and emissions in ways unprecedented before. In this thesis multiple optical and laser diagnostic techniques and their application in internal combustion engines (ICE) and gas turbines are presented.

Low temperature combustion concepts in ICEs including partially premixed combustion are implemented to increase efficiency and reduce emissions. The underlying mechanisms of these improvements are studied with optical techniques and complementary computational fluid dynamics (CFD) studies. In particular, multiple injection strategies and their effects are demonstrated in a heavy-duty optical engine.

Marine engines, due to their scale and different applications are less susceptible to the electrification tendencies seen recently in light duty engine industry. Optical investigation in an optical marine engine and dual fuel setup with methane as the main fuel and diesel fuel as pilot injection, provides insight on lowering the emissions and the usage of low-carbon fuels.

Modifications and optimizations of different parts in ICEs, including piston geometry, can increase fuel efficiency and lower emissions. A novel wave-shaped piston geometry and its effects on combustion processes and soot emissions are investigated with multiple optical and laser diagnostics, including natural luminosity, particle image velocimetry (PIV), and the results are compared to that of a conventional piston geometry.

Other than applications, a more diagnostic-focused study of different flow field measurements are presented. PIV is the established 2D flow field measurement technique in many applications. However, in contrast to its seemingly simple nature, it can be challenging and at times impossible to implement in certain applications. Instead of tracing particles, the same velocimetry algorithm is used on flame structures, and the semi-quantitative results are presented and compared to PIV technique.

Furthermore, these diagnostic techniques have been extensively implemented in a gas turbine model combustor. PIV technique combined with laser-induced fluorescence (LIF) of OH provides additional information about flow field and combustion processes simultaneously. The impacts of pilot flames, Hydrogen enrichment, CO_2 dilution are investigated and presented.

Keywords: Optical and laser diagnostics, Combustion, Internal combustion engines, Gas turbine combustors, Particle image velocimtery, Piston design, high-speed imaging

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September 2023

To my parents, Fariba and Reza

Table of Contents

Abstract

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Furthermore, these diagnostic techniques have been extensively implemented in a gas turbine model combustor. PIV technique combined with laser-induced

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Popular Science Summary

The earliest evidence for controlled use of fire by mankind are traced back to tens of thousands of years ago, however, the applications of combustion have expanded exponentially in recent centuries. Fire applications were limited to cooking, heating, source of light and safety for millennia. Fast forward now, a vast majority of energy sources in our daily life, transportation, industries, and other areas are directly related to combustion. These expansions in applications, along with all the immensely positive changes they have brought to our lives, have had some downsides as well. Fascinating developments in industries and transportation sector in early stages, have now turned into environmental challenges, with emissions and global warming, and the ever-increasing demand for energy sources are at the root of many economical and political hardships of recent decades. Simultaneously with developing combustion applications, endeavours to increase its efficiency and lowering unwanted emissions are ongoing.

This is where the field of combustion research comes to use. Amongst a variety of different methods, optical diagnostics techniques can provide a deep insight in what is seemingly a very multifaceted phenomenon, i.e., combustion. Rapid pace of chemical reactions, turbulence, and multi-physics nature of combustion have made it a challenging subject of investigation, and in recent decades, the use of optical and laser diagnostics have provided great breakthroughs. These techniques can provide temporally and spatially high-resolution information to study combustion processes.

One of the main areas in which combustion plays a pivotal role is automotive industry. Considering the vast number of internal combustion engines (ICE) in use and in production, even the slightest increase in their efficiency or emission control can yield great improvements. Research and development with this purpose is now more important than ever, and one tool at hand is optical and laser diagnostics.

Historically compression ignition (CI) and spark ignition (SI) engines consisted of two main categories of ICE. However, new combustion concepts have been suggested to reduce emissions including and not limited to partially premixed combustion (PPC). With a more complicated combustion concept, the need to implement new equipment in the engine and to investigate the effects of these new parameters to control is highlighted. For instance, multiple injection strategies which consist of pilot injection, main injection, and post injections have been shown to affect engine parameters. In current studies, these injection strategies were tested to find optimum configurations for engine performance.

Alternative fuel constitutes another pathway to the future of ICEs. Low-carbon fuels, and renewable fuels have been suggested and tested extensively. Such fuel sources, for instance methane, have the potential to reduce the greenhouse gases on one hand, and decrease our dependence on limited sources of fossil fuels. Here, a dual fuel concept is tested in a marine engine, consisting of a methane as the main fuel source, and a pilot injection of diesel fuel to ignite the mixture. An optical study on the ignition provides valuable information about ignition, combustion processes, and formation of NO_x emission marine engine industry, especially considering their reliance on ICEs as the main path road to the future.

Another influential area for improvements in ICE performance and emission control is engine parts design. More specifically piston bowl geometry in ICEs has shown great potential to influence how the engine performs. A wave-shaped piston bowl design, proved to help in reducing soot emissions. An optical replica of this design has been implemented in an optical engine and tested extensively to understand underlying mechanisms behind these improvements. Furthermore, a comparison of a conventional yet complicated flow field measurement, particle image velocimetry (PIV) with a rather similar technique named Flame image velocimetry (FIV) is discussed.

Gas turbine combustors are another area which benefit from optical and laser diagnostic tools. Despite their differences with ICEs, the goals to enhance performance, and avoid emissions are very similar here. Multiple simultaneous laser techniques, including PIV and laser-induced fluorescence (LIF), have been used to gather more information about the performance of gas turbine combustor model with different modifications. These modifications include the use of pilot flames, Hydrogen enrichment, and CO_2 dilution.

List of Papers

Paper I

M. Zhang, **S. Derafshzan**, M. Richter, M. Lundgren, Effects of different injection strategies on ignition and combustion characteristics in an optical PPC engine, Journal of Energy 203(2020), 117901

Paper II

M. Zhang, **S. Derafshzan**, L. Xu, XS. Bai, M. Richter, M. Lundgren, Transition from HCCI to PPC: Investigation of the Effect of Different Injection Timing on Ignition and Combustion Characteristics in an Optical PPC Engine SAE Technical Paper 2020-01-0559 (2020)

Paper III

M. Zhang, L. Xu, **S. Derafshzan**, XS. Bai, M. Richter, M. Lundgren, Impact of Multiple Injection Strategies on Efficiency and Combustion Characteristics in an Optical PPC Engine, SAE Technical Paper, 2020-01-1131 (2020)

Paper IV

M. Merts, **S. Derafshzan**, J. Hyvönen, M. Richter, M. Lundgren, S. Verhelst, An optical investigation of dual fuel and RCCI pilot ignition in a medium speed engine, Fuel Communications 9 (2021), 100037 (2021)

Paper V

M. Gong, **S. Derafshzan**, M. Richter, S. Hemdal, J. Eismark, O. Andersson, M. Lundgren, An Optical Study of the Effects of Diesel-like Fuels with Different Densities on a Heavy-duty CI Engine with a Wave-shaped Piston Bowl Geometry, SAE Technical Paper, 2023-01-0261 (2023)

Paper VI

F. Pignatelli, , **S. Derafshzan**, D. Sanned, N. Papafilippou, , A. A. Subash, R. Z. Szasz, , M. A. Chishty, P. Petersson, , XS. Bai, R. Gebart, A. Ehn, M. Richter, D. Lörstad, Effect of CO2 dilution on structures of premixed syngas/air flames in a gas turbine model combustor, Combustion and Flame 255 (2023) 112912

Paper VII

F. Pignatelli, D. Sanned, **S. Derafshzan**, R. Z. Szasz, , P. Petersson, , XS. Bai, A. Ehn, M. Richter, D. Lörstad, A. A. Subash, Impact of pilot flame and hydrogen enrichment on turbulent methane/hydrogen/air swirling premixed flames in a model gas turbine combustor, Submitted Manuscript

Paper VIII

M. Gong, **S. Derafshzan**, M. Lundgren, M. Richter, S. Hemdal, J. Eismark, O. Andersson, M. Lundgren, Optical diagnostic study on imporving performance and emission in heavy-duty diesel engines using wave-shaped piston bowl geometry and post injection strategies, SAETechnical Paper, 2023-24-0048 (2023)

Paper IX

S. Derafshzan, M. Gong, F. Lewiski, A. Matamis, S. Hemdal, J. Eismark, O. Andersson, M. Lundgren, M. Richter, Optical and laser diagnostics on the effects of wave-shaped piston geometry in a heavy-duty CI engine, Submitted Manuscript

Chapter 1. Introduction

Combustion of fuels has been the main energy source in the last century, and this trend is likely to continue in the upcoming decades, according to the data from International Energy Agency (IEA) [1]. Combustion of coal, oil, and natural gas historically provided a big portion of energy supply, and this statement is still valid for energy sources in 2020s. A major proportion of this energy consumption is in transportation sector, and internal combustion engines (ICE). However, other areas of combustion application in energy sector play a significant role as well.

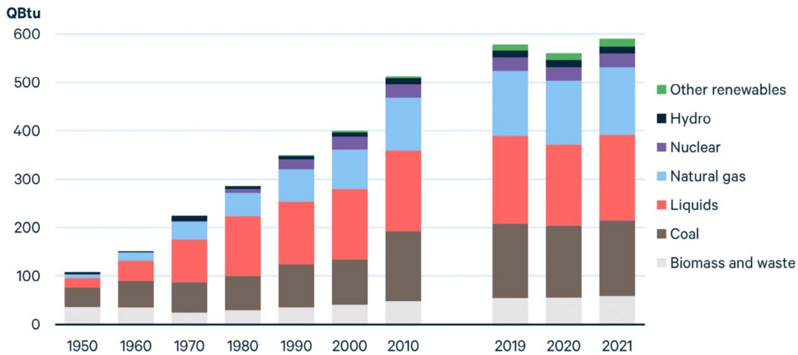

Figure 1.1. Global primary energy daemand by source, IEA

Combustion is a complex phenomenon which involves a great number of chemical reactions, thousands of different species and radicals, and the occurrence of multiple physical and chemical reactions simultaneously. To have a deep understanding of combustion knowledge of chemical kinetics, turbulence and flow dynamics, thermodynamics, heat and mass transfer, radiation, and pollutant formation is a necessity. Despite the widespread use of combustion, there is still questions that need to be answered and challenges to overcome.

Limited resources of energy on one hand and increasing regulations on unwanted emission of combustion on the other hand increase the importance of efficient and clean combustion. The importance of global warming and colossal challenges that it imposes on the environment, and pollutant from combustion such as soot and NO_x that are hazardous for mankind cannot be overstated. Attempts to lower these emissions or ideally to eliminate them are vital to have a sustainable future.

Various research tools and methods are dedicated to increase the understanding of combustion and reaps the benefits of this knowledge to make it cleaner and more efficient. Considering the complexity of combustion, investigation of combustion from different viewpoints and within different fields of studies is not only beneficial but also necessary. Optical and laser diagnostic techniques in reacting flows are important means to deepen our understanding of combustion. These techniques are essentially gateways to observe and examine combustion processes, are amongst these methods. Over the past decades, several optical and laser diagnostic techniques were developed and applied in the field of combustion research for different purposes, and these techniques and their applications are the main subject of this thesis.

Multiple optical and laser diagnostics techniques were conducted in this work, to investigate combustion in different application cases including heavy-duty and marine engines, and gas turbine combustors. Through the use of these techniques, the role of injection strategies in heavy-duty engines, the use of dual-fuel in maritime engines, novel piston designs and their effects in combustion processes, and alternative fuels in gas turbine model combustors were investigated and results and findings are presented in this text.

The thesis contains 6 chapters. After introduction in current chapter, optical techniques and methods are shortly introduced in the chapter 2. This brief introduction serves to main the coherence of the text rather than being an attempt to provide comprehensive description and details of each technique. Experimental setup and equipment are introduced in chapter 3 including the equipment used for optical studies, i.e., detectors and lasers, and the apparatus under investigations such as optical engines and gas turbine combustors. Chapter 4 covers analysis methods, mainly discussing analysis steps that important to this work. Image analysis, and flow field techniques' analysis constitutes a majority of this chapter. A summary of results from different studies of this thesis are discussed in chapter 5. Furthermore, some notes and considerations about the implementation of these experiments or relevant information is covered in this chapter. Finally, chapter 6 concludes this text and provides and outlook for future studies.

Chapter 2. Methods and Optical Techniques

In this chapter the principle of the optical techniques implemented in this work is introduced. First, natural luminosity imaging is discussed, followed by elastic Mie scattering, and laser-induced fluorescence, and lastly, two techniques for flow field measurement, particle image velocimetry and flame image velocimetry are discussed.

2.1. Natural Luminosity

High speed imaging of combustion natural luminosity provides valuable information about combustion processes, despite its relative simplicity of implementation compared to laser diagnostic techniques. The light captured in this technique consists of chemiluminescence of different molecules, and black body radiation of glowing soot particles. Combustion consists of a great number of chemical reactions, and many intermediate species and radicals are formed in these reactions.

Chemiluminescence is radiation emitted by excited molecules which are produced in chemical reactions as they de-excite back to their ground energy level. Molecules have specific energy levels and this chemiluminescence radiation is wavelength specific for different molecules and it is usually possible to single out and detect specific emissions from different molecules. Some of intermediate species in combustion processes are more commonly traced as they provide valuable information about different stages of combustion. OH, CH, CH2O and other molecules, are specifically informative about combustion, flame front and temperature. These molecules can indicate structural regions in a flame, including preheat zone, reaction zone, and product zone.

Black body radiation from soot particles is another source of radiation detected in this method. Glowing soot particles which are formed in hot temperature reacting environment emit light. Broadband radiation of soot particles is temperature dependant and follow Planck's law. This signal increases greatly in fuel-rich mixture combustion as soot is more prevalent.

The ratio between these two signals can differ depending on many factors including combustion regime, fuel type, and other factors. However, black body radiation from soot particles usually has higher intensity. It is important to consider that natural luminosity imaging is a line-of-sight technique and the signal is accumulated through the optical volume. Figure 2.1 is an example of high-speed imaging of natural luminosity of combustion in an optical engine to demonstrate flame propagation in combustion chamber.

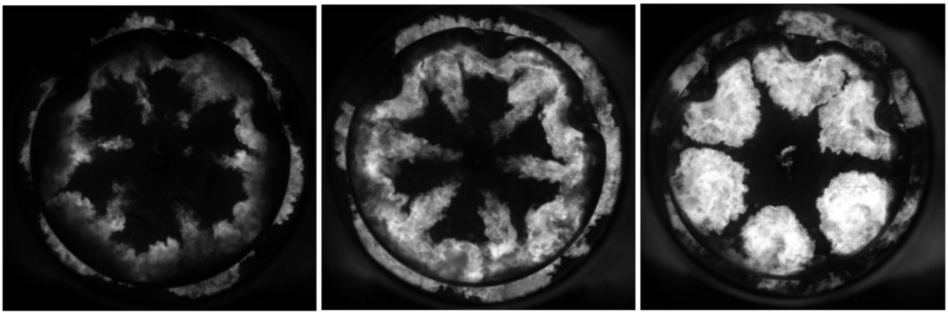

Figure 2.1. Natural luminosity images of Combustion in a heavy-duty optical engine with wave piston

2.2. Mie Scattering

Elastic light scattering is the phenomenon of scattering light by molecules or particles without a change in their energy and wavelength [2]. There are two regimes of elastic scattering, Mie scattering, and Rayleigh scattering. Mie scattering is referred to the scattering of light from the particles with the size equal to or larger than incident laser light wavelength. Rayleigh scattering which describes the scattering of light when the wavelength is smaller than particles size, however, the scattering of such small particles, and their weak detectable signal is not discussed in this work. Mie scattering signal can be used to visualize injected fuel spray inside an optical engine (Figure 2.2).

Figure 2.2. Natural Fuel spray visualization with high-speed imaging of Mie scattering in optical engine.

2.3. Laser-Induced Fluorescence

Laser-induced fluorescence (LIF) is another laser diagnostic technique which is used extensively in combustion research. LIF is light emitted from an atom or molecule relaxing from a higher energy state, which was initially excited by absorption of laser light [2].

LIF has the advantage of being species-specific since different atoms and molecules have different energy levels and the energy differences between these levels are unique (Figure 2.3). This proves to be advantageous since interference from other sources such as background fluorescence can be filtered. A great number of species, molecules, and radicals are formed in chemical reactions of combustion. A few of these molecules such as OH, CH, and CH_2O are more important as they are indication of flame front, temperature estimation, and fuel decomposition. LIF measurements of these species can provide valuable information about the combustion processes.

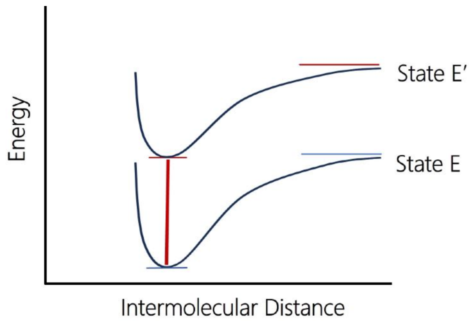

Figure 2.3. Energy diagram of a molecule

LIF is used extensively as a laser diagnostic technique in combustion research, as it is capable of detecting species down to hundreds of ppb, making it a great tool for short-lived low-concentrated species available in combustion reactions. It is used as qualitative and quantitative tool and can be achieved in 2D (planar) or 3D (volumetric) studies. In short, LIF capability to target specific species in reactive flows, along with high temporal and spatial resolution has made LIF a powerful technique.

2.4. Particle Image Velocimtery

Flow field measurements are of great importance in a variety of applications, including combustion research. Mixing processes, flow movement, and turbulence play a vital role in combustion, and particle image velocimetry (PIV) is an established technique to visualize the flow field [6,7].

The basic principle of this technique is to track the movements of particles floating in the measurement environment and assigning their velocity to the flow of that environment. As these particles move, they scatter the incoming laser light, and their movements can be recorded in two consecutive frames. In a simple illustration in Figure 2.4. in the first frame, the particles are located certain locations (pixels) in the image, and as they move, their new location is captured in the second image. By tracking this dislocation, and knowing the time in which this displacement happens, velocity vectors can be assigned to small areas of the image or interrogation windows (IW).

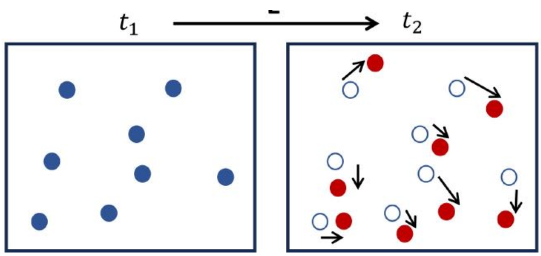

Figure 2.4. An illustration of moving particles in PIV measurement

Velocity vectors calculations are based on cross-correlation algorithms to predict probable destination of groups of particles residing in each of the IWs [8]. A simple schematic of a PIV experimental setup and its working principle is demonstrated in Figure 2.5. A set of two laser pulses with a short known intraframe time between them is used to illuminate the plane of measurement, and the movement of particles are tracked by imaging the scattered light from them onto the camera sensor [9]. Certain criteria for choosing particles, laser light, and the recording system should be considered independently in different applications which are further discussed in chapter 4.

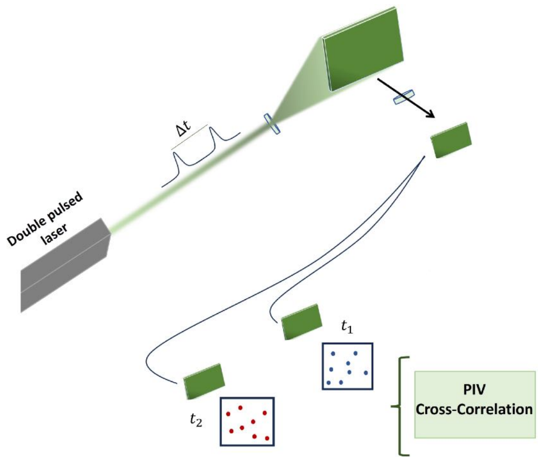

Figure 2.5. A schematic setup for PIV measurement and its working principle

2.5. Flame Image Velocimtery

Despite its wide application in flow field visualisation, PIV has shortcomings which make it hard and, in some applications impossible to utilize. However, the underlying principle of PIV which is tracking small particles and assigning their movements to flow field can be used in a different way. In combustion, glowing soot particles, can be regarded as the moving particle of PIV, and by running the images with the same cross-correlation algorithm of PIV, flow field can be extracted [10,11]. This technique is referred to as flame image velocimetry (FIV).

This technique which is also referred to as combustion image velocimetry (CIV) benefits from its rather simplicity of application in comparison to PIV, as neither seeding particles nor laser source is needed, and the bright patterns in reactive environment, i.e. the movements of the flame between two consecutive natural luminosity images is tracked.

The advancements in detector technology and access to high-speed cameras with high resolution makes this technique a capable tool. High temporal resolution of the measurement is vital to be able to track the movements of the flow between two frames, and their high spatial resolution makes it possible to track smaller features otherwise overlooked.

While the straightforward nature of this approach is appealing, the obvious disadvantage is related to the detected signal, which is accumulated over the line of sight. The importance of this shortcoming can varry in different cases, depending on how non-uniform the flow is the axis perpendicualr to the sensor, or how long this dimension is in the flow. Regardless, FIV can provide qualitative understanding of the flow in most cases.

Chapter 3. Experimental Setups and Equipment

In this chapter the experimental equipment and setups used for studies in this thesis are illustrated. The equipment is divided in four categories, light sources (lasers), detectors including high-speed CMOS and ICCD cameras, optical engines based on heavy-duty and marine engines, and gas turbine combustors. These devices were used in several research projects to measure natural luminosity, fuel injection, flow field and combustion processes in ICEs, and Gas Turbines.

3.1. Light sources

Most of the optical techniques utilized in this work included illuminating light source of lasers. A short description of these lasers, along with the criteria for choosing them in different projects are discussed here.

3.1.1. Diode laser

Conventional laser systems which are typically used in the field of laser diagnostics have the advantages of having high power output, short pulses, high repetition rates, or a combination of this factors. However, these capabilities are inherent with an obvious disadvantage, a large footprint. While this trade-off is usually neglected, in some applications the advantage of size along with less demanding expectation of the laser light directs the setup equipment in other directions. Laser diodes with their smaller size can be of use in these situations where the complex setup and unforgiving environment around an optical engine is prohibitive. Laser diodes can be small, so small that the whole system around them can fit in one hand, and still have high coherence as a light source and their use are convenient and cost effective. The power output suffers from this small footprint; however, it can be high enough

for some applications, including its use in this work for illuminating fuel sprays in Mie-scattering regime.
For this purpose, a laser diode with in-house design, that only consists of the diode, power adapter, small cooling fan, and a diverging lens mounted in front of it is used. The output is a continuous wave diverging sheet profile of light at 452 nm wavelength and 2-Watt power [12]. This blue light is used for imaging of sprays, and it was mounted in front of an optical window to illuminate the fuel spray inside the cylinder.

3.1.2. Nd: YLF dual-cavity laser

For PIV measurements included in this thesis, Nd: YLF (neodymium-doped yttrium lithium fluoride) solid-state laser is used. This specific dual-cavity design makes the laser suited for PIV measurements since the two cavities can be operated separately allowing for the time separation of image pairs in PIV measurement to be chosen as needed and not being limited by the pulse rate of a single laser. This flexibility is pivotal in PIV, and it is not to be confused with the temporal resolution of the experiment. The temporal resolution is limited by the repetition rate of any of these single cavities, however, to be able to capture the flow movement the time separation needs to be flexible and tuneable beyond the repetition rate limits. The Q-switched Nd: YLF laser with output wavelength of 527 and approximately 30 W power at 1 kHz repetition rate is used for PIV measurement in this thesis. The time separation between two pulses was chosen according to each experiment, in optical engine it was set to 15 μs for instance.

3.1.3. Dye laser

Laser light characteristics of LIF measurements differ from PIV as the capability of tuning the output wavelength and the pulse energy is of utmost importance. The change in wavelength allows to select different species depending on their energy level, and the laser pulse energy should be high enough to increase the quality of recorded LIF signal. For this purpose, a tuneable dye-laser pumped by a Nd: YAG laser is used in current work.

The pulse duration of Nd: YAG laser is typically close to 10 ns, which is generally fast enough to capture different phenomena in combustion applications. The wavelength of Nd: YAG lasers is 1064 nm, in IR. Using second, third, and fourth harmonic generator (SHG, THG, FHG), 532, 355, and 266 nm laser wavelengths are achieved, which can be used for LIF measurements. However, in current work they were only used as a pump for the dye laser. Second harmonic generator (SHG) output of the Nd: YAG laser at 532 nm was used to pump the dye laser. Rhodamine 590 was used as dye in the dye-laser, and wavelength was tuned to 283 nm after a frequency doubling of the output. This wavelength is selected to target OH.

3.2. Light detectors

Light detectors play a vital role in optical and laser diagnostic techniques. Different techniques have different criteria for detectors. In combustion related research, the rate and length scale of the phenomena under study calls for fast and precise detectors to make high spatial and high temporal measurement achievable. Several optical detectors with different technologies were used in this thesis and while the detailed description of these detectors is beyond the scope of this text, an overview of their strength and weaknesses can be relevant as it clarifies their application cases.

Most research projects in this thesis include high speed imaging, and CMOS detectors were used for this purpose. CMOS stands for complementary metal-oxide semiconductor and high-speed CMOS cameras can reach extremely high sampling rates. Historically these detectors were not the most sensitive detectors in light-collecting compared to other technologies and speed was their major advantage. However, higher sensitivity CMOS cameras such as "scientific CMOS" or sCMOS emerged recently, combining the high-speed recording rate with better sensitivity and performance.

Two different models of CMOS cameras, Photron FastCam SA-X2 and SA-Z were used here, which are capable of recording at 12500 and 20000 fps with full frame resolution of 1 MP (1024 x 1024 pixels). Considering the limited optical access of an engine, and the need for higher sampling rate in combustion processes different settings with slightly lower resolution and higher fps recording were chosen in different applications. Regardless, these cameras were capable tools in recording different phenomena.

Another type of detectors in current study is charge-coupled device (CCD) cameras [13]. Intensified CCD cameras (ICCD) are well-suited for applications were higher sensitivity for detecting incoming photons are needed. This higher sensitivity is usually at the cost of having lower sampling rate. ICCD cameras were used in PLIF measurements inside gas turbine combustor in this work.

3.3. Optical engines

Internal combustion engines typically have no optical access for observation and investigation of different phenomena inside the combustion chamber. While conventional engine research depends on other methods of sensing, including pressure sensors, emission control and similar tools, optical engines were designed to take advantage of optical and laser diagnostics techniques in engine research and development. Optical engines are designed based on their normal metal engine counterparts with modifications to provide optical access to the cylinder and combustion chamber. This optical access is usually provided through the implementation of optical windows and glass pistons. A common optical engine design is Bowditch design [14], which consists of a see-through glass piston, usually made of quartz, side windows or fully glassed liner and a 45-degree mirror at the bottom of the cylinder, providing optical access form the sides and the bottom, respectively.

In Figure 3.1 an optical engine based on Volvo MD13 heavy duty engine and the experimental setup for laser diagnostic measurement is demonstrated with an image and schematically. Optical engines in this work were designed by extending one of the cylinders to accommodate optical components and provide optical access. Other cylinders are fitted with tungsten weights to counterbalance the weight of this extended liner. Cylinder head design is similar to normal production engine. Below that extended liner and optical piston Bowditch mirror is mounted with 45-degree angle towards the liner axis. This mirror provides a bottom to top view of the combustion chamber and is usually made of Aluminium with UV enhanced coating. The detectors, i.e., cameras or spectroscopes, are placed in front of this mirror to capture the signal.

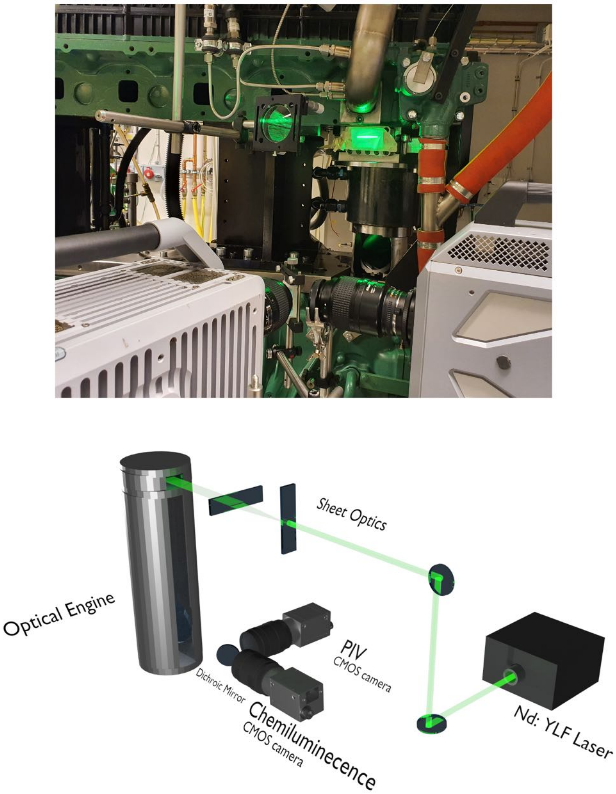

Figure 3.1. Heavy-duty optical engine, Volvo MD13, and PIV-FIV experimental setup (top), Schematic illustration of the setup (bottom)

Optical components are made of quartz due to its durability in harsh conditions inside an engine and transparency to visible and UV segment of electromagnetic spectrum which allows the implementation of optical and laser diagnostics techniques. These components include optical windows or fully quartz liners, and optical pistons. Quartz has lower heat conductivity compared to metals in the piston and heat transfer from quartz is not as efficient as metal. Higher surface temperature of optical components in an optical engine can change the combustion processes, for instance start of combustion can happen earlier in the cycle compared to normal engine of the same design. This issue is addressed by using skip-fire mode, having a few combustion cycles followed by several motored cycles. Running optical engine in skip fire mode is also advantageous in maintaining optical components and avoiding extreme thermal load that can cause damage.

Optical pistons and their design are especially important not only due to their effects on engine performance, but also for acting as the glasses through which combustion is observed [15,16]. Different designs of optical pistons were used in this work, from a more conventional re-entrance bowl shape design to Volvo wave piston (Lunda-wave) []. While the general aim is to design optical pistons as close their metal counterpart as possible, different needs make it necessary to have slight changes in certain applications. A flat piston configuration is sometimes used to avoid the distortion and loss of optical access to combustion chamber. Lunda-wave which is inspired by Wave design, differs in the way that it has a flat bottom, thus avoiding the need of image distortion correction, and it has waves only on one side of the piston bowl. Having waves only on one side prohibits light deflection from wave protrusions. Moreover, this design makes it possible to compare the wave effect visually to non-wave side.

Another optical engine in this thesis is the modified Wärtsilä W20DF marine optical engine. This six-cylinder dual fuel engine with 200 diameter bore was used to investigate dual fuel combustion. Modifying the engine for optical design is very similar to what is described previously in heavy-duty engine, however, engine’s footprint which is noticeably larger posed technical challenges. Furthermore, this optical engine has four optical windows accessing the combustion chamber.

In Figure 3.2 the schematic of the elongated cylinder of the optical setup is demonstrated. Other cylinders are fitted with weights, and the engine was run in skip-fire mode. The glass sections of the setup, Bowditch mirror, piston, and optical windows, are displayed with yellow colour [17,]. Operation of this engine, lab environment and the vibrations were seriously prohibitive for the use of laser, and high-speed imaging of natural luminosity was opted instead.

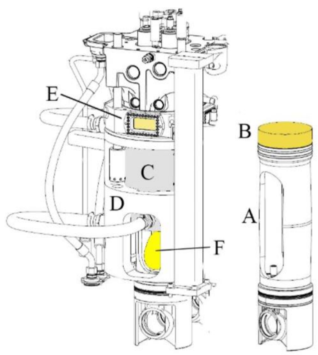

Figure 3.2. A schematic of Wärtsilä optical engine and optical components (yellow parts) [17]

3.4. Gas turbine combustor

Gas turbines are rotary engines commonly used in aviation and for electric generation in stationary applications. Similar to ICEs, increasing efficiency and reducing emissions amongst main goal for gas turbines research and development. Optical and laser diagnostic techniques can help increase the understanding of combustion processes in gas turbines.

A gas turbine consists of three main stages: compression stage, combustion stage, and expansion stage. The intake air is compressed to a high pressure and temperature in the compressor at first. This high pressure compressed air is then mixed with the fuel and combusted in the combustion chamber. This combusted mixture with high energy content is directed to the turbine and the energy is transferred to turbine's blade. The spinning of these blades produces mechanical energy which can be used to general electricity or propel aircrafts.

In this work a gas turbine combustor model with swirl burner called CeCOST burner is used. A schematic of the burner is shown in Figure 3.3, and more detail can be found in papers VI and VII and [19,20]. The possibility of having less restricted optical access in this burner further increases the appeal of optical and laser diagnostics.

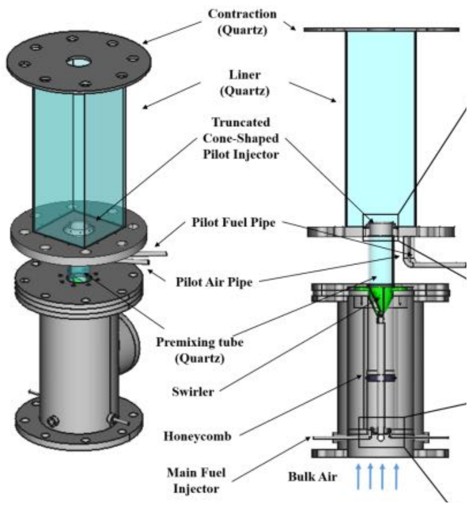

Figure 3.3. CeCOST gas turbine combustor model [20]

A schematic of the experimental setup for this burner is illustrated in Figure 3.4. Optical access to the burner is well suited to accommodate the possibility of performing multiple simultaneous diagnostic techniques with very few limitations. PIV and LIF laser sheets are overlapped and passed through the central plane inside the glass container around the burner. OH PLIF camera is mounted perpendicular to this light sheet on one side, and PIV and chemiluminescence cameras are mounted in the opposite site. Seeding the flow is also less challenging compared to optical engines both in better control of seeding density and slower rate of accumulation on surfaces.

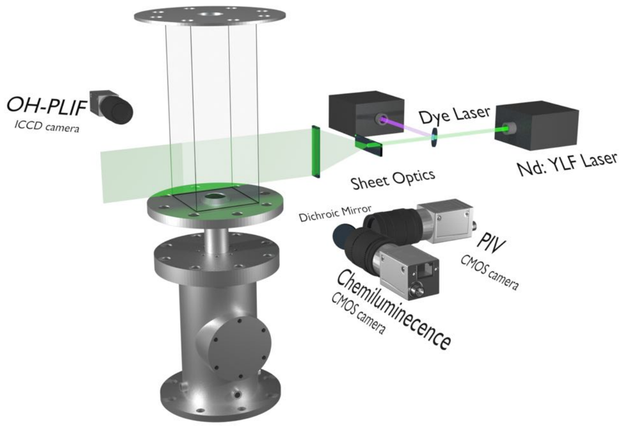

Figure 3.4. Experimental setup in gas turbine combustor, Chemiluminescence, PLIF, and PIV

Chapter 4. Analysis Methods

In this chapter, the analysis methods including image processing, post processing of the optical results, flow field techniques and its algorithms are discussed with a focus on the sections that are not discussed in the papers.

4.1. Image Analysis

Optical and laser diagnostics rely heavily on images since they are the major representation of the results. Great attention goes into planning, implementation and the extraction of the data during the measurements. The followup step which is the analysis of recorded data in image form can be decisive as well. Different sections of this work that has benefited in a major way from these anlysis are mentioned in this section. This is a highlgiht of impportant aspects rather than being an exhaustive description of every steps in image analysis.

4.1.1. Image distortion correction

Glass components in an optical engine can cause distortion in the image due to their curvatures. These curvatures exist either in the optical windows or fully quartz liners which usually have the same curvature as cylinder’s interior surface, or curvatures of the optical piston. Optical pistons are usually designed to replicate their metal counterparts which results in a variety in their shape, for instance bowl-shape designs or stepped lip designs [45]. Due to the interaction of light with these curved surfaces the recorded images are distorted, and image distortion correction algorithms must be utilized.

A target paper with checkerboard patterns with known size and pattern is placed in the experimental setup where the flow is detected by comparing the distorted image with the actual pattern in normal condition, image transform algorithm in MATLAB© is implemented to correct the distorted image (Figure

4.1). This is done by tracking the boxes in checkerboard and their dislocation and creating a transformation matrix to convert this distorted image to its normal shape [12]. The same inverse transformation is then used to correct all the combustion natural luminosity images accordingly. This is an important step to extract morphological and quantitative information from the images when the piston is curved. Furthermore, this target paper can be used to calculate the image ratio of the experiment i.e. mm/pixel conversion ratio.

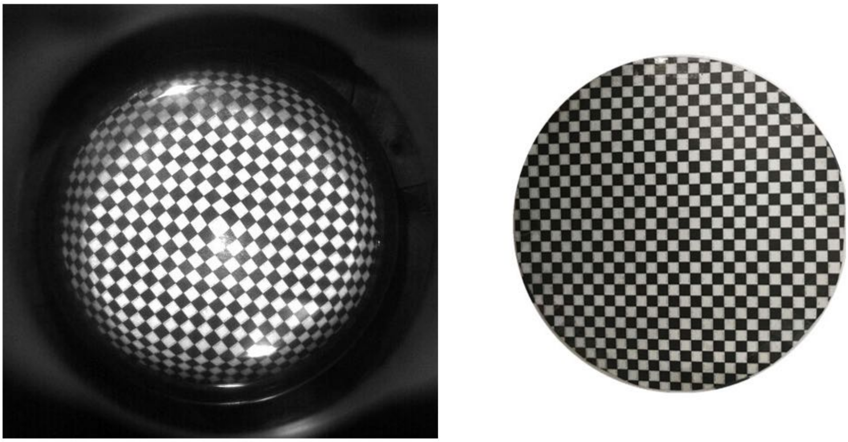

Figure 4.1. Distortion of target image inside the optical piston (left), target image(right)

Image pre-processing in PIV

In PIV, like other techniques, the goal of image manipulation is to bring forward the part of the detected light that are of interest and to remove or lower unwanted background signal. In PIV measurement, light scattered from the seeding particle is the signal and the aim is making this signal stand out from other sources. There are several steps to accomplish this goal including and not limited to masking the areas without flow or areas in which particles don't reside, removal of background light from different sources such as scattered light from reflections or the flame luminosity.

Background flame luminosity and stationary structures from the image such as the edges of valves and injector are removed using sliding square kernel. Furthermore, normalizing the image increases the contrast which improves the visualization of particles with weaker scattering. More steps including binarizing the image are suggested in the literature [21]. However, having variations in the scattered light from particles is helpful in cross-correlation algorithms as they increase the distinction of a group of particles in an IW.

Figure 4.2 shows a sample raw PIV image and the steps to pre-process the image before feeding it to the PIV software. The masked area which are highlighted with red colour is the edges of the piston bowl and the protrusion is the wave structure of the piston and flow field is calculated inside the piston bowl. Truncated part of each image separates the part of the plane that illuminated with laser sheet. Laser light is entering the combustion chamber through the optical window (bottom of the image) and it expands inside the combustion chamber, and a rectangle with the width of laser sheet entering the chamber is selected for analysis.

To the left, a reflection of laser light from the wave illuminates adjacent intake valve and creates a source for background noise. Piston bowl edges also scattered the laser light. A high pass filter with the size of 5 by 5 pixel can remove these structures while maintaining the seeding particles (middle). Furthermore, intensity capping function is used thresholding the intensity and increasing their intensity. This procedure was performed for PIV measurements in motored condition, and while similar approach takes place in reactive flows, the details of image pre-processing varied in different flow and lighting conditions. Yet the goal in this step is straightforward, removal of other sources of light as much as possible and to increase the detectability of seeding particles.

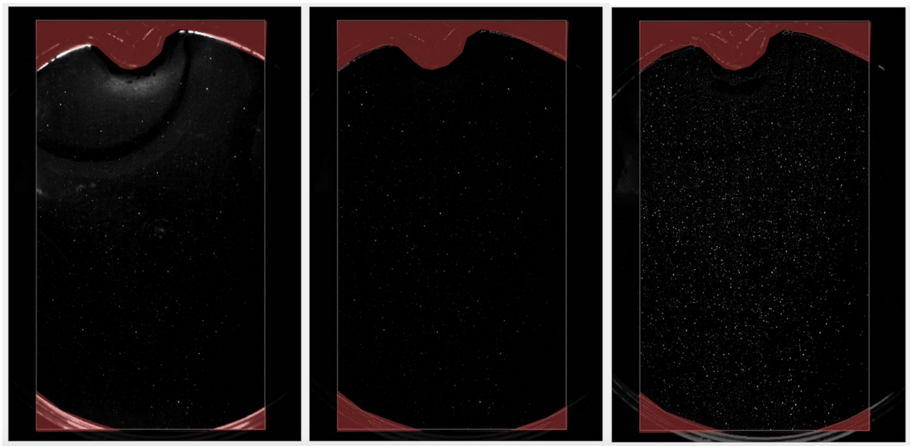

Figure 4.2. Image pre-processing for PIV, raw image(left), high pass filtered (middle) and intensity capped (right)

In reacting flows during fired cycles, additional sources of light needed to be dealt with. In Figure 4.3. sprays scatter the laser light were removed in pre-processing of the images. Additionally, the scattered light from the optical window entrance, piston bowl edges, and wave structures are stronger compared to previous figure. This is in part since in fired cycles laser power was increased to keep the detectability of seeding particles despite strong flame luminosity.

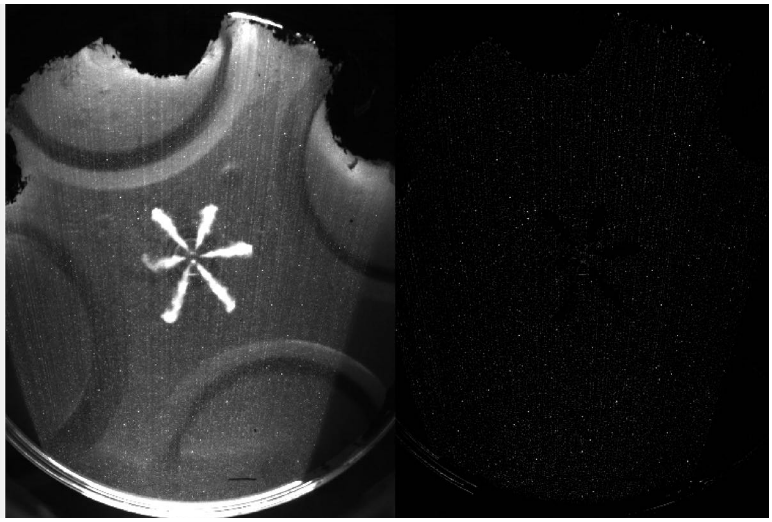

Figure 4.3. Raw PIV image in reacting flow with sprays, and pre-processed image (right)

4.2. Flow Field Techniques

Optical and laser diagnostic techniques are commonly used for velocity measurements. From laser doppler velocimetry (LDV) which is applicable for point measurements of velocity to tagging velocimtery techniques like molecular tagging velocimtery (MTV) to follow the movements of single particles, these techniques offer different advantages in certain applications. Particle image velocimtery (PIV) became increasingly popular in flow field measurements in planar 2D measurements with planar PIV, stereoscopic PIV and volumetric PIV measurements with advanced laser and camera systems.

Velocimetry measurements in reactive flows are performed using PIV technique to demonstrate the flow field [22]. The principle of this technique was discussed in chapter 2. Here, details about experimental procedure and analysis of the data are focused on. First a simplified PIV setup is presented followed by practical considerations in performing PIV measurements. These technical aspects are not always discussed in research publications, however, having an understanding of them can be useful for similar measurements.

A typical experimental setup for PIV is illustrated in Figure 4.4. Laser light source, usually at 532 or 527 green light, is formed to a thin plane inside the targeted area of the flow, and the scattered light from seeding particles are recorded. These seeding particles are added to the flow and are chosen so that they can follow the flow without causing changes in flow pattern thus maintaining the non-intrusiveness of the technique. A pair of laser pulses with short time separation between them illuminates the plane and the scattered light is recorded on the camera. The movements of groups of particles are tracked in smaller areas of the image, or interrogation windows (IW) to calculate velocity vectors for each of these IWs with cross-correlation algorithms.

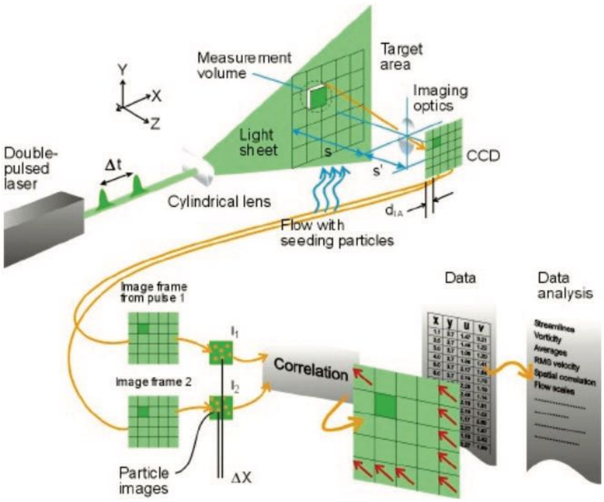

Figure 4.4. A schematic representation of a PIV measurement [9]

Technical aspects in PIV measurements

There are certain criteria for a successful PIV measurement, which can be considered as general guidelines rather than a fixed set of rules, some of which are discussed here [22].

One of the first steps in PIV measurements is choosing seeding particles [23,24]. Two main criteria for this choice are the possibility of following the flow and the practicality of their use in certain environment. In reactive environments they must withstand extreme heat and pressure and metal oxides such as TiO_2, SiO_2, or Al_2O_3 are amongst typically used candidates.

Other than the practical aspect, it is of utmost importance that these seeding particles can follow the flow, i.e. their movements can be attributed to the flow movement. This characteristic is usually based on a dimensionless number, Stokes number (St) which is the ratio of particle relaxation time to the inherent flow time [6] :

$$St = \frac{t_p}{t_f} = \frac{t_p}{\frac{L_0}{U_0}} = \frac{t_p U_0}{L_0} \qquad \text{Eq. 4.1.}$$

Where t_p is particle relaxation time and t_f is the characteristic time of the flow. U_0 and L_0 are the velocity and dimension of the flow respectively, and relaxation time is calculated by eq:

$$t_p = \frac{\rho_p d_p^2}{18\mu_f} \qquad \text{Eq. 4.2.}$$

Where particle density and diameter are ρ_p and d_p and μ_f is flow viscosity. Low Stokes number means that seeding particles are neutrally buoyant in the flow, for instance Stokes value of 0.01 is considered acceptable in this regard [25].

Furthermore, high seeding concentration inside the measurement plane and uniform distribution of them are considered merits. Higher seeding concentrations increases the ability to capture smaller scale flow patterns and increase the spatial resolution of the measurement. However, this is not an achievable goal as the reactive environment and its turbulent flow, and technical challenges of adding these particles to the device usually limits the upper limit for seeding concentration. In practical applications the lower limit can be more concerning due to the fact that with a dispersedly seeded flow it is not possible to track the movement of smaller groups of seeding particles movements. It has been suggested [6] that having approximately 8-20 particles in each IW can guarantee the quality of the extracted velocity vectors.

In practical applications in reactive environments, achieving this condition is sometimes hindered due to different factors. First, an excess of seeding can saturate the detector and the flow structures are lost in that situation. Furthermore, windows staining as a result of accumulation of these particles is another challenge, which is usually mitigated by running the experiments in shorter periods of time. Finally, the high pressure inside combustion chamber can push these particles away from the flame and decrease their concentration in certain areas of the measurement plane.

Another criterion that needs to be tuned in each application is the time separation between the two laser pulses (ΔT). The time separation should be fast enough so that the movements are captured, yet not so fast that the two frames are technically frozen in time! The displacement of ¼ of the final IW as a rule of thumb is suggested in the literature [].

In design and implementation of a PIV setup, the thickness of the laser sheet is an important factor since a thick light sheet, records the out of plane movement, which is desirable for 2D3C stereoscopic PIV but degrades the quality of 2D planar PIV measurements. A thin laser sheet with sub-millimetre thickness is good for this application.

In order to calculate the displacement of particles in the images, i.e., converting pixel shift to physical displacement, a calibration is necessary. This calibration also shows the optical magnification of the optical setup. In 2D planar PIV, calibration can be achieved simply by having a 2D object in the plane of imaging, a ruler or any other measure that can translates length scale to pixel number and vice versa.

4.3. PIV and FIV algorithms

Cross correlation algorithms are used to calculate the velocity of seeding particles. For this purpose, each pair of images are divided into smaller sub images, or interrogation windows (IW), and the movements of particles in these sub-images are estimated. While cross-correlation of these sub-images is the main function of PIV calculations additional post-processing steps such as removal of erroneous vectors, thresholding the results, smoothing the vectors can be performed. Software packages for PIV can calculate other flow related properties such as turbulence kinetic energy (TKE).

Commercial softwares for PIV cross correlation algorithms, including Lavision and Dantec. These commercial softwares are usually part of a whole PIV setup including lasers and cameras and are designed for those equipment. However, an open access PIV software, PIVlab was used in this work [26,27]. PIVlab works in Matlab environment as a plugin program. Choosing an open source PIV package was deliberate even though access to commercial packages were possible for research projects in this thesis. The reasons to opt for PIVlab was mainly the freedom it provides with experimental setup and hardware, and the level of control in working with the software. The possibility of using the software on any sets of data independently from the hardware was favorable especially in FIV measurements. In FIV flame natural luminosity and its development is tracked and it differs from PIV both in recording of the data and in processing it.

It is also possible to access and modify PIVlab functions in Matlab or use them elsewhere and software settings for pre-processing, post processing and other steps are abundant. PIV results from PIVlab and commercial softwares were compared where previous data from the commercial software were available. While it is not claimed here that any of them can yeild better results, they were in good agreement generally and the use of PIVlab was justified [27].

Figure 4.5. shows sample PIV results (left) and FIV results in two different luminosity level which correspond to different engine loads (middle and right). The green section of the signal is separated through a dichroic mirror recorded with PIV camera, and the rest of the spectrum is recorded with FIV camera. Distinctions between these two techniques and the results they yield are discussed here. PIV image is narrower in comparison to FIV since only the section that the light sheet passes through is selected.

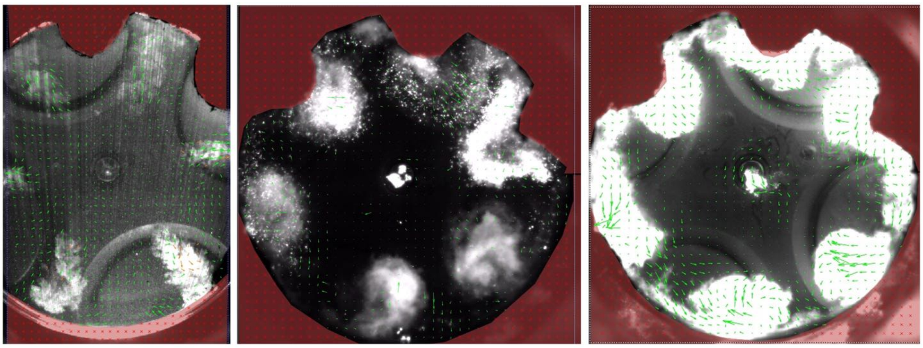

Figure 4.5. Flow field inside wave piston, PIV (left), and FIV (middle and right)

PIV can provide flow field vectors where the seedings are available and detected. In reactive environments such as in ICEs, thermal expansions caused by flam can push the seedings away and flame luminosity can also make the detection of scattered light from particles more challenging. Using bandpass filters to select the green light can mitigate the latter issue, however, it cannot be fully effective, and loss of data is probable.

In FIV, movements of the flame especially around the edges are desired data sources for flow field calculations. Velocity vectors are detected through the variations of signal intensity inside and around the flame. In lighting conditions close to saturation (fig. right) only the bigger structures are traceable. Moreover, FIV uses flame luminosity images and as a result is a line-of-sight technique and the qualitative outcomes from FIV are more robust than precise velocity vectors that it produces. Still, it can provide better understanding of flow patterns through less challenging optical techniques such as natural luminosity imaging. It is worth mentioning that it is possible to combine this method with other laser diagnostics tools in a similar way. For instance, PLIF images can be cross-correlated, and their flow structures can be extracted. In that case, the technique is considered planar since it used PLIF data from a thin sheet of light. A condition that must be met for PLIF or other techniques to be used in combination with cross-correlation algorithms is time difference between adjacent frames. The sampling rate must be high enough to be able to detect flow movements.

Simultaneous PIV and high-speed imaging of natural luminosity in wave piston studies were performed. Figure 4.6 (left) demonstrates an overlay of raw images from PIV and natural luminosity in which the flame have red colour code and the raw PIV image is blue (Right). It is possible to overlay FIV results on PIV flow field. Figure. 4.6 (right) demonstrates this overlay in which green vectors are generated with PIV and orange vectors are FIV results. This example showcases the complementary role that FIV results can provide for flow field measurement. Areas of the PIV image with flames that do not contain seeding particles or are outshined by flame luminosity can take advantage of FIV results and a better understanding of the flow in the entire region is provided.

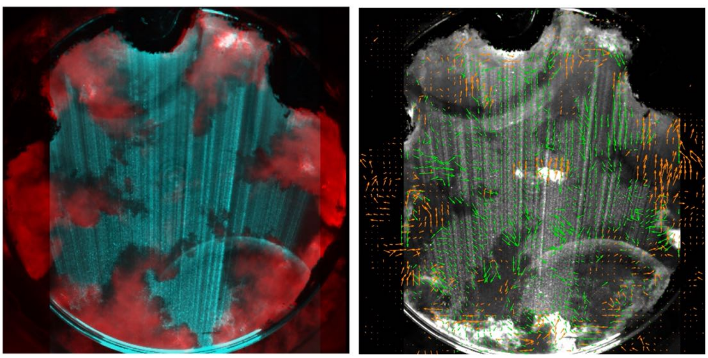

Figure 4.6. An overlay of raw PIV and flame luminosity in a optical engine with wave piston (left), and overlay of velocity vectors from PIV and FIV (right)

Chapter 5. Results

A summary of results from different research campaigns with a wide range and scope of application which are included in this thesis is discussed in this chapter. These results are divided in different sections including multiple injection strategies in a heavy-duty engine, dual fuel combustion in marine engine, wave-piston, and gas-turbine model combustor studies using a variety of optical and laser techniques. The studies are separated in chronological order of their execution which also expands on the complexity of the setup and optical techniques. The usefulness of tools and insight provided by these optical and laser techniques in multiple industrial applications is the common theme of this chapter.

5.1. Optical Studies of Multiple Injection Strategies

In this section, a summary of various studies of multiple injection strategies in a heavy-duty optical engine is discussed by focusing on optical results. First, HCCI and PPC concepts are introduced.

Numerous advanced combustion concepts have been proposed to decrease emissions in CI engines [28,29]. These concepts are generally described as low temperature combustion concepts (LTC) [30,31]. In conventional diesel combustion, the autoignition occurs shortly after the injection of fuel, and fuel is burned in the combustion chamber.

The main characteristic of these low temperature combustion concepts is the use of exhaust gas as a buffer gas. This affects the charge reactivity and temperature history, resulting in change in the mixture and longer ignition delay times. The extended ignition delay helps premixing fuel and air, which in turn increase efficiency while avoiding soot and NO_x.

The exhaust gas recirculation process or EGR is used in a variety of engine processes. Two known branches of these concepts are homogeneous charge compression ignition (HCCI), and partially premixed combustion (PPC).

Homogenous charge compression ignition (HCCI) is a combination of SI and CI engine, like in SI engines, fuel is introduced inside the intake port (port injection). After mixing with the air, a homogenous mixture like SI engines is prepared. The common characteristic of HCCI with CI engines is the autoignition. As opposed to SI engines, no spark ignition is utilized in HCCI, and the mixture autoignition causes a rapid combustion reaction [32-25].

The advantages of HCCI include its high thermal efficiency, and low soot and NO_x emission. HCCI combustion is kinetically controlled, and the reaction is very abrupt and rapid. This rapid reaction results in higher pressure rise rate inside the cylinder, which can be problematic as it increases the noise and hinders the capability of reaching higher loads. Increased amount of EGR can adverse this effect and lower pressure rise rate. HCCI also suffers from unburned hydrocarbons (UHC) emission, caused by wall wetting of fuel, and fuel trapped in crevices and cylinder wall quenching [8].

Partially premixed combustion (PPC) is another novel LTC which has been brought to attention in recent years. In PPC, fuel is injected in the last quarter of compression stroke. PPC also utilizes high amount of EGR. The combination of this injection strategy with high EGR, keeps the efficiency high while avoiding soot and NOx emissions. Like HCCI, PPC also suffers from UHC emissions. Post injection strategies, which are simply dividing the fuel injection into a main injection, and one to several post injections (also pilot injection in some cases), proved to be helpful in reducing these emissions. Multiple injection strategies improve efficiency in PPC engines [37-40], however, the mechanisms leading to these improvements are not completely clear and optical results can shed more light in this area.

In this study, single, double, and triple injection strategies with different injection profiles, i.e., injection timing and fuel ratio of each injection are examined in an optical engine. Fuel spray visualization and natural luminosity imaging were performed for this purpose.

Image distortion correction was performed on each image to reverse the distortions in the image caused by curvatures in piston bowl. Figure. 5.1 shows the recorded image (left) and the modified image after distortion correction. It should be noted that the target image with checkerboard pattern is placed inside the piston bowl to demonstrate the distortion close to TDC. The images in this study were recorded from 40 CAD bTDC and onwards. The level of distortion can vary as the piston moves inside the cylinder, and ideally a CAD-specific distortion correction which corrects each image corresponding to its target image counterpart at the same position would be more accurate. However, in this setup these variations in distortion were negligible as the distance travelled by the piston is rather short and one target image was used for all images.

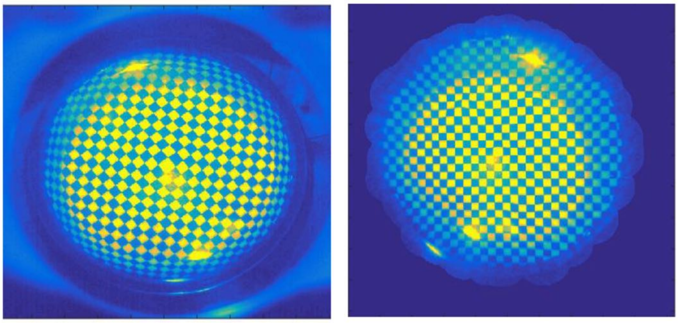

Figure 5.1. Distorted target image inside the piston (left), corrected image (right)

High-speed imaging of Mie-scattered light from fuel sprays was conducted first. Different injection profiles were tested and recorded through the optical access of Bowditch mirror. A continuous laser light from a diode laser which was mounted in front of optical window around the liner illuminated the spray and the scattered light from the sprays were recorded. Figure 5.2 contains sample images recorded from two single injection case with injection duration of 400 μs, and different SOI. On the left, the earlier SOI of 40 CAD before top dead centre (bTDC) and on the right the later SOI of 6 CAD before bTDC is demonstrated. With late injections and higher pressure and temperature inside the cylinder this length reduces.

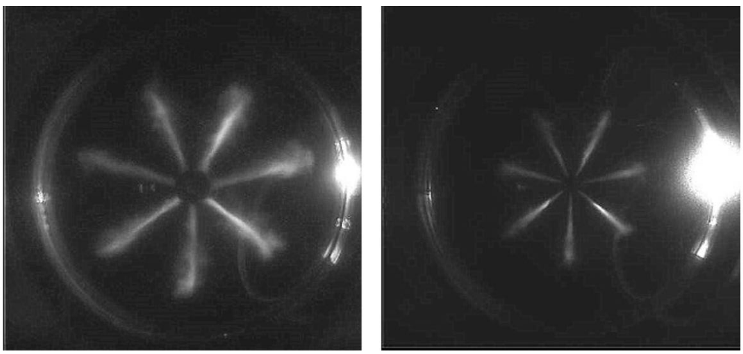

Figure 5.2. Fuel sprays visualization in multiple injection strategies for early and late injections (left and right, respectively)

Furthermore, high-speed imaging of combustion natural luminosity is utilized to investigate combustion process variations under these injection conditions. These variations are found in ignition location, jet-jet interactions of pilot, main, and post injection and combustion phasing. Natural luminosity of the combustion is recorded with a high-speed CMOS camera, Photron Fastcam SA-X2 and three phases of combustion is selected for different injection cases. These three phases include: ignition phase, combustion phase (CA50) and late cycle combustion phase.

The first column in Figure 5.3 shows the ignition phase, in which auto-ignition in different locations inside combustion chamber is clearly visible. Furthermore, the evolution of the combustion is followed up in each row for different injection cases. Complete analysis of these natural luminosity images is discussed in paper I to III, however, some general notes on this technique and its use for reactive environment inside an optical engine are mentioned here.

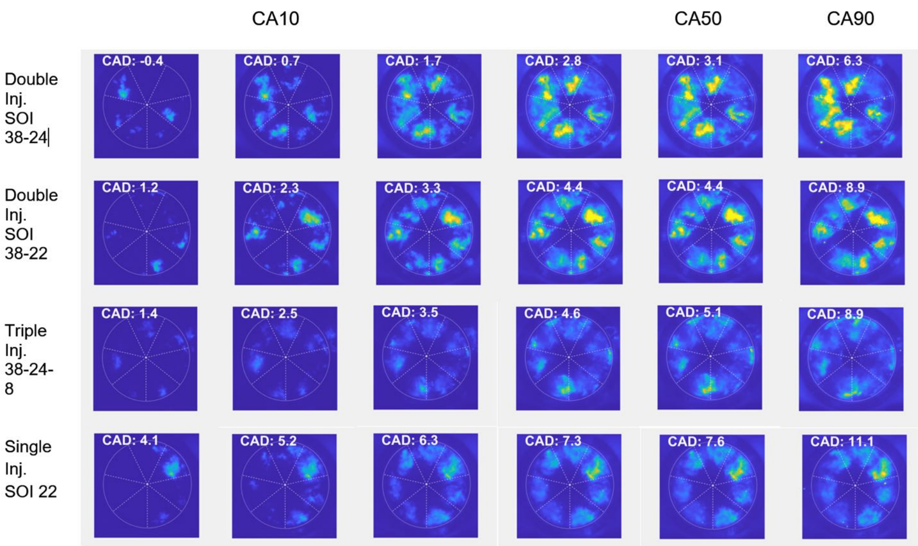

Figure 5.3. Natural luminosity for various injection strategies

Looking at the bigger picture, this capability, to investigate the engine and capture different aspects and phenomena can be immensely valuable. For engine manufacturers, this serves in two different ways, by showing the reasons and mechanisms behind the results that might have been noticed in normal engines, and by inspiring new concepts, and design changes, from this unorthodox source of results.

A typical challenge in optical measurements of reacting flows, is choosing the optical components and recording settings to increase the quality of information perceivable. These criteria can be categorised in two sections, hardware, and settings. Choosing suitable optical components, filters, lenses, and detectors depending on the environment under study and the goal of the measurement is a vital first step. Furthermore, different settings, for instance, objectives $f_{\#}$, shutter speed and recording speed of the camera fall under the setting category. In this study, with the goal of recording natural luminosity during the entire combustion phasing, the challenge of capturing weaker signals of ignition and late combustion phasing without sacrificing image quality through saturation of the sensor existed. A proper set of settings, from $f_{\#}$ to shutter speed and the use of filters like ND filters is chosen and fine-tuned considering the image quality. Regardless, in a few of the images, small saturations are seen, especially near CA50 where the signal is strongest. This compromise was necessary to preserve the information in previous or follow-up frames where the signal is not as strong, yet the structures are important for the understanding of combustion processes.

Optical data which was collected in this study demonstrated fuel spray, jet-jet interactions, and combustion-jet interactions for different injection strategies in an optical PPC engine. A combination of optical results, heat-release data from pressure sensors and thermodynamic analysis, together with CFD modelling of these strategies served to pinpoint combustion phasing and engine performance for different injection profiles.

5.2. Dual Fuel Combustion Engine Studies

In this section the results of high-speed imaging of natural luminosity in Wärtsilä marine engine in medium speed range is discussed. The dual fuel configuration with diesel as pilot and methane the main injection, is used in conventional dual fuel (CDF) and reactivity controlled compression ignition (RCCI) in an attempt to lower emissions, and altering toward methane as a renewable low-carbon fuel [17]. A small pilot injection of diesel in ignites the mixture of premixed methane. In RCCI, the early injection of pilot fuel provides more mixing of the fuel, while CDF has late injection timing. Optical diagnostic technique was performed to increase the understanding of ignition process, as it plays a pivotal role in a dual fuel engine, its performance and emissions, for instance NOx formation.

To study pilot ignition, pilot injection and the effects of start of injection (SOI), injection duration, and injection pressure was investigated. Optical results including the position of the ignition inside combustion chamber, and ignition delay are combined with heat release data gathered from pressure sensors and thermodynamic analysis to provide a better understanding of these effects.

Figure 5.4 demonstrated the setup of the optical engine, with Bowditch design modifications. This medium speed engine with its size, i.e. 8.8 L volume, 200 mm Bore, 280 mm Stroke, and 584 long piston extension, is considerably larger than conventional the heavy-duty engine in previous section and both implementation of the design, and running the engine were challenging[17,18].

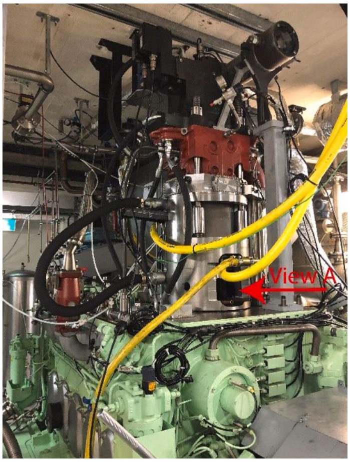

Figure 5.4. Optical Engine based on Wärtsilä W20DF marine engine

High-speed imaging of the ignition and combustion was performed at 15 kHz frame rate to be able to study the ignition in high temporal resolution. In a dual fuel engine, the difference in fuel properties and their combustion makes it necessary to optimize the optical setup and settings to collect information from both fuels. Here, natural gas combustion is rather faint compared to diesel, and to accommodate these two different levels of brightness a compromise was necessary. No optical filter was mounted in the setup, and only a protective layer of glass was placed in front of the camera. With a small opening of the objective at $f_{\#}$ 11, the pilot diesel was still on the edge of saturating the sensor.

Results were segmented to ignition delay, start of combustion and its position, and different stages of combustion phasing in their order of occurrence and differences between CDF and RCCI cases were highlighted. Detailed analysis of these information is discussed in the related paper; however, some parts of optical results are discussed here.

Location of start of combustion can be detected in this imaging technique and it can serve in understanding different phenomena related to combustion. Figure 5.5 shows this location for CDF and RCCI. In CDF cases (left) the ignition takes place closer to the injector tip and is more central while in RCCI cases (middle) the ignition is further away from the centre. This difference can be explained with the late injection of pilot in CDF cases which results in shorter period for the pilot injection before ignition. Figure 5.5 also shows the trend of this radial distance in these two cases for different amount of pilot injection.

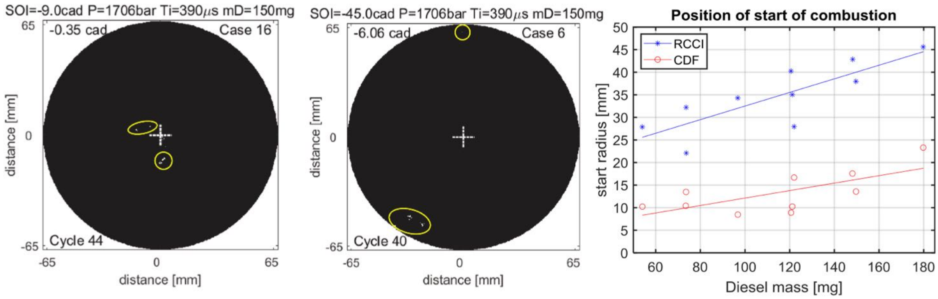

Figure 5.5. Ignition location for RCCI and CDF

These differences in combustion phases can be tracked further on in the cycle. Figure 5.6 shows the continuation of combustion for CDF case (left), RCCI case (middle) and a sample image of pure diesel combustion as a reference. This illustration is helpful to investigate the effect of pilot diesel ignition on the combustion of main fuel. As it is demonstrated in the figure, in CDF case the peak of intensity is close to the center where the ignition takes place, furthermore the jets are formed and visible, relatively similar to pure diesel case. However, in RCCI cases, combustion is expanding far away from the injector, in regions where pilot fuel is ignited.

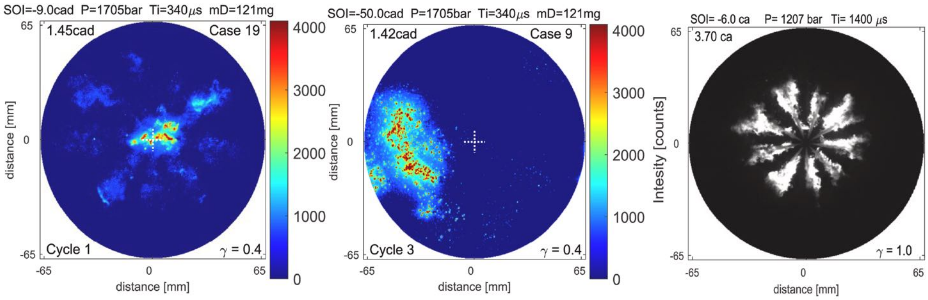

Figure 5.6. Combustion luminosity in CDF (left), RCCI (middle), and pure diesel (right)

Further optical investigations coupled with heat release and emission data provided more insight into the effects of dual fuel utilization and it can be used to design optimal comustion conditions. In RCCI cases, early injection and prolonged ignition delay ignition and combustion occur far away from the injector tip in the peripheral area, and the diltion of fuel mixture, prevents a strong peak in heat realease rate which is an indicator of NO_x formation.

A separate study performed in this engine, which does not fall under optical diagnostics but shows an interesting case of high-speed imaging tools. In running this engine in a follow-up experiment, it was suspected that the timing of one of the inlet valves and its opening behaves improperly. This hypothesis was tested by optical observation of the valves opening and timing. Figure 5.7 shows the setup for this test, from different angles. The bowditch mirror, optical piston and other optical components were removed from the cylinder and an array of LED lights were mounted inside the cylinder to illuminate cylinder roof and the valves. High-speed camera was mounted in front of the optical window.

This test was performed to monitor the opening and valve performance with similar timings to the actual engine experiment. Recorded high-speed images which were captured at 20,000 fps, showed a small variation in timing of one the intake valves, and a rather odd behaviour in opening and closing. This issue was only noticable even in this high-speed recording and the engine results were not indicative of any major change. This troubleshooting experience proved to be an inconventional example of optical diagnostics in engine research.

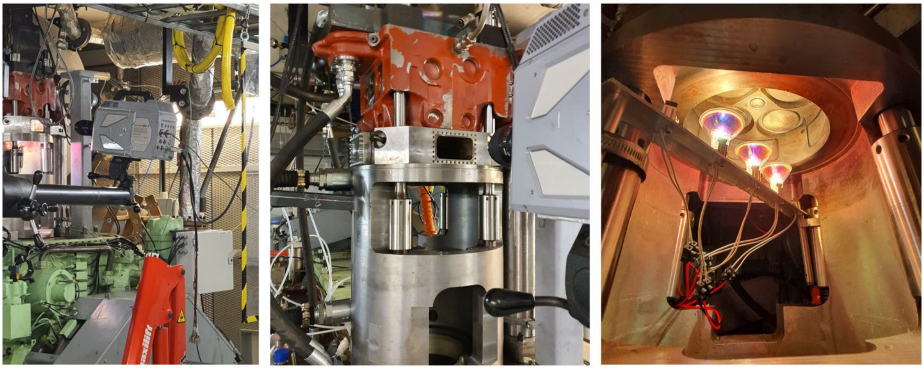

Figure 5.7. Optical setup for tracking intake and outlet valves opening and closing in W20DF optical engine.

5.3. Optical and Laser Diagnostics on Wave-Piston

In this work, a novel piston design with wave-structures on the side (Figure 5.8), was studied to investigate the effect of the waves on fuel and air mixing, and combustion in a Volvo heavy-duty optical engine [43,44]. PIV was used to capture the flow field within the combustion chamber, and natural luminosity was recorded to show the effects of wave-design on combustion.

Figure 5.8. Volvo wave piston (left) and optical wave piston (right)

PIV measurements in this study required adjustments in the setup to maintain the quality of the images. It is a common practice in optical measurements to avoid reflections and other unwanted sources of light as much as possible. In an optical engine, cylinder surface can scatter the light, especially when a laser light is utilized. An additional surface that can reflect light in this setup was the wave structures. Figure 5.9 demonstrate these reflections and the taken measures to circumvent them. An example of this reflection I shown in the left. In order to mitigate this, graphite sprays were used to cover the cylinder roof and the wave structures and avoid light scattering from these surfaces. At the end the bottom view of the piston is not altered drastically, and only the wave structures are covered (Figure 5.9, right). These procedure of covering surface were repeated in every other running of the engine to maintain its uniformity throughout the measurements.

Figure 5.9. A view of the wave piston reflections (left) and sprayed surface (middle) and resulted FOV (right)

Another consideration in performing PIV measurements in an optical engine is the accumulation of seeding particles inside the cylinder covering the piston and optical windows and compromising optical access. Figure 5.10 shows the accumulated seeding particles covering the piston (left) and optical windows (right). The concentration of seeding particles added to intake air is controlled in a way to achieve desired seeding density and cannot be lowered independently. The practical approach to circumvent this issue is frequent removal of these particles by cleaning the surfaces. Air blown with high pressure were also used when the accumulation of the seeding around the valves were hard to remove, even though it was not necessary to perform as frequently as cleaning.

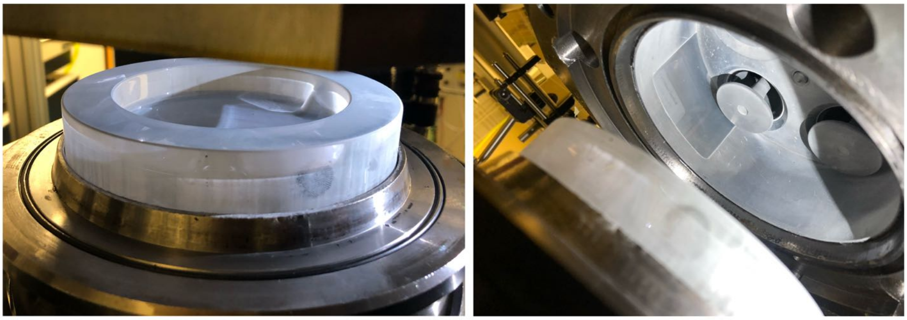

Figure 5.10. Accumulation of seeding particles on the optical piston, optical windows, and inside cylinder

Comparing the wave-side and non-wave side, clearly different structures and phenomena were seen in different stages of the combustion. Different jet-wall and jet-jet interaction, which leads to different mixing of fuel and air, and subsequently different ignition and combustion were seen in both techniques, and detailed analysis of these differences are addressed.

Fuel sprays and their interaction with the wall (jet-wall) and with each other (jet-jet) are shown in Figure 5.11. High level of EGR is used for this measurement to avoid the ignition and to be able to visualize fuel jets and the differences of wave side and non-wave side of the piston. For the non-wave side of the piston which is the in the bottom of each sub image in this view, after jet wall interaction, adjacent jets collide with each and lose their momentum and stagnated. For the wave side, on the other hand, the interaction of the jets with wave directs the spray toward central parts of the piston. This agrees with other observations in this study for fired cycles.

It should be noted that this development of fuel sprays will not happen in actual engine running conditions without this high level of EGR as autoignition takes place at some point during the cycle. However, it serves to visualize the effects of wave structures on fuel spray inside the piston bowl. Moreover, the dissipation of fuel in the measurement plane for the non-wave side is possibly out of plane movement of the spray. Different out of plane motion of fuel sprays can be a result of difference between jet-wall interactions with the presence of wave structures.

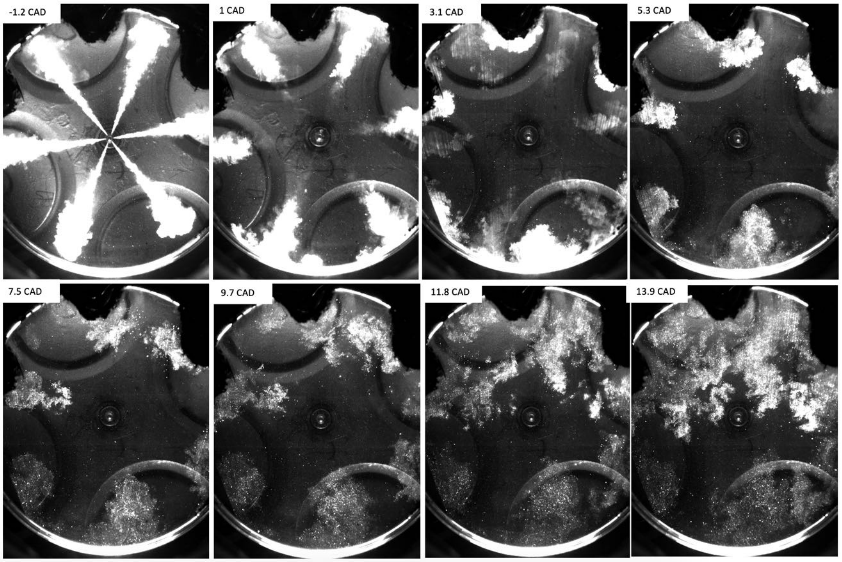

Figure 5.11. Fuel spray visualization inside the wave piston with high level of EGR and without ignition

In fired cycles when ignition happens, distinctions between wave side and non-wave side were observed. Figure 5.12 shows the ignition and flames in similar shape to the stagnated fuel jets for the non-wave side, meanwhile in the presence of waves, the ignition takes place in more central areas. And trailing edge movement of the flow provides fresh air to the mixture and enhances late cycle mixing [44,45].

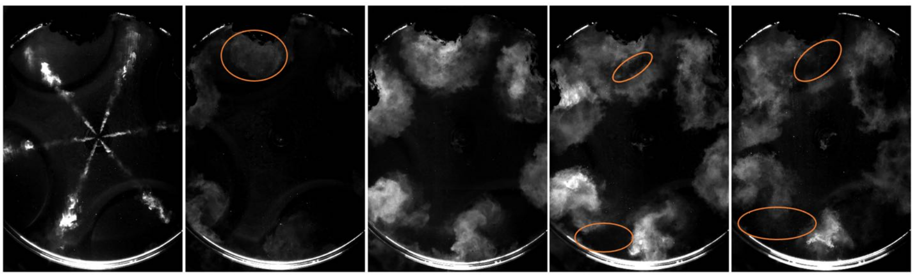

Figure 5.12. Different stages of combustion process inside the wave piston

This difference is pinpointed in Figure 5.13. in which flames travel noticably longer toward the center in the wave side showing positive effects of wave design in air utilization.

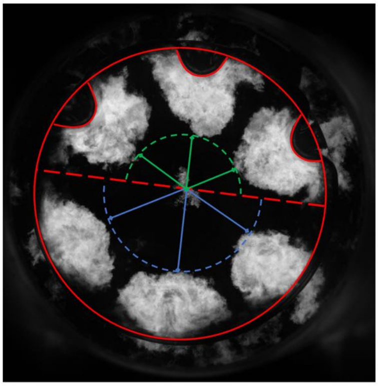

Figure 5.13. Flame development inside wave piston and the distinctions between wave and non-wave side

An interesting observation was the location of accumulated soot inside the piston bowl. As mentioned before, frequent routines of cleaning optical components in the engine is a necessity to sustain the quality of imaging. After running high load cases, which produce more soot, a difference in soot accumulation was noticed. For the non-wave side which is highlighted in Figure 5.14 (left) soot is accumulated in smaller areas close to the wall and appears to have higher amounts (not tested, just visual examination). While for the wave side, Figure 5.14 (right) is covering larger areas, and reside further inside the piston bowl almost reaching the center.

Figure 5.14. Distinctions of soot accumulation pattern in wave side and non-wave side in higher engine loads

5.4. Gas Turbines LIF and PIV Studies

A summary of the results from multiple optical diagnostic measurements in a gas turbine combustor is discussed in this section. The CeCOST burner is studied previously in different research campaigns, and the part of the study that is more relevant to this text is the optical and laser diagnostics, their implementation and analysis of the data. Details related to the burner running condition, fuel type, and similar aspects are of less importance to this section.

Multiple simultaneous optical and laser diagnostic tools were utilized to investigate the burner. (Fig. Setup). High speed imaging of chemiluminescence, and PIV, and OH PLIF measuremtns are used (Figure 5.15). Certain aspects of optical and laser diagnostics techniques can be implemented with fewer constrains for this combustor compared to optical engines. One reason is the full view optical access that is available. Moreover, seeding particles for PIV are easier to control in burner and easier to exhaust. These factors allowed the possibility of fine-tuning different aspect of PIV measurements, including finding suitable range of seeding concentration for optimal results.

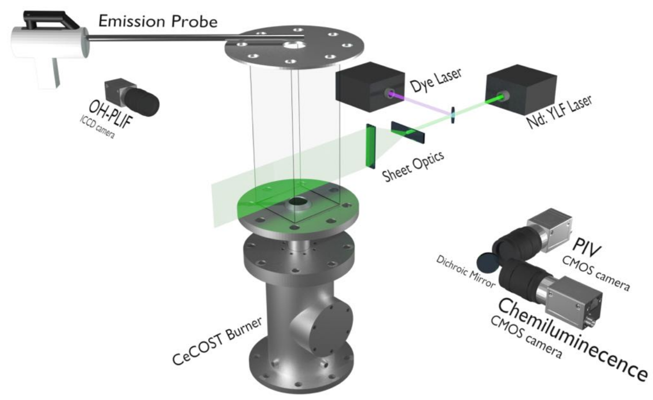

Figure 5.15. Schematic illustration of gas turbine burner setup

Figure 5.16 demonstrates a case of combining PIV vectors with OH PLIF images. Combining these two techniques leads to deeper understanding, as flame fronts are marked with higher OH concentration and simultaneously the movements and flow field is tracked and visualized.

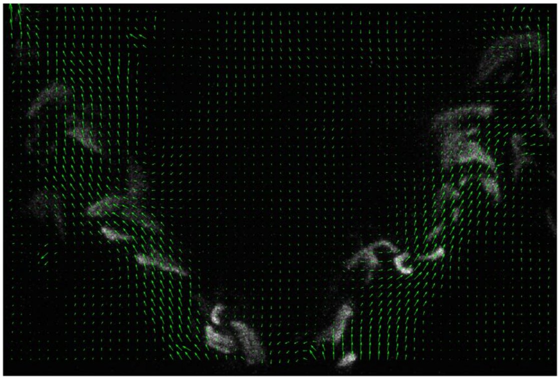

Figure 5.16. Overlay of flow field vectors from PIV on OH PLIF image

Combining velocity field, both instantaneous and averaged with OH concentrations are demonstrated in papers VI and VII similar to Figure 5.17.

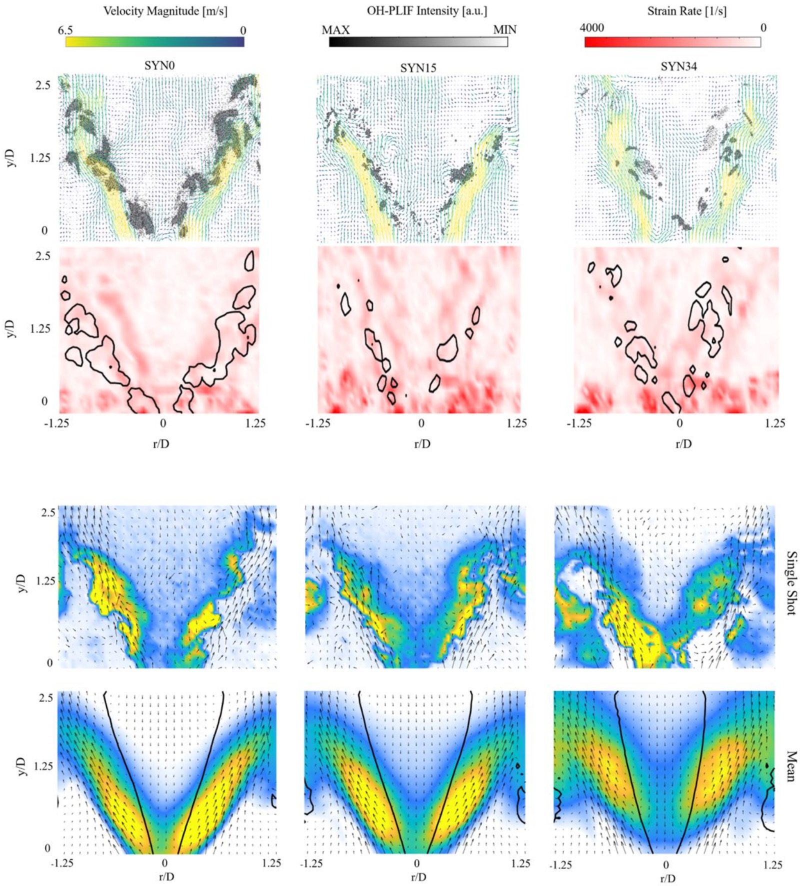

Figure 5.17. Instantaneous and averaged flow field and OH PLIF images [20]

Chapter 6. Conclusions and Outlook

In previous chapters an overview of the role of optical and laser diagnostic techniques and their application in combustion-related areas, including ICEs and gas turbines combustors were demonstrated. A description of the principle behind these techniques, their implementation in experimental analysis, and the information that are extracted were covered. Furthermore some aspects of the work that were not covered in publications but were still relevant to the scope of this thesis were discussed.

The outlook of the works that cobstitutes this thesis can be devided to two categories. The future of combustion applications and the outlook of optical and laser diagnostic techniques used in combustion related reseach.

The goal to reach higher efficiency of combustion in different applications and lowering emissions is of utmost importance and research and developments will continue to play an important role for forseeable future. Research projects performed here included the use of new strategies, design changes, alternative fuels, and other tools to enhance the performance of these devices. Optimizing injection strategies proved to be effective in increasing engine performace and similar concept can be investigated in other engines to find the optimum running conditions. The role of dual-fuel configuration in marine engine can be studies further, possibly with laser techniques such as LIF to increase the understanding of combustion of pilot and main fuel. Wave-piston design will be studied and the plans to use natural gas as fuel (Gas-wave) is planned.

Moreover, diagnostic tools are simultaneously developing to provide solutions for new needs, or increase the quality of existing solutions. These developments can be achieved via multiple paths. Experimental tools are becoming increasingly more capable, and improvements on current techniques or the possibility of developing new diagnostic tools are materializing as a result. The improvement is also taking place in the processing of optical results. Here, cross-correlation algorithms were used to calculate flow field in

PIV and FIV techniques. Other techniques, including optical flow can be used for similar purposes. FIV results were compared to similar results for the same data set from optical flow briefly but a complete comparison of these two methods, and implementation of such tools can increase the strength of optical techniques. This is of especial interest since a major breakthrough of artifical inteligence tools and their application is taking place recently and it is not hard to imagine that the analysis of data can expand as a result. Furthermore, simpler approaches such as FIV can be used to form a better understanding in different areas of combustion research without the need for complex laser diagnostic setup requirements.

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It's already two page now, and I am not even trying to come up with nice sentences, I am mostly suppressing them to keep it short! Let's change the style for brevity.

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To my loved ones and family, what would life be without you. Mom and Dad, you are both angels living amongst us, you have taught me the value of love and respect, you were always selfless towards me and everyone around you, you are both wonderful human beings. This gift, to grow up in the presence of love, is a virtue that I am just beginning to appreciate truly as I grow older. I am speechless, you know how much I love you!

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Author's contribution to the papers

Paper I

I took part in planning the study, the design of experiment was mainly conducted by M. Zhang. The optical setup implementation and recording the data was my responsibility, and I selected optical components and parameters to best fit the experimental goals. The analysis of the data was mainly conducted by M. Zhang and I provided help in optical analysis. M.Zhang has written the manuscript, and I wrote the optical setup part and provided help in analyzing and writing the optical results.

Paper II

The planning was a shared responsibility of the authors, and the design of experiment was conducted mainly by M. Zhang. I took the responsibility of implementing the optical setup, choosing optical components and parameters. The experiments were carried out by M. Zhang and I as a shared effort. Analysis of the data and writing the manuscrit was conducted mainly by M. Zhang. I wrote the section on natural luminosity and provided input in optical results.

Paper III

In this paper, the data gathered for paper I and paper II was used to validate CFD models. I designed the optical setup. I carried out the experiments with M. Zhang. L. Xu was responsible for simulations. Post-processing the data and writing the paper was carried out by M. Zhang. The parts on optical setup are written by me and I provided help in optical results part of the paper, and reviewing the paper.

Paper IV

I designed the optical setup and adjusted related recording parameters. The planning and the design of experiment regarding engine running parameters was conducted by M. Merts. The optical setup implementation and recording the data was my responsibility. I ran the experiment with M. Merts as a shared effort, in which I was resonsible for gathering optical results. The analysis and writing was conducted by M. Merts. I provided input in optical sections of the paper, and in reviewing the paper.

Paper V

In this paper, the implementation and operation of the optical part of the setup was done by me, with helps from M. Gong. Running of the optical engine was done by M. Gong with maintenance help from me. The experiments were carried out by me and M. Gong. Furthermore I participated in analysing of optical results, which was mainly conducted by M. Gong. M. Gong has written the paper and I provided input in diagnostics section of the paper, and edit and review of the text.

Paper VI

In this paper my input was in optical setup implementation, running the combustor, and data analysis discussions, together with co-authors F. Pignatelli, D. Sanned, and A. Subash. My main focus during the experiments and in data analysis was PIV implementations, improving the existing optical setup and checking the quality of optical results. Post processing of PIV results was a shared effort by me and F. Pignatelli. F. Pignatelli has written the manuscript. Moreover, I provided input in optical results, and in editing and reviewing the text, especially optical sections.

Paper VII

In this paper my input was in optical setup implementation, running the combustor, and data analysis discussions, together with co-authors F. Pignatelli, D. Sanned, and A. Subash. My main focus during the experiments and in data analysis was PIV implementations, improving the existing optical setup and checking the quality of optical results. Post processing of PIV results was a shared effort by me and F. Pignatelli. F. Pignatelli has written the manuscript. Furthermore, I provided input in optical results, and in editing and reviewing the text, especially optical sections.

Paper VIII

In this paper, the implementation and operation of the optical part of the setup was done by me, with helps from M. Gong. Running of the optical engine was done by M. Gong with maintenance help from me. The experiments were carried out by me and M. Gong. Furthermore, I participated in analysis of optical results, and FIV section. M. Gong has written the paper and I provided input in diagnostics section of the paper and edit and review of the text.

Paper IX

In this paper, design and implementation of the optical setup, DOE, and data collection was conducted by me. Running the experiment was conducted by M. Gong. I am the main responsible for the analysis and writing the paper.