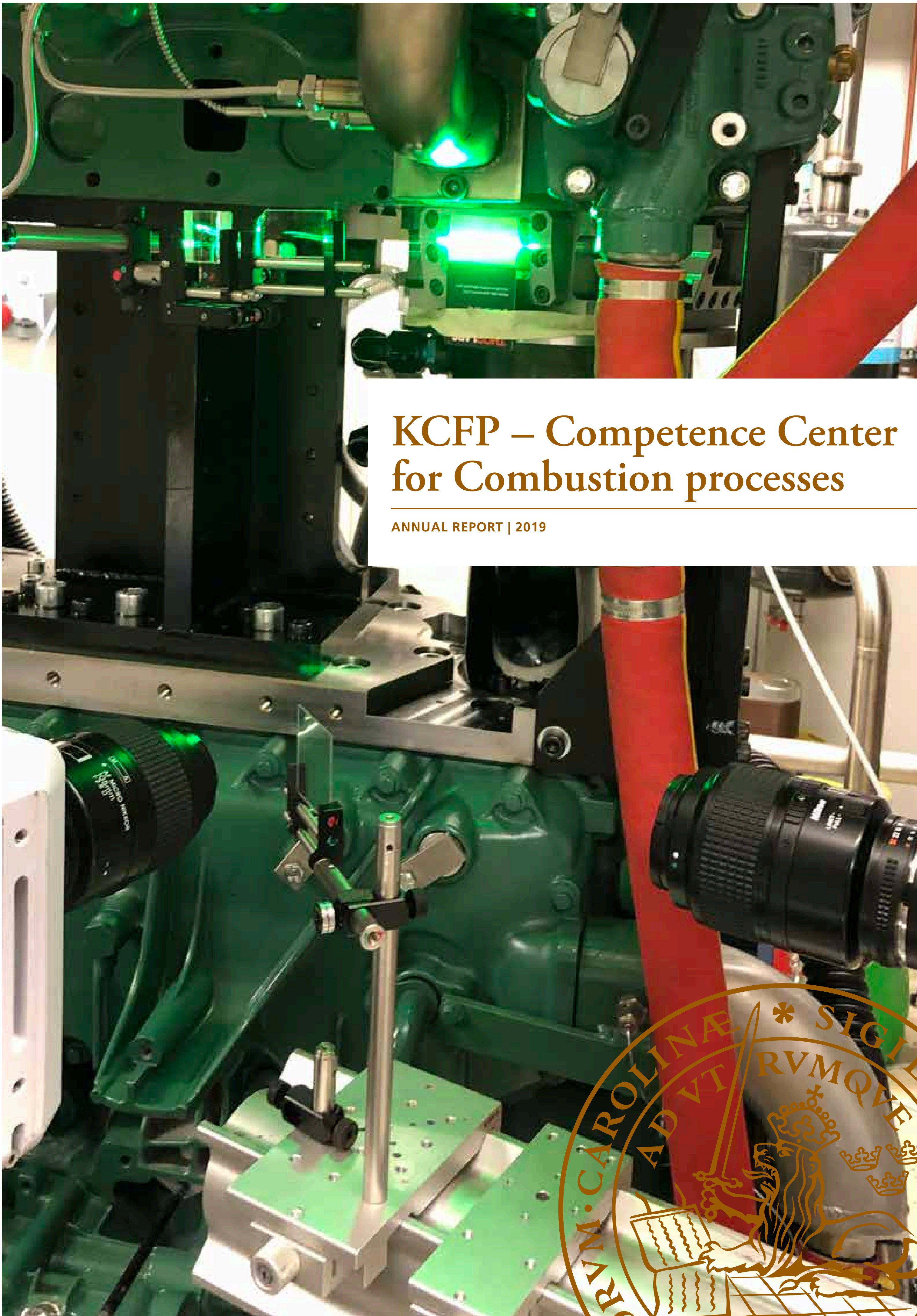
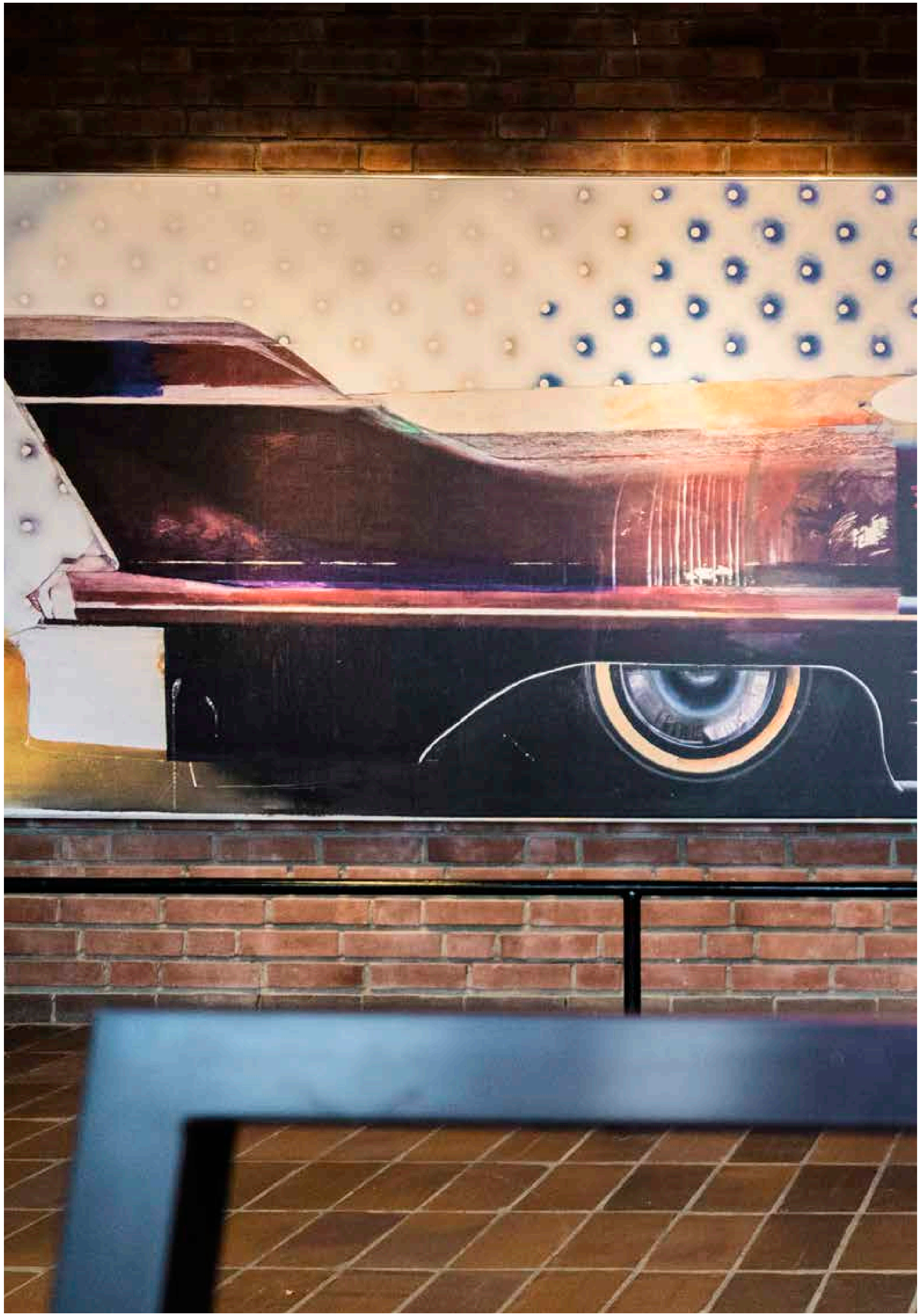


KCFP – Competence Center for Combustion processes

ANNUAL REPORT | 2019

KCFP – COMPETENCE CENTER FOR COMBUSTION PROCESSES
ANNUAL REPORT | 2019



THE COMPETENCE CENTER FOR COMBUSTION PROCESSES (KCFP)

Introduction

The purpose of KCFP is to conduct high-quality academic research in close collaboration with automotive industry within the fields of combustion and thermodynamics for engines in order to contribute to an efficient, sustainable and competitive transportation system.

Advanced methods for analysis, measurements, simulations and synthesis as well as a high-class engine laboratory contribute to improve the understanding of fundamental phenomena which enables researchers within KCFP to identify new technological possibilities and solutions for combustion and thermodynamic systems in engines.

In KCFP, new concepts and understanding of fundamental processes are generated which manifests itself in both physics-based and phenomenological models. This is enabled by access to unique experimental and computational resources. The activities within KCFP are conducted in line with the long-term priority of a fossil-independent transportation fleet by 2030 as an intermediate step towards the vision of a fossil-free Sweden by 2050.

KCFP should support Swedish automotive industry and other stakeholders with relevant innovative research with a main horizon of 10–15 years. This does not exclude individual activities and projects with a shorter time perspective.

KCFP should be a stable and efficient long-term foundation for research, education and societal interaction. The center should recruit and educate future technical leaders and experts. The width of competences is ensured through collaboration between researchers within the center where four academic subjects are represented (combustion engines, fluid mechanics, combustion physics and automatic control) as well as collaboration with experts from industry and society at large.

Vision and mission

The KCFP vision is to generate knowledge and methods that contribute to making the combustion engine an environmentally sustainable alternative in future transportation systems. More specifically this means that net emissions from combustion engines with exhaust aftertreatment should be zero regarding:

- Harmful emissions (nitric oxides, particles, carbon monoxide and hydrocarbons)
- Greenhouse gases

In addition to the zero vision regarding emissions, the research is driven by a vision of combustion engines that are substantially more energy efficient than today's engines and that are suitable for broad implementation in the transport system.

In KCFP the challenge of the zero vision regarding emissions from combustion engines is met with leading edge research on combustion and thermodynamics in engines. The research within KCFP is directed towards new technologies and methods that can contribute to substantial improvement in energy efficiency, zero emissions in real operation and 100% renewable fuels.

KCFP should conduct multidisciplinary research with collaboration between academy and industry in order to create a positive vision that inspires innovative technological solutions for sustainable transportation. KCFP should also educate experts in the fields of combustion and thermodynamics for engines.

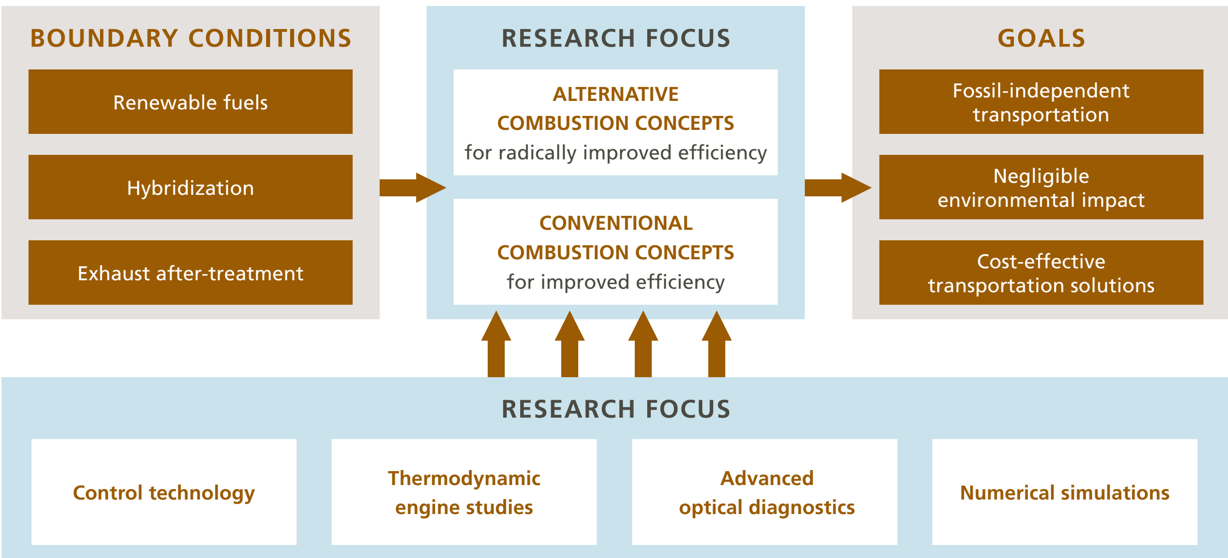
KCFP should conduct research to facilitate a transition to more knowledge- and research-based methods in order to reduce development times for more efficient, cleaner and, if applicable, hybrid drive trains powered to a substantial extent by renewable fuels.

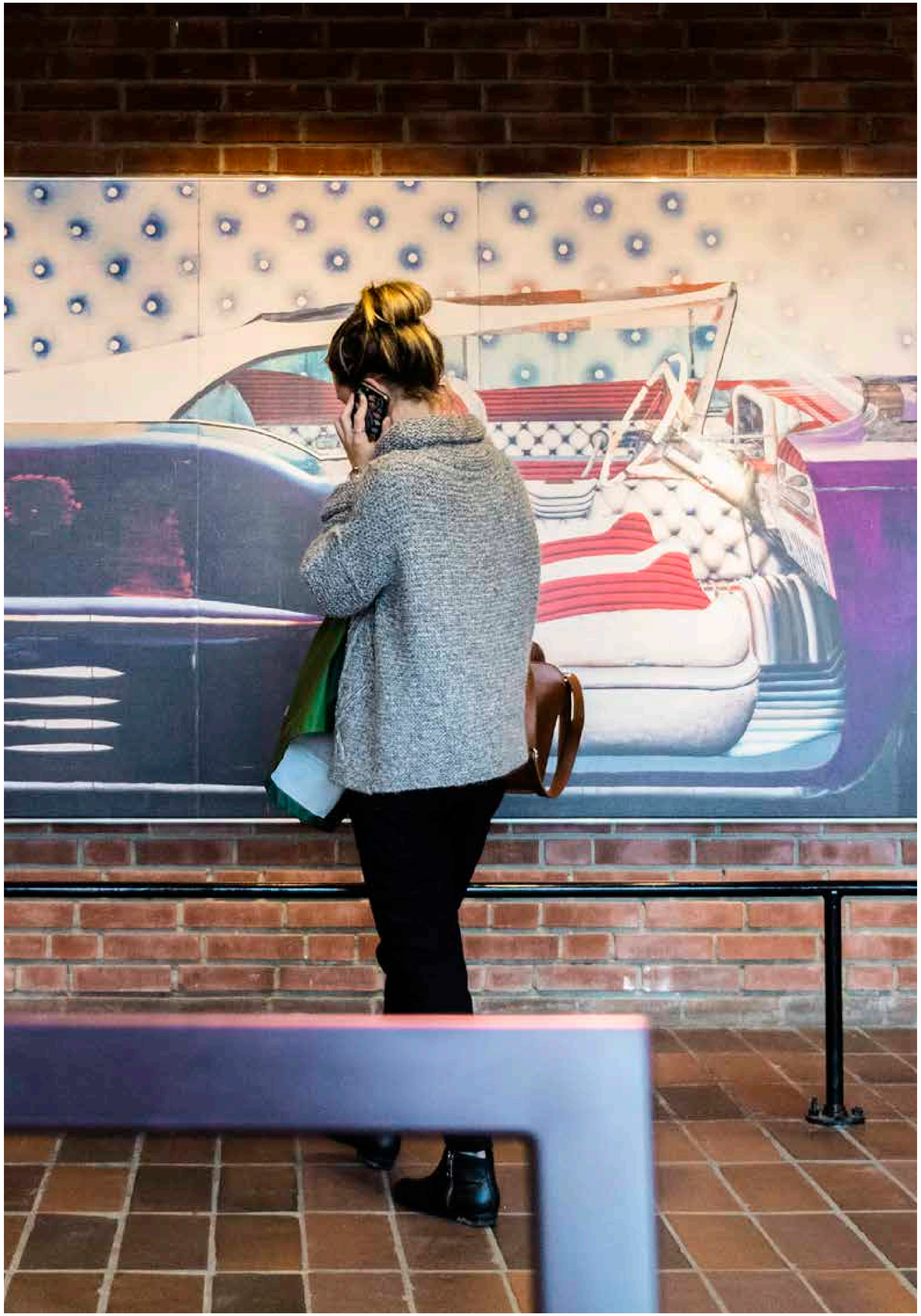
Goals

The main goal of the program is to generate research results and knowledge that, over a 10–20 years horizon, enables:

- development of zero-emission combustion engines (zero vision)development of combustion engines for fossil-free fuels with at least 53% brake thermal efficiency over a substantial part of the operating range
- development of combustion engines that, together with a hybrid drive train, consume 20% less fuel relative to today's conventional drive trains
- development of fossil-independent combustion engines for transportation over land and sea and production of heat and power

The goal of KCFP is to be a leader both in Sweden and internationally regarding thermodynamics and combustion in engines.





Important events during 2019

Two "KCFP Days" events were conducted during 2019, one in May and one in November. Both featured one and a half day of research seminars as well as open discussions about the activities in the center. A new addition to the KCFP Days was keynote presentations by KCFP seniors where a synthesis of KCFP research within a subject over the years could be presented. This was very well received by the participants and will be a recurring element of the KCFP Days.

KCFP is presently operating at a reduced activity level. The original plan had additional PhD students in combustion control and CFD studies and light-duty PPC activity throughout the program period. One reason for the reduced activity is that KCFP was running at an increased activity level the first two years since PhD students from the MOT-2030 project were incorporated into KCFP when the financing for an extension of MOT-2030 was cancelled. The other reason is that Volvo Cars for company-strategic reasons has left the center and subsequently rejoined without cash contribution and at a severely reduced in-kind contribution level.

Measures are taken to improve the situation both by including new members and by increasing the in-kind contributions from existing members. Alfdex and Metatron are two new members that will join during 2020. Alfdex is a Swedish company with a large market share in separators from crank case ventilation and Metatron is an Italian company that develops and produces engine control units for heavy-duty gas engines.

One of the measures that will be taken during 2020 to increase the in-kind contribution from existing members is the start-up of a new SI-engine activity for diluted operation with alcohol fuels. This activity will require engine hardware, development ignition systems and simulation software from both existing members and possibly also from new KCFP members.

During 2019 the following PhD students were awarded their doctoral degrees:

- Christian Ibron based on the thesis "A numerical study of mixing phenomena and reaction front propagation in partially premixed combustion engines"
- Mateusz Pucilowski based on the thesis "Numerical Studies of Methanol PPC Engines and Diesel Sprays"Sara Lönn based on the thesis "Investigation of PPC in an Optical Engine: With focus on Fuel Distribution and Combustion Characterization"
- Erik Svensson based on the thesis "System Simulation of Partially Premixed Combustion in Heavy-Duty Engines: Gas Exchange, Fuels and In-cylinder Analysis"
- Michael Denny based on the thesis "On the Combustion Characteristics of Closely-Coupled LD Diesel Injection Strategies"
- Sam Shamun based on the thesis "Characterization of the Combustion of Light Alcohols in CI Engines: Performance, Combustion Characteristics and Emissions"

Organization

BOARD

Sören Udd, Chairman | Johan Engström, Malin Ehleskog, AB Volvo | Carolin Wang-Hansen, Håkan Persson, Volvo Car Corporation AB | Per Stålhammar, Eva Iverfeldt, Scania CV AB | Erik Swietlicki, Maja Novakovic, Lund University | Sofia Andersson, Anders Johansson, Swedish Energy Agency | The board has had regular meetings on March 20th, October 1st and December 4th.

MANAGEMENT TEAM


DIRECTOR
Professor Per Tunestål
Supervisor for:
Combustion, Control


Administrator
Catarina Lindén


Financial officer
Julia Hansson


Professor Rolf Johansson
Supervisor for: Control


Professor Marcus Aldén
Supervisor for:
Combustion diagnostics


Professor Martin Tunér
Supervisor for:
Combustion, fuels


Professor Öivind Andersson
Supervisor for: Combustion,
Combustion Diagnostics


Professor Mattias Richter
Supervisor for:
Combustion diagnostics


Professor Xue-Song Bai
Supervisor for:
Combustion CFD


A. Professor
Marcus Lundgren
Supervisor for: Combustion,
Combustion Diagnostics


A. Professor
Sebastian Verhelst
Supervisor for: Combustion

MEMBERS

The following organizations have been members of KCFP during 2019 Lund University | The Swedish Energy Agency | Scania CV AB | Volvo Car Corporation AB | AB Volvo | Cummins Inc. | LogeWärtsilä Finland Oy | SEM AB

KCFP RESEARCH STAFF

The following PhD students and postdocs have had a substantial part of their research activity within KCFP during 2019. Ted Lind (postdoc) | Christian Ibron | Mateusz Pucilowski | Saeed Derafschzan | Alexios Matamis | Amir bin Aziz | Xinda Zhu | Xiufei Li | Erik Svensson | Michael Denny | Nikolaos Dimitrakopoulos | Menno Merts

Research

Highlights from KCFP research activities are presented in this section. Some activities are described both from an engine perspective and from an optical diagnostics perspective which means that there will be some repetition.

CI combustion

Though alternative powertrain technologies are slowly emerging, CI engines are still the dominating power sources for road transport. Three studies are presented under this heading. One covers developments of a new diagnostic for tagging selected parts of a fuel injection, which can be used to trace movements of particular fuel elements in the combustion chamber and their interaction with other features. This diagnostic is expected to be useful when investigating the potential for increased efficiency in CI engines, whether using standard or renewable fuels. Another study investigates of the mechanisms involved in controlling combustion noise by pilot injections, which will be important when aiming to combine the often-conflicting demands on low combustion noise and high engine efficiency. The third study investigates how injector ageing and fuel additives affect the combustion and emissions of diesel engines, which has implications when developing strategies for achieving in-use compliance with emission standards throughout a vehicle's lifespan. Although the studies presented here are applicable to current CI engines, most of the results are generic enough to be applied to other engine types and combustion processes as well.

Project leader:
Professor
Öivind Andersson

Researcher:
Ted Lind

Supervisor:
Öivind Andersson

Collaborators:
Zheming Li,
Mark Musculus,
Sandia National Labs

PHOSPHORESCENCE TAGGING IMAGING

Objectives

The objective of this study was to develop a new technique, allowing to tag specific parts of the fuel injection and track its movements during the cycle.

Introduction

Different parts of the injection sequence are believed to contribute differently to combustion features and emissions. For example, a small pilot or post injection probably behaves differently if injected into a combusting region than if injected into a region mostly containing fresh air. As the efficiency of CI engines depends on the portion of the heat released in the tail after the main combustion event, it is also of interest to investigate where the fuel burning in the tail is originating from. For these reasons, a diagnostic allowing us to track different parts of the injection would open up a range of opportunities for further elucidating in-cylinder processes leading to incomplete combustion and reduced combustion efficiency, as well as processes governing the thermodynamic efficiency.

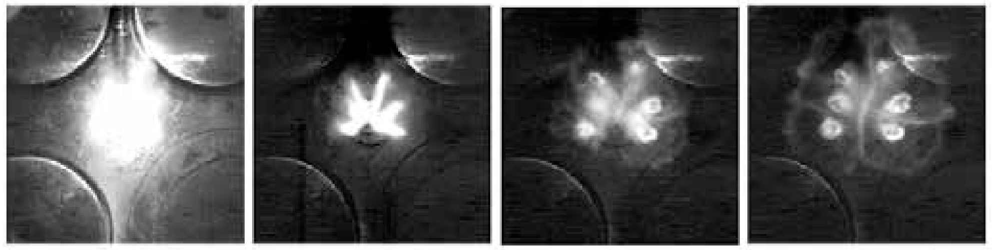
Methods

A new optical diagnostic technique has been developed together with colleagues at Sandia National Laboratories. By doping fuel with nanosized YAG:Tb particles and by illuminating the doped fuel with a 266 nm laser sheet, we were able to track the flow of fuel in both liquid and vapor phase. Due to the fact that the phosphorescence lifetime of YAG:Tb is on the order of milliseconds, and also constant at temperatures up to over 1000 K and at high pressures, this technique can be employed under realistic engine conditions. The nanoparticles were suspended in the fuel by mixing and subsequently sonicating the mixture. There are still many things left to understand about the nanoparticles and their behavior, especially when they are submerged in a liquid. It is currently not possible to use the diagnostic with a non-polar fuel and it is therefore best suited for measurements with alcohols, such as methanol or possibly ethanol.

Results

In Figure 1, a CAD resolved progression of the injected fuel can be seen. The in-cylinder temperature is more than 900 K and the TDC pressure is close to 4.5 MPa. The first frame contains emission from both fluorescence and phosphorescence whereas the following three images only contain emission from the phosphorescing YAG:Tb nano-particles. By timing and targeting the laser pulse at specific parts of the injection, it is possible to follow the selected fuel parcel through the cylinder. The results are currently a demonstration that the method is working and the next step is to implement it in specific experiments.

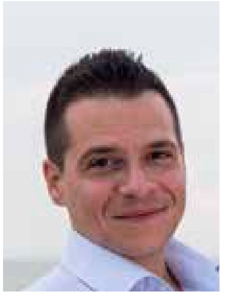
Figure 1
Set of images showing the phosphorescence and motion of the doped fuel, both in liquid and vapor phase.



Conclusions

This method could be especially useful for studying interactions between multiple injections. For instance, previous studies using fluorescence have not been able to distinguish between the two injections and thus it is impossible to know where and when (or even if) the injections interact. With this new technique, it becomes possible to illuminate only one of the injections. Another possible extension of the technique is to measure the temperature of the fuel. By adding another phosphor that, as opposed to the YAG:Tb, has a temperature-dependent lifetime, it should be possible to use the signal from the YAG:Tb to first normalize the signal from the other phosphor after which the decay of the signal from the other phosphor can be used to calculate the temperature of the fuel. Using two cameras with sufficiently high frame speed, it should also be possible to reconstruct the 3D flow fields of the injection using tomographic reconstruction.

INTERACTION BETWEEN FUEL JETS AND COMBUSTION ZONES DURING CLOSE-COUPLED INJECTIONS IN AN OPTICAL DIESEL ENGINE



Researchers:
Michael Denny,
Alexios Matamis

Supervisors:
Mattias Richter,
Öivind Andersson

Collaborator:
Håkan Persson

Objectives

The objective of this study was to understand the underlying mechanism explaining the undulations in the heat release rate that give rise to elevated combustion noise levels.

Introduction

Undulations during the early part of the heat release have previously been identified as the origin of pressure fluctuations leading to elevated combustion noise. It was hypothesized that dips in heat release can result either from depletion of fuel from the previous injection, or from extinguishing of the existing combustion zones as new fuel is injected into it, causing evaporative cooling of the flame. This study tests this hypothesis by imaging combustion intermediates associated with the extinction event.

Method

Two imaging techniques were used to investigate the interaction between combustion zones from earlier injections and partially oxidized fuel (POF) of a subsequent injection. POF was visualized by planar laser induced fluorescence, while high-speed imaging was used to capture the natural luminescence of the combustion. Three different fuel injection strategies were studied. One strategy consisted of two moderately separated pilot injections followed by single main and post injections. Both of the other strategies had three close-coupled pilots followed by single main and post injections. The separations between these pilots were several times shorter than in the reference case, which is why they are termed close-coupled.

Results

Figure 2 shows heat release rates from the three injection strategies. Up to the main heat release peak, the close-coupled cases had more linear heat release rates than the reference case (the red and blue curves). This lead to much lower combustion noise levels. The combustion noise was found to correlate with the amplitude of the undulations, meaning that the reference case had the highest noise level.

The imaging experiments showed that, when the fuel jet from a pilot injection overlapped with an existing combustion zone, that zone was extinguished to some degree. This was seen as a drop in the natural luminescence signal and a simultaneous appearance of POF signal in those zones, indicating that hotter combustion products were replaced by cooler intermediates. As a result, the heat release decreased in the overlap zones, creating dips in the heat release rate. This extinguishing phenomenon was thereby responsible for increasing the combustion noise, as undulations in the heat release rate create undulations in the pressure trace.

Conclusions

In summary, a wide spacing of the pilot injections lead to an undulating heat release rate, as each injection burns more or less completely before the next one is injected. This increases the combustion noise. As the injections become more closely coupled, the undulations decrease and the combustion noise drops. However, as fuel from subsequent pilot injections eventually penetrates into an existing combustion zone, the heat release drops locally, again leading to larger undulations and increasing combustion noise.

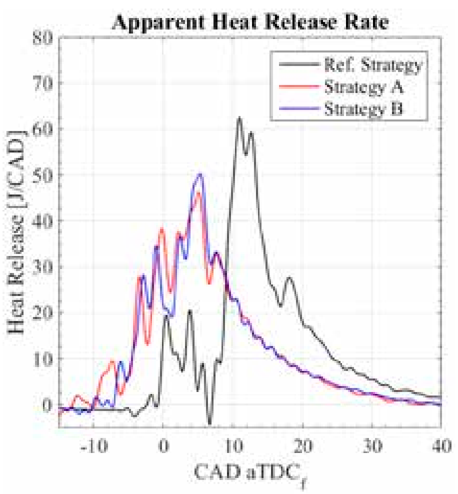


Figure 2
Ensemble averaged apparent heat release rate for each injection strategy.

EFFECTS OF INJECTOR AGEING AND FUEL ADDITIVES ON COMBUSTION AND EMISSIONS FROM A LIGHT DUTY DIESEL ENGINE

Researcher:
Xinda Zhu

Supervisor:
Öivind Andersson

Objectives

Injector ageing has been reported to affect combustion and emission characteristics and could thus have repercussions for in-use emissions compliance. Fuel additives are commonly used to improve combustion and emission characteristics. The objective of this study was to study the effects of injector ageing and some common additives simultaneously.

Introduction

The fuel injection is one of the most important processes affecting engine emissions. It is affected both by the injection system hardware and the fuel properties. As fuel injection systems evolve with finer nozzle holes, the sensitivity to hardware variations increases. For this reason, injector aging could significantly affect the combustion and emission formation processes. Knowledge about this is thus important for engine developers, who are now faced with stricter demands on maintained emissions compliance throughout a vehicle's lifetime. Such knowledge is also important for finding relevant countermeasures to the aging effects. The fuel itself is another critical factor. Additives are commonly used to modify the fuel to achieve ideal properties, for example for reducing pernicious emissions, improving ignition, improving the viscosity over a wide range of temperature, or preventing deposits. Since a range of additives are added to commercial fuels, it is important to understand how they affect important in-cylinder processes and emissions.

Methods

Diesel injectors were tested in a light-duty diesel engine with the purpose to investigate how injector ageing and some common fuel additives affected combustion and emissions. A set of new injectors were compared with a set that had been aged during 100 000 km of field tests in a car. Both sets were tested with a baseline fuel and blends of this fuel and three additives: a soot reducer (tripropylene-glycol monomethyl ether, or TPGME), an ignition improver (2-ethylhexyl nitrate, or EHN), and a flow improver consisting of quaternary ammonium salts.

Results

The aged injectors were initially expected to show a reduced flow rate due to internal deposits but, on the contrary, showed an increase in injected fuel quantity. The conclusion that no deposits had been formed in the aged injectors was also confirmed by X-ray tomography of the nozzles. The increased fuel quantities could be due to erosion of the holes, leading to higher fuel flow rates, but more likely to changes in the injector actuation characteristics. This is illustrated in Figure 3, showing heat release rates from the new and aged injectors. It can be seen that the pilot injection quantities increased more than the quantities in the main injections. This observation is inconsistent with an increased flow rate, which would yield the same relative increase for all injections. If, on the other hand, the needle opening pressure were to decrease with ageing, the injector would open earlier and close later during a given injector energizing pulse. This would yield a greater relative increase of the fuel quantity in shorter injections, in agreement with the observations.

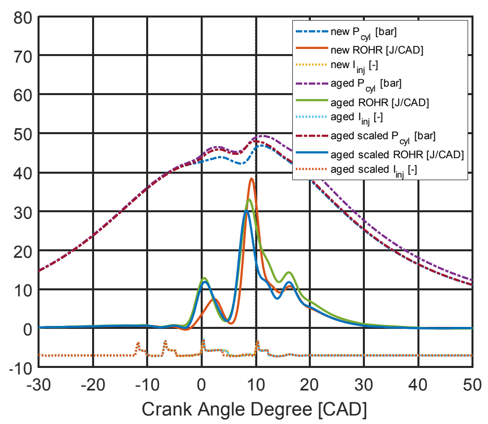


Figure 3
Cylinder pressure, rate of heat release and injector current for new and aged injectors. Results are shown only for the baseline fuel.

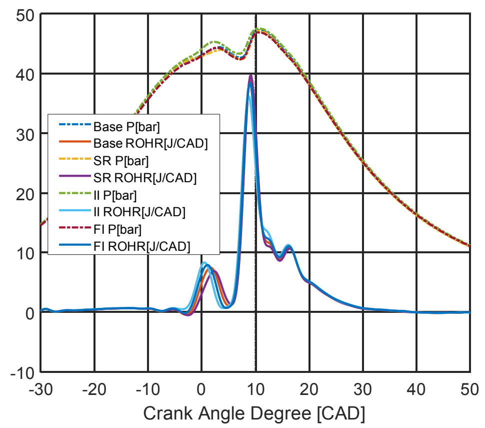
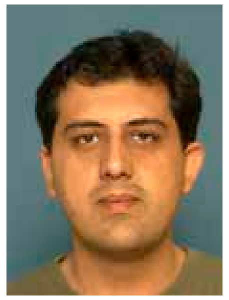


Figure 4
Cylinder pressure and rate of heat release for the different fuels. Results are shown only for the new injector set.

As the aged injectors delivered more fuel, they also produced a higher load. To compensate for this, a scaled down operating condition was introduced, where the main injection was reduced to obtain the same load as for the new set (denoted "aged scaled" in Figure 3). It can be seen that the increased heat release from the pilot injections advance the combustion of the main injection for the aged set. This results in less premixing (as seen in the lower peak heat release rate) and a larger share of mixing controlled combustion (as seen in the higher late cycle heat release of the green curve). The advanced combustion resulted in higher NOx emissions for the aged injector set. Some effects of the fuel additives are shown in Figure 4, where the ignition improver is denoted II, the flow improver FI, and the soot reducer SI. The additives affected combustion less than the injector ageing, the most notable effect being that the ignition improver advanced the start of combustion (just as expected). The flow improver also advanced autoignition somewhat in relation to the baseline fuel, while the soot reducer retarded it. These changes in the pilot combustion had no significant effects on the main combustion. Overall, the additives did not have any substantial effect on the emissions, apart from the soot reducer which consistently decreased the emissions of soot.

Conclusions

In summary, the injector ageing shows a greater influence on the combustion and emission characteristics than the fuel additives, at least in the low to medium load operating points chosen for this study. The higher fuel flow rate delivered by the aged injectors is suspected to be related the injector the needle actuation, for example through drift in the needle opening pressure. This study serves as a reference test for upcoming experiments on the same optically accessible diesel engine that the previous pilot-injection study was performed in. The aim of the coming study is to explain the trends observed here through insights into the spray formation and combustion processes.



Researcher:
Hesameddin Fatehi

Supervisor:
Öivind Andersson

MELCO – MECHANISMS OF ENHANCED LATE-CYCLE OXIDATION IN DIESEL ENGINES

Objectives

The primary purpose of the project was to build knowledge about the mechanisms that link spray and flow processes to more efficient late-cycle combustion during the expansion stroke. Among other things, this was to be manifested in the form of a conceptual model as a useful mental image in the development and evaluation of new combustion systems.

Introduction

Stricter emission legislation and demands for increased efficiency create a need for detailed knowledge of the mechanisms that control these engine characteristics. In diesel engines, both efficiency and soot emissions are linked to the turbulent mixing during the latter part of the cycle. If this process is made more efficient, a faster late-cycle combustion is obtained, which reduces soot emissions and increases the thermodynamic efficiency. The MELCO project (mechanisms of enhanced late cycle oxidation in diesel engines) aimed at mapping out the in-cylinder processes involved using CFD as the main research tool

Methods

The interaction between spray and gas movement was investigated using CFD simulations. The purpose was to clarify how the injection pressure affects the turbulent mixing in the late cycle, in combustion systems with and without swirl. The effects of bulk flows and turbulence were studied to determine how the final combustion during the expansion stroke could be improved. The studies included geometries with different cylinder bores, combustion chambers, injection pressure and gas movement (stationary as well as swirling) in order to build generic explanatory models that are useful in different types of combustion systems.

Results

Using a re-entrant system as an example, the left-hand panes of Figure 5 show the development of flow structures using a nominal swirl ratio of 1.7 At 380 CAD (i.e. 20 CAD after TDC and well after the end of injection). Here, the colored arrows indicate that the spray has set up clockwise vortex transporting both oxygen and fuel downwards-inwards and then upwards-outwards in the bowl. The red arrow shows the general direction of the flow. The red zone at the center represents the soot (also indicated by a white circle). As seen in the figure, the flow lifts the soot up from the bowl floor and transports it to a region where there is oxygen available to oxidize it. The bottom-left pane shows the situation at 395 CAD, where the soot is surrounded by oxygen. When the swirl ratio is reduced to zero (right-hand panes of Figure 5), the clockwise vortex is no longer present. Instead, the remaining momentum from the spray is directed into the squish region above the piston crown and does not interact at all with the soot at the bottom of the bowl. As seen in the bottom-right pane, the soot is still trapped in the bowl at 395 CAD where the floor blocks the access to oxygen, aggravating the soot oxidation. This situation results in poor late-cycle oxidation, high emissions of soot, and poor efficiency.The clockwise vortex is formed by a combination of the spray momentum (which pushes the gas downward-inward in the bowl) and the centrifugal force arising from the rotation of the swirling flow. The centrifugal force becomes stronger as the swirl is compressed by the sprays to a smaller radius, and thus pulls the gas upward-outward from the center. The reason why the clockwise vortex is not formed at zero swirl is that there is no centrifugal force, and this upward-outward force is therefore absent. As a result, the flow stagnates at the bottom of the bowl.

Conclusions

Although all of the combustion systems studied had different features and were based on different flow patterns, when they worked well, they shared the following characteristics:There were flow structures present that transported oxygen to fuel-rich (sooting) regions and promoted mixing there.There were flow structures present that transported fuel-rich (sooting) regions away from walls, which blocked the access to oxygen, and towards regions where oxygen was available.If engine developers are informed of these conceptual guidelines when developing combustion systems, this will contribute to cleaner and more energy efficient road transports, without associated additional systems or additional costs.

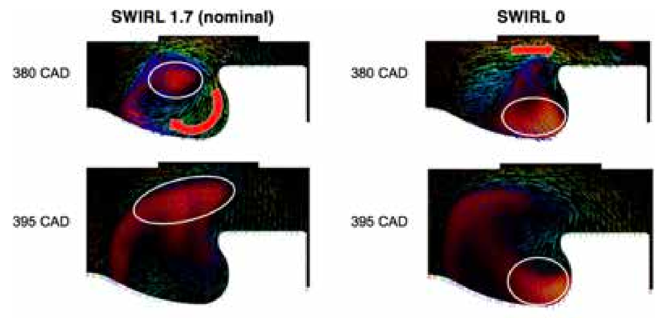


Figure 5:
Conceptual description of flow structures in the light-duty re-entrant combustion system.

Low temperature combustion

Low temperature combustion (LTC) emerged as a means to reduce emissions from combustion engines. The potential for reduced fuel consumption and operation on renewable fuels are other benefits that have been explored through intensive research. The fundamental idea of LTC transformed over time into several different combustion engine concepts to maximize the benefits and facilitate implementation into commercial engines. Examples of such concepts are homogeneous charge compression ignition (HCCI), reactivity charge controlled ignition (RCCI) and partially premixed combustion (PPC).

Five studies are included under the LTC heading. These focus on different aspects of PPC from fundamental studies to characterize PPC through fundamental thermodynamic engine studies and optical diagnostics; strategies to improve control of PPC engines; the implementation of PPC in commercial engine hardware; and finally an analysis of a complete PPC engine running on renewable methanol fuel.

Professor
Martin Tunér

Researcher:
Amir Bin Aziz

Project leader:
Martin Tunér

IMPACT OF SINGLE TO TRIPLE INJECTION STRATEGIES ON METHANOL PPC COMBUSTION

Objective

The objective of this study is to evaluate the impact of injection dwells and mass proportions on the required intake temperature, performance, and emissions of PPC methanol under low load conditions.

Introduction

Partially premixed combustion (PPC) is an advanced combustion strategy which has been proposed to gain higher efficiency and lower emissions than conventional compression ignition.

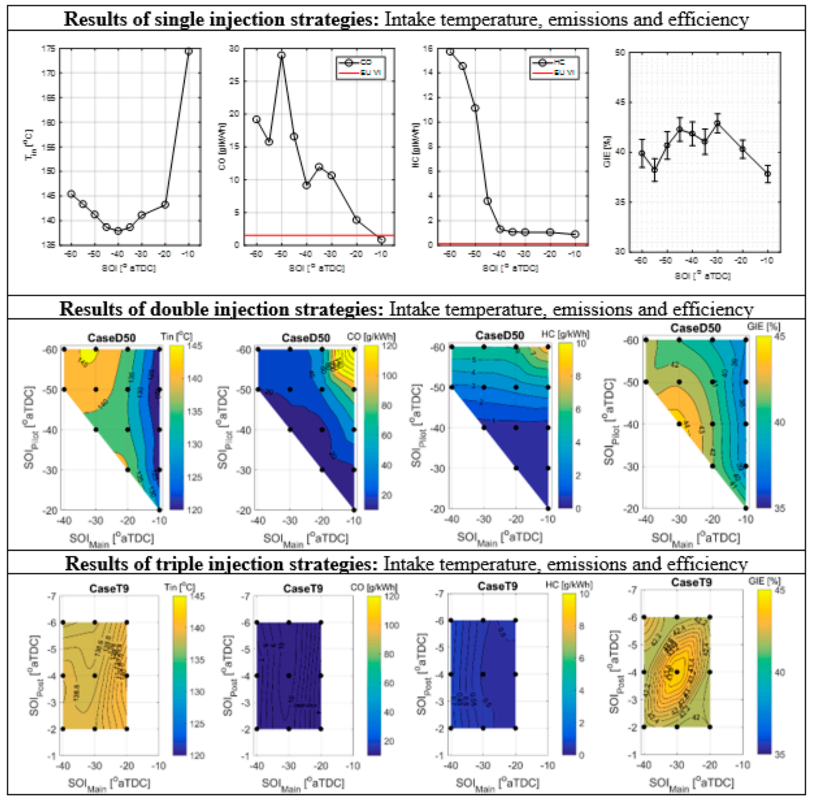
The PPC concept is based on the idea to reduce emissions and improve efficiency by reducing the heterogeneity of conventional diesel combustion through an increased separation between the fuel injection and the combustion event. This can be achieved by using a fuel with higher octane rating and thus higher resistance to auto-ignition. This works well at higher loads but one of the challenges with PPC is low load performance which requires high inlet temperatures to initiate combustion. Methanol has very high-octane rating and requires even higher inlet temperatures at low load operation. This phase of the work evaluates the impact of multiple injection strategies on the required intake temperature, performance, and emissions of PPC methanol under low load conditions.

Methods

The experiments were performed on a single cylinder Scania D13 engine with the standard piston with 17.3 in compression ratio, but an alcohol compliant fueling system with a 12-hole 120° narrow spray angle injector of 230 µm diameter holes. For double and triple injection strategies, the dwell as well as mass of pilot or post and main were varied simultaneously. The intake temperature was tuned at the same time to keep a constant CA50 at 3 oaTDC under 4 bar IMEPg. The Pin was the same for all cases (Pin=1.25 bar), EGR = 0%.

Results

Single Injection: Very high Tin required for late injection timing. The CO and HC are very high during early injection timing. Peak GIE was 42.9 % at SOI -30 oaTDC.
Double Injection: Lower required Tin towards late injection but a trade off with GIE. Higher CO and HC with early main injection due to fuel injection outside piston bowl.
Triple Injection: Slightly lower Tin towards late injection. Lower HC and CO emissions since all fuel is injected inside the piston bowl. Highest GIE was 43.5 %.



Conclusions

Multiple injections are an effective way to reduce the required intake temperature (Tin). Nevertheless, there was a trade-off between having the benefit of lower Tin and loss in the gross indicated efficiency (GIE).UHC and CO emissions were shown to be sensitive with the early pilot injection as well as the mass proportion in the pilot.It was found that, the triple injection strategies give the highest GIE and the lowest emissions compare with single and double injection.

ANALYSIS OF PPC ENGINE EFFICIENCY USING AN OPTICAL ENGINE

Researcher:
Miao Zhang

Supervisor:
Marcus Lundgren

Introduction

Partially premixed combustion (PPC) is a promising combustion concept. PPC not only reduces NOx and soot emission simultaneously but can also increase engine efficiency to reduce CO2 emission. Although there are a lot of unknowns regarding the mechanisms behind the PPC efficiency. Therefore, the motivation of this study is to further explore how efficiency "looks like" by using optical diagnostics.

Methods

The experimentation in this study was carried out in a heavy-duty optical engine, modified from a six-cylinder Volvo MD13 engine. The fuel used was gasoline-like fuel (PRF87). To investigate the efficiency mechanisms, several parameters like injection timing from homogenous fuel and air mixtures (HCCI) to stratified mixtures (PPC), multiple injection strategies (single injection, double injection and triple injection) and boundary conditions (intake temperature and EGR), have been swept to achieve different levels of engine efficiency. This was coupled with the combustion process by using the following diagnostics tool: high-speed camera, Mie-scattering, thermodynamic analysis, and CFD simulations. Here certain attention was given the ignition location, the spray development and combustion process.

Results

Initially, double injection was used to combine well premixed zones with more stratified mixtures. Here, the jet-jet interaction can cause two features depending of the injection timings. Firstly, a the too-lean fuel mixture can be enriched by the second injection and therefore promote the start of combustion, as seen green box in case 30/14 in Figure 1. However, if the timing is poorly designed, it's seen that the part of the first injection (that recirculate against the piston bowl wall) can be sucked into the wake of the second injection passing through the bulk of the combustion chamber, in case 30/6 in Figure 1, marked with a red box at -1 CAD aTDC. In turn, the first injection prevents the second injection to reach the available oxygen within the combustion chamber. However, cases with injection timings where the two injections avoid this interaction results in a higher combustion efficiency.

Thermodynamic analysis was conducted from three aspects; the combustion phasing, heat transfer losses, and heat release shape. The cases with early combustion phasing can take advantage of a higher effective expansion ratio and normally reach a high efficiency, however cases with a late combustion phasing can also gain a high engine efficiency. The main reason is believed to be lower heat transfer. In the simulations the high-temperature regions are located further away from the combustion chamber walls, granting enough space between the piston and cylinder head to isolate the released heat within the combustion chamber.

For triple injection, the local temperature and jet-jet timing are the two key factors that affect the combustion of the third fuel injection, that in turn affect the combustion efficiency. The two first injections are constant in this case and have recirculated into the piston bowl where the combustion start. Meanwhile the third injection starts. Three scenarios are found depending on the start of the third injection. First, with an early third injection the jet of case 38/24/8 impinges the piston bowl wall before the start of combustion, see Figure 2, causing the third fuel jet to burn against the wall, and result in poor combustion efficiency. Secondly with a well-timed fuel injection, the third jet of case 38/24/6 passes through the combustion zone at the onset of combustion, and is rapidly consumed by the combustion, increasing the combustion efficiency. The third scenario includes a too late third injection in case 38/24/4. Here the third injection have not reached the "combustion zone" before the start of combustion, thus the third jet burns in very rich conditions, again causing the combustion efficiency to drop.

Conclusions

This research presents an insight into how to improve and mainly understand the mechanisms behind engine efficiency with PPC. The main conclusions of this research can be summarized as follows:

- The jet-jet interaction and jet-piston interaction have a significant effect on the ignition location, combustion propagation, and efficiency.
- The jet-jet interaction plays both a positive and a negative role in engine efficiency for PPC. In PPC, the jet-jet interaction should be avoided because the collision between the first fuel jet and the second fuel jet inhibits the second fuel jet reach the available oxygen.
- Different injection strategies (single-, double-, and triple-injection) affect the CA50, heat transfer loss, and combustion loss. For the triple injection cases, a well-timed third injection can increase the combustion efficiency by directly being consumed by the onset of combustion from the two first injections.

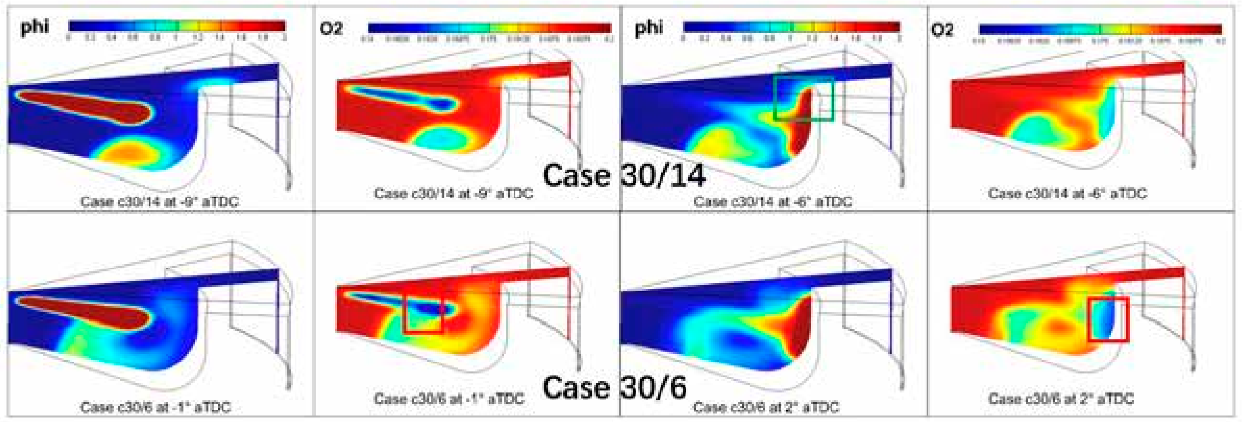


Figure
In-cylinder phi distribution and oxygen distribution for double injection case 30/14 and case 30/6. The first and second columns represent the fuel and oxygen distribution at 2CAD after start of second injection. The fuel and oxygen distribution at 4 CAD after start of second injection, are shown in the third and fourth columns, respectively.

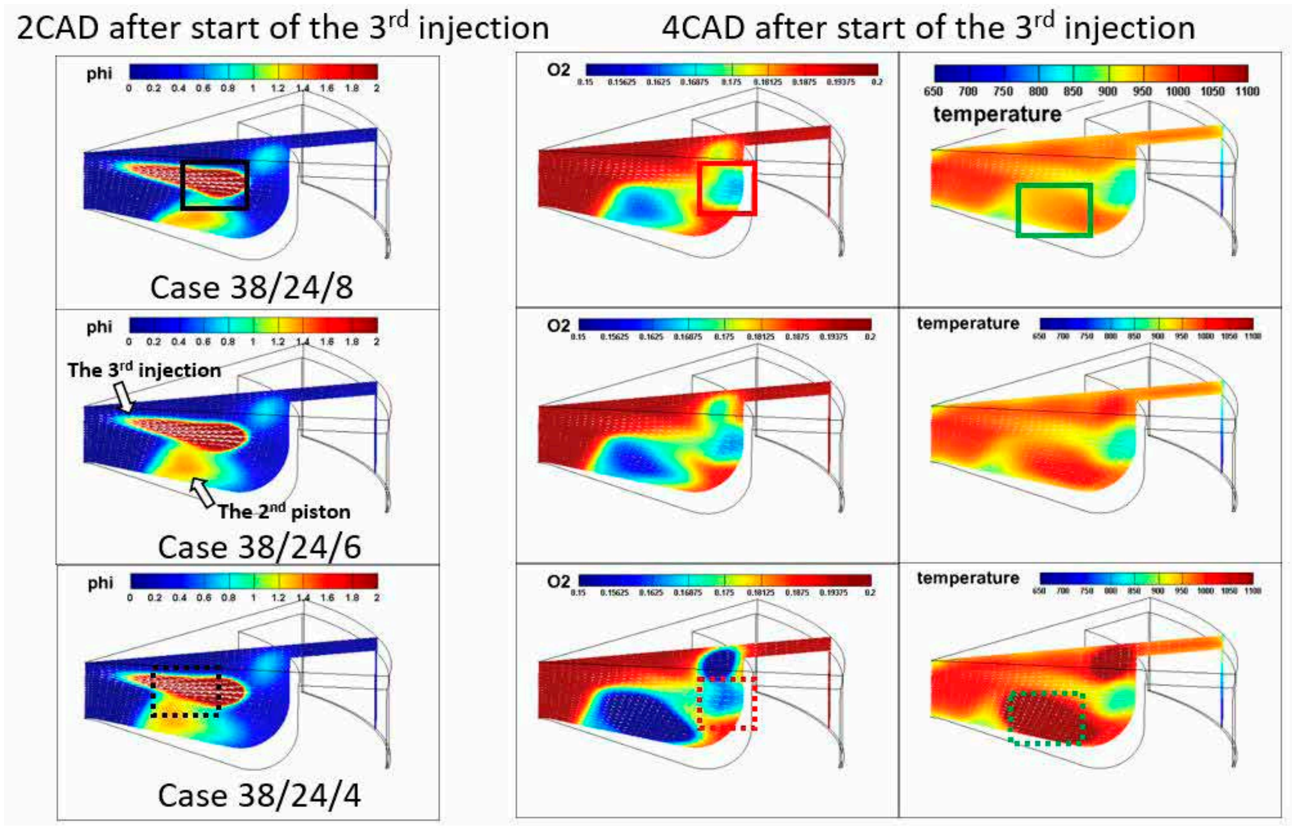


Figure
Phi distribution at 2 CAD after start of the 3rd injection (left part) and the distribution of oxygen and,temperature at the 4CAD after the start of the 3rd injection (right part) for the triple injection cases 38/24/8, 38/24/6, and 38/24/4.

PPC-COMBUSTION CONTROL

Researcher:
Xiufei Li

Supervisors:
Per Tunestål
Rolf Johansson

Objectives

Partially Premixed Combustion (PPC) is a promising advanced combustion mode for future engines in terms of efficiency and emission levels. The combustion timing should be suitably phased to realize high efficiency. However, a simple constant model based predictive controller (MPC) is not sufficient for controlling the combustion during transient operation. A learning-based model predictive control (LBMPC) approach is used to achieve controllability and feasibility.

A flex-fuel engine can operate on different fuels and their mixtures. Today, flex-fuel engine mainly refers to spark-ignition (SI) engines operating on a blend of ethanol and gasoline. However, a compression-ignition (CI) engine, operating normally on diesel and/or biodiesel, can also serve as a flex-fuel engine. Various combustion modes (HCCI, PPC, RCCI) and fuels (biodiesel, gasoline, ethanol) are investigated for a CI engine. However, the flex-fuel CI engine brings up new control challenges. Unlike the flex-fuel SI engine, which operates with only gasoline and ethanol, the flex-fuel CI engine doesn't know the fuel species in advance. Thus, the control method based on detecting specific fuel species will not work. In this situation, an adaptive control method is necessary.

Introduction

Starting from May 2019, the research focus was shifted from learning-based MPC control of PPC combustion to flex-fuel compression-ignition combustion control. The research is conducted on a multi-cylinder Scania D13 engine. Results from both these activities are briefly presented.

Methods

Learning based MPC requires two different model parts: the base model and the learning model. The base model is a constant model, usually with clear physical meaning. The learning model is learned and updated online from sensor data by statistical learning. Here the learning model is used to capture the unmatched combustion timing variations. Then the learning based MPC problem is formulated where the base model is used to satisfy constraints and the learned model is utilized for prediction to get better performance. Safety and performance are decoupled within an optimization framework in this way.

An adaptive model predictive control approach, as outlined in Figure 3, was proposed to control the flex-fuel CI engine combustion process to track the varying fuel properties and their influence on the engine. The combustion timing and ignition delay are extracted from cooled in-cylinder pressure sensors and simultaneously controlled by manipulating injection timings, intake oxygen concentration and intake pressure using an exhaust-gas recirculation (EGR) system and a variable-geometry turbocharger (VGT). A physical ignition delay model was used, and the parameters were estimated with a Kalman filter in real-time. An MPC problem is formulated based on the adaptive model. Diesel, gasoline/n-heptane mixture, and ethanol/n-heptane mixture were used in the experiments. The method was validated in fuel transitions from diesel to gasoline mixture and from gasoline mixture to ethanol mixture.

Results

The performance of MPC and Learning based MPC for PPC control are compared in the 6-cylinder Scania D13 engine. Figure 1 and Figure 2 show that LBMPC had a significant reduction in overshoot and gave a faster response compared to a constant model MPC approach. Meanwhile LBMPC had lower variance on steady-state conditions.

A fuel-adaptive controller can track combustion timing and ignition delay references well and satisfy constraints during a fuel changing transient, see Figure 4, Figure 5 and Figure 6. Meanwhile, the possible ignition delay range calculated by the adaptive model can be used for fuel property detection. The innovation in this work is control of a flex-fuel CI engine where the fuel choice is not limited to two specific fuel species and are unknown in advance to the controller, which is not the case for contemporary SI engine flex-fuel controllers.

Conclusions

Learning-based MPC control of PPC combustion as well as flex-fuel CI combustion control have been demonstrated with promising results. Due to the shift of focus in the project, flex-fuel CI combustion control will be the main focus during 2020.

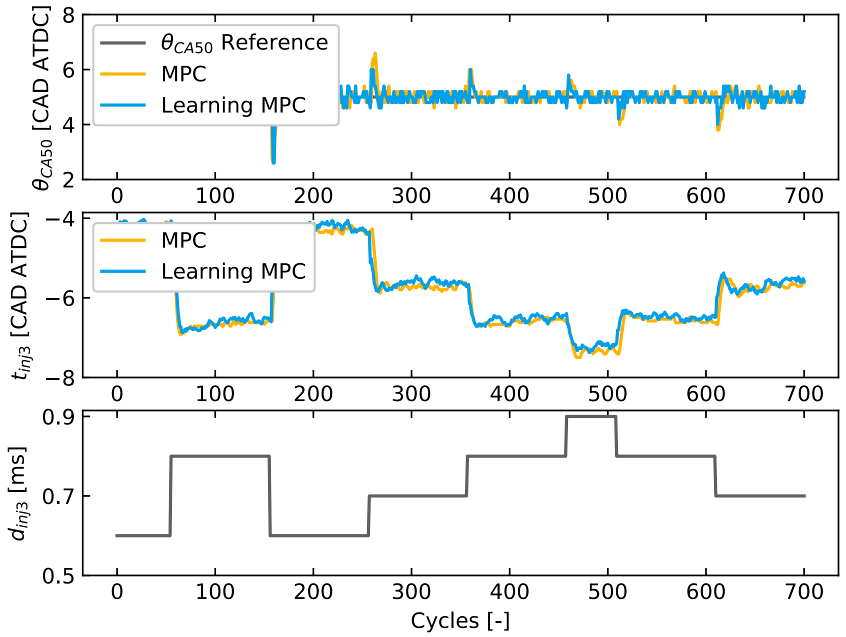


Figure 2
PPC load transient. MPC control with and without learning.

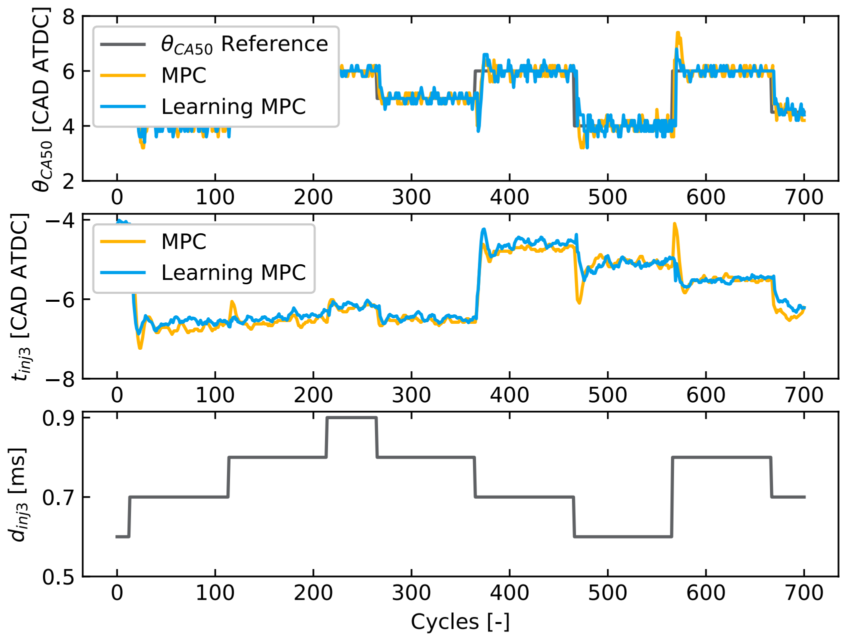


Figure 3
PPC combustion timing transient. MPC control with and without learning.

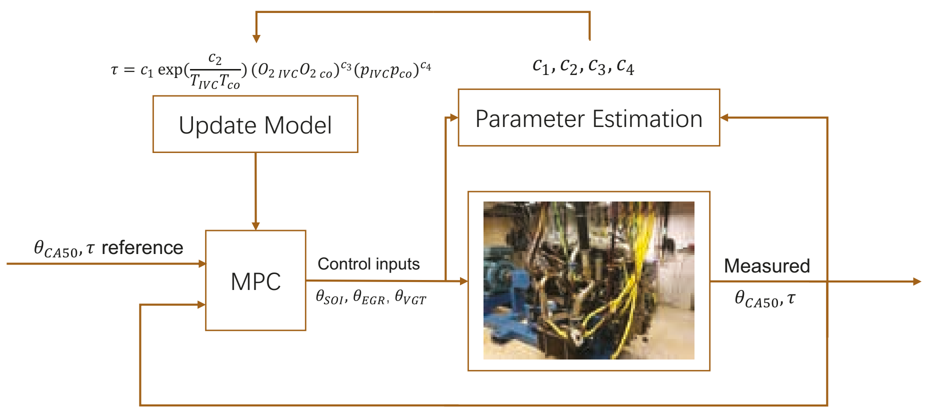


Figure 4
Apdaptive MPCcontrol design.

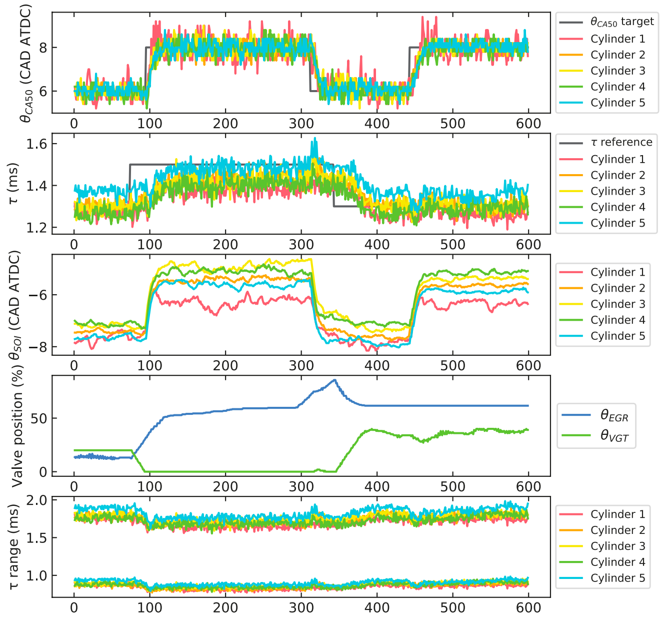


Figure 5
Controller behavior at the start of the fuel change from diesel to gasoline/n-heptane.

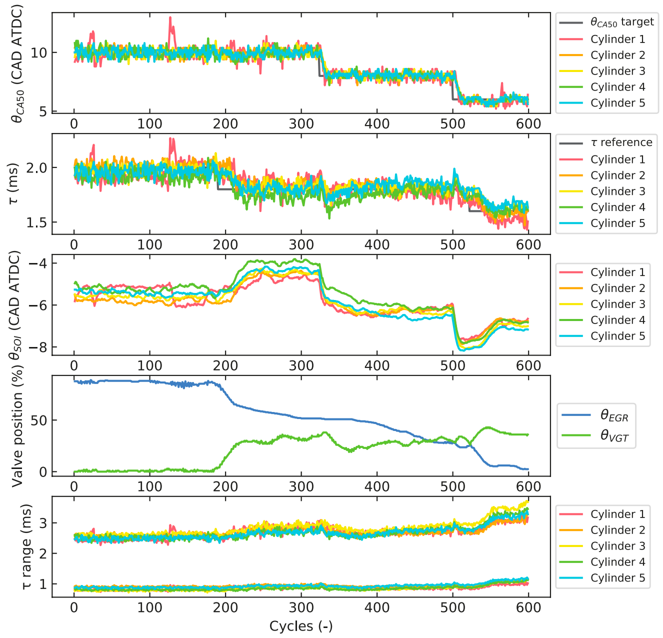


Figure 6
Controller behavior in the middle of the diesel to gasoline/n-heptane transition.

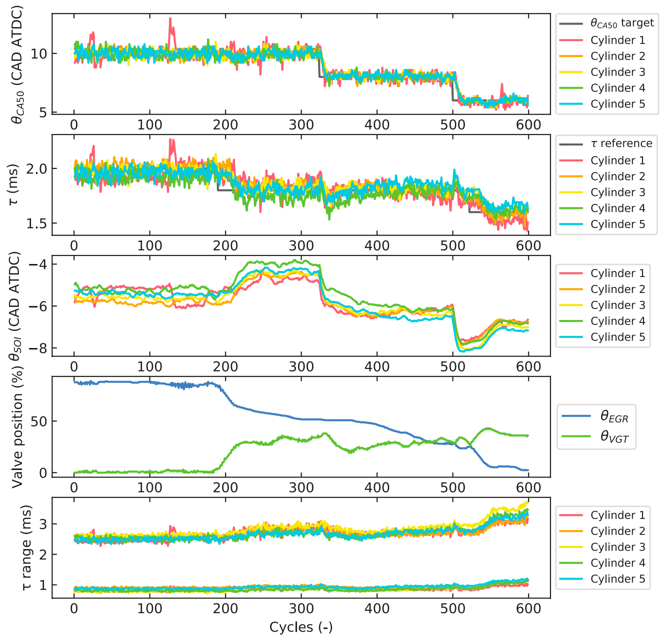
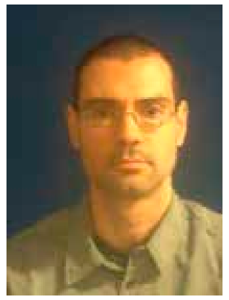


Figure 7
Controller behavior towards end of gasoline/n-heptane to ethanol/n-heptane transition



Researcher:
Nikolaos Dimitrakopoulos

Supervisor:
Martin Tunér

PPC PERFORMANCE USING LIGHT-DUTY DIESEL ENGINE HARDWARE

Introduction

The PPC-LD (Partially Premixed Combustion – Light Duty) project focuses on the application of the PPC concept on a commercially available engine. PPC, an advancement over the older HCCI concept, promises both high fuel efficiency and low exhaust emissions, something that the traditional SI and CDC cannot provide at the same time. Low emissions are achieved by combining; high amount of EGR, around 30%–50%, to reduce the combustion temperatures and hence the NOx formation; and earlier injection timings, to premix the fuel and reduce the low oxygen areas that promote soot formation. High efficiency is due to the premixed type of combustion, a fast combustion event is possible, giving a higher effective expansion ratio.

Background

One of the questions in the PPC-LD project is how large operating range that can be achieved with PPC on renewable alkylate gasoline and the standard diesel engine hardware used in the project. In addition to that, the work aim at answering the quality of performance within that load range (combustion, emissions and efficiencies) and also to explore means to improve efficiency, reduce emissions and extend the load range while respecting operation quality thresholds such as operation stability and combustion noise. The final part investigates the performance of gasoline PPC in a hybrid vehicle compared to a conventional diesel car.

Methods

The experimental part of the work was performed on a standard Volvo Car 2-liter diesel engine with a twin turbo setup. The engine system was modified with a long route EGR loop, an in-house control system and various measurement sensors [1]. Conventional E5 gasoline, alkylate gasoline and diesel fuel where used in the experiments. For the vehicle simulations, experimental engine data was shared with CTI in Spain who modelled the vehicles with the numerical tool GT-Suite [2].

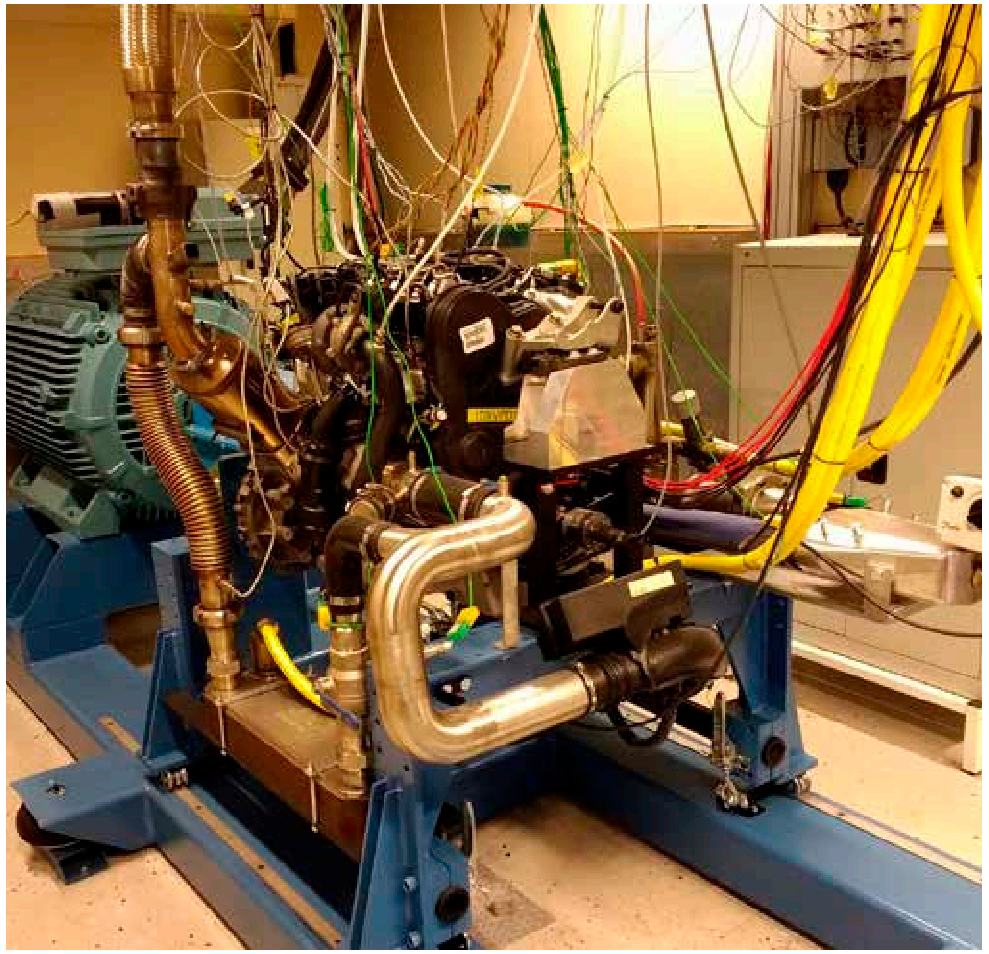


Figure 1
Experimental setup

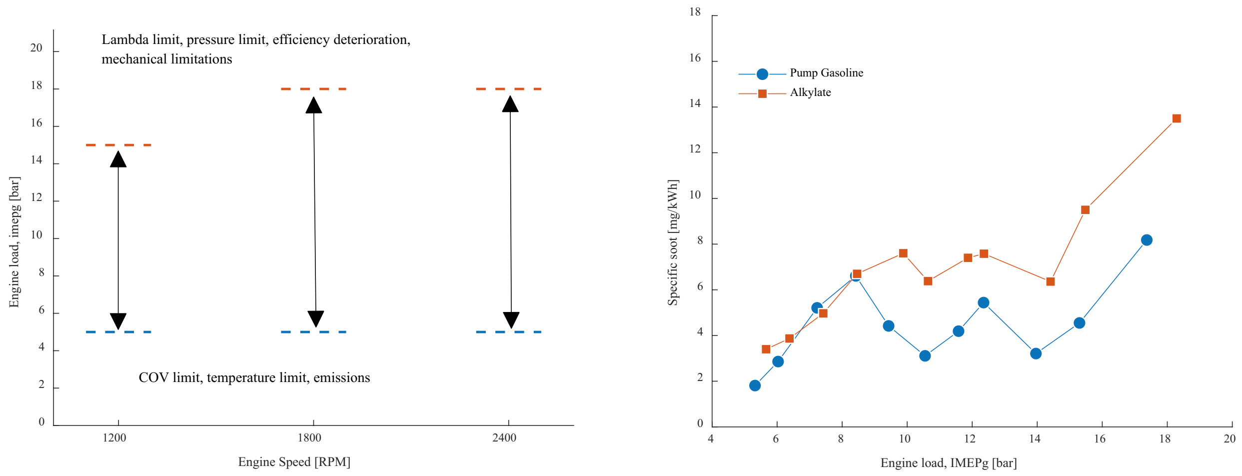


Figure 2
Operating range and limitations (left) and soot (right)

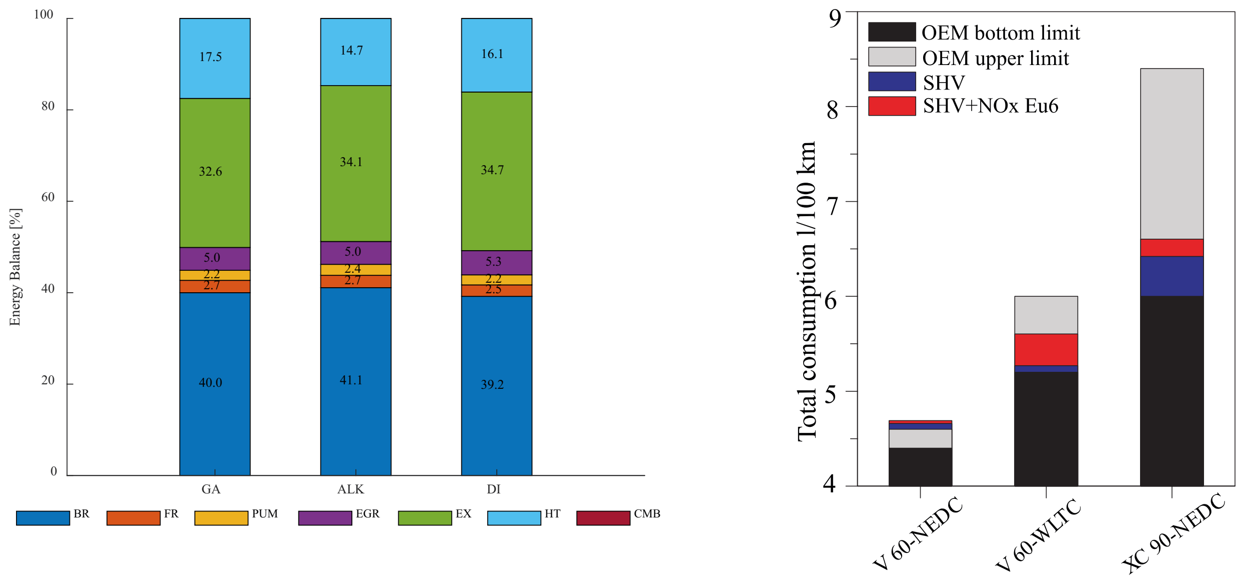


Figure 3
Energy balance with three different fuels (left) and in-vehicle performance in the NEDC and WLTC drive cycles (right)

Results

The results show that PPC-LD on alkylate gasoline provides some advantage over conventional gasoline in terms of efficiency [3]. The peak gross indicated efficiency reaches 47% while the brake efficiency reaches 41% which is higher than with diesel fuel operation and substantially higher than conventional gasoline engines. Soot is unexpectedly higher for the low aromatic alkylate gasoline, compared to conventional gasoline, but still orders of magnitude lower than operation on diesel fuel. HC and CO emissions are generally low while NOx is higher than the limit for Euro6 emission levels. The indicated peak load is 18 bar, which is about 25% lower than for diesel fuel operation. Low load limit is about 5 bar, but glow plug assistance helps in reducing the required inlet temperature and increases operation stability at lower loads [4]. The far from optimal approach with a series hybrid with PPC engine on renewable gasoline is still very competitive on overall energy consumption compared to the same vehicles operating on diesel fuel [3]. Overall the performance is good for an engine system that is not optimized in any way for the combustion principle and fuel that were used.

Outlook

Dr. Nikolaos Dimitrakopoulos defended his doctoral thesis on February 20, 2020.

Researcher:
Erik Svensson

Supervisor:
Sebastian Verhelst

SYSTEM ANALYSIS OF A HEAVY-DUTY METHANOL PPC ENGINE

Objectives

After the MOT2030 project, Erik moved into KCFP to continue his studies on how methanol compared to other high octane fuels, in PPC-type combustion. The low sooting nature of methanol in particular, opened up new routes for optimization.

Introduction

The PPC concept relies on a high degree of dilution with exhaust gas recirculation (EGR) and air. This dilution and premixedness lead to a lower global temperature, which reduces NOx emissions and wall heat transfer which therefore results in a high thermodynamic efficiency. However, a high level of dilution reduces the exhaust temperature and thus leads to a lower gas exchange efficiency because the turbine needs to compensate by generating a higher exhaust back pressure.

The first part of the work, mostly done within the MOT2030 project, investigated the influence of dilution on the gas exchange performance. The gas exchange efficiency was seen to decrease exponentially at high levels of dilution. In addition, a low inlet temperature led to an increase in both brake and gross efficiencies. Furthermore, an evaluation of turbocharger configurations revealed that, although a two-stage turbocharger only negligibly increased the brake efficiency, it enabled a substantially higher engine load than the two single-stage turbochargers. Finally, the gas exchange efficiency was increased with 4 %pt. by using a combined low and high-pressure EGR system.

The second part, mostly done within KCFP, focused on optimizing the engine boundary conditions, choice of fuels, and injection strategy, of which the results are reported below.

Methods

The work employed a combination of 0D and 1D simulation tools, validated on single and multicylinder measurements. The first PPC coupling of a stochastic reactor model and GT-suite was used to enable full cycle simulation. Furthermore, the particle swarm algorithm was applied to conduct engine operating point optimizations.

Results

With methanol it was possible to obtain a 2.2 %pt. higher brake efficiency compared to gasoline. Moreover, if the engine compression ratio was increased to 21.6:1 (compared to the standard of 17.3:1) the brake efficiency increased 1.4 %pt. further. A significant increase in brake efficiency was obtained by applying an early injection strategy with methanol. However, it was found that the sensitivity of combustion to inlet conditions was large for these early injection strategies. The large degree of thermal stratification was found to be responsible for the lower maximum pressure rise rates with methanol. Erik defended his PhD on June 13th

Conclusions

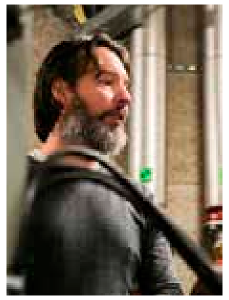
Amir Bin Aziz has been testing the simulations as enabling high efficiencies, to validate the results. Further validation will be carried out within the EU Horizon2020 FASTWATER project starting in the summer of 2020.

Gas engine research

Methane based gases such as biogas and natural gas represent a small but important portion of the total fuel usage for internal combustion engines worldwide because of the relatively low carbon content in methane as well as the potential to prevent methane release into the atmosphere through production of biogas. Furthermore the worldwide natural gas reserves are enormous and would last hundreds of years at today's rate of consumption.

KCFP has two gas engine projects, one focusing on diesel pilot ignited natural/bio gas combustion and a newly started project on spark ignited gas engine control using ion current feedback. Initial results from optical studies of early and late pilot injection are presented below indicating e.g. that combustion stability benefits from a conventional late pilot injection. Further analysis will improve our understanding of dual fuel combustion and the interation between diesel ignition and natural gas combustion. The gas engine control project is in the initial stage of engine installation and plans for future activities regarding engine control based on real-time ion current analysis are outlined below.

Professor
Per Tunestål



Researchers:
Menno Merts
Saeed Derafshzan

Suvervisors:
Sebastian Verhelst
Mattias Richter
Marcus Lundgren

OPTICAL DIAGNOSTICS ON DUAL-FUEL COMBUSTION IN A MEDIUM-SPEED WÄRTSILÄ MARINE ENGINE

Introduction

As a follow up on the KCFP work of now dr. Pablo Garcia, new research has been conducted on the Wärtsila W20DF medium speed marine engine at Lund University. In 2019 the work consisted of optical diagnostics, on dual fuel combustion. The diagnostics chosen for this investigation is high-speed imaging of natural luminosity (NL) in the combustion chamber of the optical engine.

This investigation has been carried out by Menno Merts, responsible for the dual fuel combustion and running the engine and Saeed Derafshzan, in charge of the optical diagnostics part.

Objectives

Natural-gas/diesel dual fuel combustion enables the usage of a low carbon (bio) fuel at high, diesel-like, efficiency. Applications with a wide range of gas diesel ratios are seen. For marine applications the most interesting configuration is the pilot ignited gas engine. The combustion chamber has optimized parameters for gas operation, while only a very small pilot injection is used to ignite the premixed natural gas. The Wärtsilä W20DF engine at Lund's engine laboratory is such an engine. A high replacement ratio of diesel by natural gas can be achieved, but challenges can still be found in complete combustion of all natural gas, and low enough NOx emissions. For this reason more insight is required to understand the start of combustion by the diesel pilot, the interaction between diesel and gas combustion, and the propagation of gas combustion. This forms the goal of the actual KCFP work in Testcell 12 of Lund University.

Methods

In a previous period the engine has been tested in single-cylinder metal configuration, as reference. After that it was converted to optical access, by a Bowditch design. This was part of the thesis work of Pablo Garcia, but start-up problems prevented the intended testing. In 2019 the configuration was made up and running. A few engine modifications, along with a more rigorous maintenance of the optical surfaces (mirror), made it possible to record the natural luminosity. The piston design in this engine is flat, thus eliminating the need to make distortion correction on the images (otherwise in post-processing the distortions in the images had to be corrected by using a target image). The field of view was chosen to get a view as big as possible on the glass piston top. The result is a circular view (represented by the red circle in Figure 1) on the combustion chamber, coaxial with the centrally placed injector. The view covers the majority of the intake and output valves. Natural luminosity was recorded with a high-speed Photron SA-X2 camera, at 15000 fps, which is fast enough to record different phenomena during the combustion. Skipfire operation, sequencing 6 fired cycles with 6 motored cycles, was applied to limit the thermal load on the glass piston-top. The engine was operated at medium load at 900 rpm, with a gas equivalence ratio close to 0,5. A range of diesel injection pressure and lengths have been applied, covering Gas/diesel energy ratio's between 80 and 90%. Both early (RCCI-like) and late (conventional) diesel SOI has been investigated.

Figure 1
Field of view through piston top.

Results

The engine was able to run successfully on the chosen dual fuel operating points, and clear images could be recorded, without blurring by engine-oil on the optics.

Differences could be recognized between the early and late diesel injection. With an early injection the optical images showed the diesel fuel was highly premixed before acting as ignition source. In the late injections the conventional diesel jet could be recognized and it was observable that this is where combustion started. The natural gas combustion flame front propagates from the jets through the combustion chamber. Both the optical recordings and cylinder pressure measurements showed a lower cycle to cycle variation for the late injection cases. The coverage by combustion of the full chamber filled with premixed gas appeared higher in this late injection mode.

An example of recorded images for a late-injection case can be seen in Figure 2. Here the 9 plumes can be recognized, each corresponding to a nozzle hole of the diesel injector. These late injections resulted in brighter combustion plumes indicating radiation soot from the rich combustion of the diesel fuel, while earlier injections created more homogenous combustion, with less bright images. To have a comparable benchmark, exposure and f# of the camera, were kept constant during the experiments. This resulted in a slight saturation in a few of the images, which was just acceptable. Applying a smaller exposure time or a bigger f# was not possible since this would result in loss of information for some of the recorded images in early injection cases. With their leaner premixed diesel combustion they produce less light, which then partly would not be captured.

Conclusions and outlook

The experiments have been conducted fully at this point, and clear phenomena such as ignition and its location, and flame propagation and their dependence on engine parameters are well captured. Further post-processing and analysis of the data which is ongoing will help us to better understand this dual-fuel approach and the interaction between diesel ignition and natural gas combustion. A conventional late diesel injection seems favorable for combustion stability and higher utilization of the premixed gas. Optimizations can be expected in injection (SOI and pressure) and injector (throttle ratio, nozzle design) parameters. This should result in a higher efficiency and lower emissions (NOx and uHC) while operating at a low diesel share.

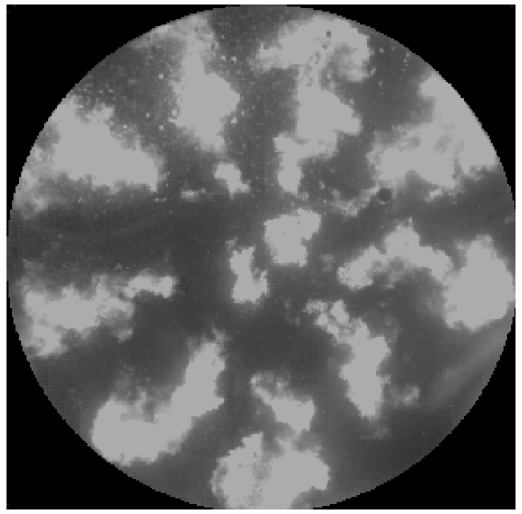


Figure 2
Typical late-injection case

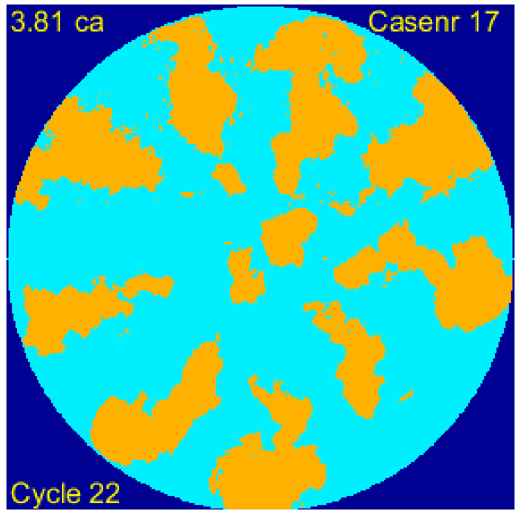
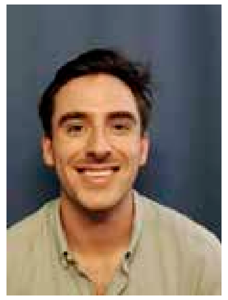


Figure 3
High and low intensity light from dual fuel combustion



Researcher:
Ola Björnsson

Supervisor:
Prof. Per Tunestål

GAS ENGINE CONTROL THROUGH ION CURRENT MEASUREMENTS

Objectives

Natural gas / biogas is an abundant low-carbon (bio) fuel with many spark-ignited heavy duty and medium speed applications. Large variations in fuel quality both regionally and over time cause spark-ignited gas engines to operate with lower than nominal efficiency due to incorrect combustion timing.

Introduction

A new project on gas engine control was initiated during the year. Ola Björnsson joined the project as a PhD student in June. The project focuses on using ion current feedback to improve efficiency. Ola Björnsson has a background in signal processing which is going to be an important element for interpretation of the ion current signal.

Methods

By measuring and analyzing the ion current in each cylinder, using the spark plug as sensor, information about combustion timing and knock, among other things, can be extracted and used for feedback control of both ignition timing and fuel injection (figure 1 and 2). Methods from signal processing and control theory will be applied

Results

During the year a 6-cylinder, 13 liter SI gas engine has been supplied by Volvo AB (figure 3). The engine was first shipped to Metatron in Italy where the ECU, wiring harness and some sensors were fitted. The engine arrived at Lund University in December and installation and necessary adaptations were initiated. Literature study and planning of research activities are being conducted in parallel with the mechanical installation work.

Conclusions

First fire-up of the engine is planned for beginning of the second quarter 2020. Subsequently some weeks will be spent on a simplified calibration of the ECU in order to allow at least steady-state operation in the entire speed/load operating range. Existing methods for estimating the peak pressure location from ion current measurements will be evaluated and used for combustion timing control.

Figure 1
Ensemble average of ion current measurements.

Figure 2
Ion current of a knocking cycle. High frequency "ringing".

Figure 1

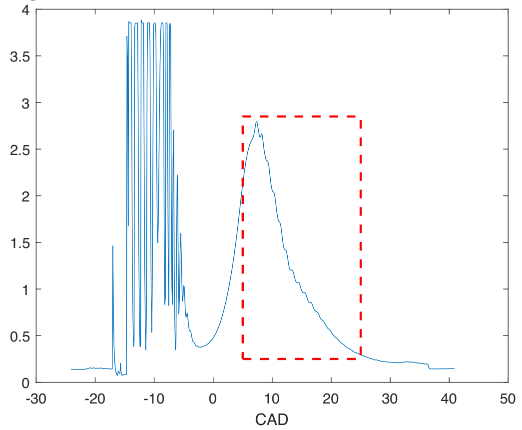


Figure 2

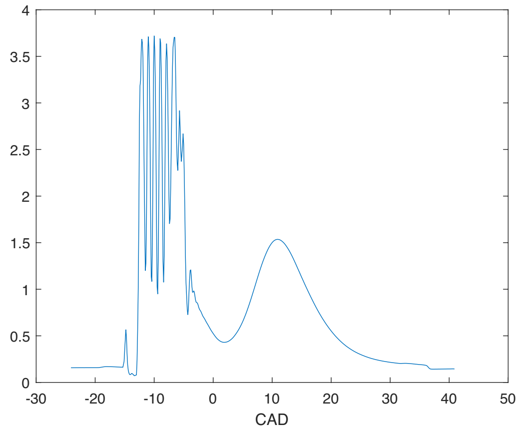
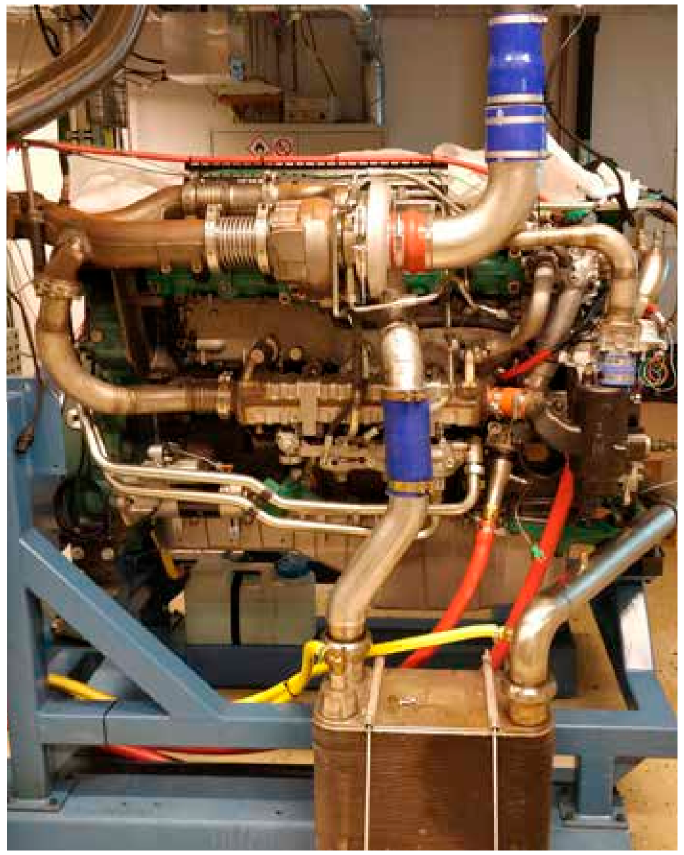


Figure 3
The test engine from Volvo being installed in the engine lab.



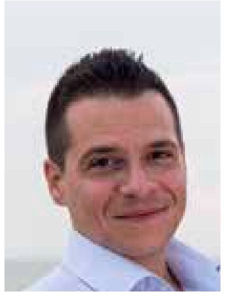
Optical diagnostics

Optical measurement techniques are employed for in-cylinder diagnostics, within the different research areas of KCFP. In general, optical diagnostics have merits, such as superior temporal and spatial resolution, which are highly valuable for engine applications. Another great benefit associated with optical measurements, is the remote probing capability where there is no physical interaction with the studied object. Through knowledge of the spectroscopic properties, optical diagnostics such as laser induced fluorescence, can be species specific. This facilitates the capturing of, e.g. 2D concentration distributions of individual species such as fuel, OH-radicals, formaldehyde, etc.

By using powerful pulsed lasers, the probing time or exposure time when performing imaging, can typically be set to 8 ns. At 1200 rpm, this time corresponds to less than 0,00006 crank angle degrees. Hence, measurements can be performed on a time scale where both the flow field and the chemistry of the studied processes are frozen. Most of the powerful lasers used for diagnostics operate at 10 Hz. This generally facilitates one measurement per combustion event. By phase-locking the laser and detectors to the engine, measurements can be carried out at any desired timing. Data recorded at different CAD (in different cycles) can then be put together to study phase-averaged development as a function of CAD. Due to the significant cycle-to-cycle variations it is sometimes desirable to resolve a single cycle event. At Lund university there is an extensive infrastructure and capability to perform optical measurements at high repetition rates. This includes for example high-speed filming of flame development using CMOS-cameras to capture chemiluminescence, or high-speed MIE scattering for temporally resolved measurements of droplet penetration length in fuel sprays. By employing unique high-speed lasers, such as Multi-YAG's or Burst Mode Lasers, also more sophisticated laser based imaging techniques can be employed at repetition rates up 100 kHz.

The output from the optical diagnostics is used to gain better understanding of the in-cylinder processes, both from a direct engineering perspective and through coupling to the CFD simulations performed within the competence center.

Professor
Mattias Richter



Researcher:
Alexios Matamis

Supervisor:
Mattias Richter

OPTICAL CHARACTERISATION OF METHANOL COMPRESSION IGNITION

Objectives

The aim of this study is to optically characterise methanol injection and combustion in compression-ignition processes. Looking through the literature there is a surprising lack of data on how methanol behaves in spray-driven and Partially Premixed Combustion (PPC). The reason for this is methanol's high heat of vaporisation which makes auto-ignition of methanol challenging. However, techniques such as exhaust gas recirculation and multiple injections can reduce the heat required for auto-ignition of methanol. By analysing methanol combustion in a compression-ignition optical engine along with prior work on metal engines, the knowledge accumulated within this project aims at demonstrating the potential of methanol as an exceptional alternative fuel, since it is possible to combine low emissions and high engine efficiency.

Introduction

The majority of the work during 2019 consisted of analysing the data acquired during the 2018 experimental campaigns with the Scania D13 optical engine. The experiments mostly focused on the optical evaluation of methanol as a renewable fuel suitable for Partially Premixed Combustion (PPC), due to the extreme Ignition Delay (ID) that methanol offers, and a comparison was made with a more conventional PPC fuel, in this case PRF81. However, due to the vastly different engine operating conditions required for similar operation of the different fuels, the comparison to PRF81 is limited to liquid spray length observations in identical, non-reacting conditions which will be used for CFD validation.

The following key aspects of methanol injection and combustion were discovered and analysed:

A wide range of Start-Of-Injection (SOI) timings were tested at non-reacting conditions that provide useful calibration data for methanol spray modelling, both in terms of where the fuel is distributed and how the liquid length varies while ambient temperature and pressure varies.

The injection pressure effect was studied while maintaining combustion phasing, load and thus fuel amount constant. The operating conditions were established from previous work on a conventional Scania D13 engine. The analysis of this data is currently ongoing.Ignition location and combustion behaviour were captured relative to fuel distribution and stratification for different injection timings ranging from PPC to spray-driven combustion modes.

Ignition location is found close to the middle point of the radius of the combustion chamber, regardless of where the majority of the fuel is located, indicating a complex ignition mechanism.

Results

Methanol vs PRF81

A direct comparison between methanol and PRF81 was attempted in non-reacting conditions, for two different SOI timings, -17° and -35°. These SOI's were chosen as benchmark cases, with the same injector and at identical ambient conditions. More data comparing the two fuels exists, however not at identical operating conditions and not with identical engine hardware. The interesting outcome from this comparison is the liquid length of PRF81 proved to be far less sensitive to ambient conditions compared to methanol. In Figure 1, snapshots of the sprays are overlaid with false-colour (methanol in green and PRF81 in purple). In the late injection timing of SOI -17, the liquid length is comparable for the two fuels as indicated by the snapshot overlay and by the graph with measured liquid length over the number of frames in the high-speed sequence. In the case of methanol, the fully developed liquid length is consistently shorter in comparison to PRF81 while in transient conditions (injector needle opening and closing), liquid length is similar for both cases. In the early injection timing however, where pressure and temperature are lower, the liquid penetration length of methanol appears much larger and in fact exceeds the field-of-view (FOV) allowed by the piston, thus the plateau on the blue curve for the SOI -35 case.

Liquid Length vs SOI

In order to validate methanol spray models, a few non-combusting cases were chosen in order to capture the temperature and pressure effect on the liquid spray length. Three SOI's were selected, representative of the typical SOI range that might be implemented in PPC and spray-driven combustion, consisting of SOI -8°, -25°, -46°. Intake pressure was set at 1.5 bar and intake temperature was set at 70°C, lower than required to obtain combustion in any of the SOI timings. The results are summarised in Figure 2, plotted along with the in-cylinder pressure trace. A trend is obtained of how the transient and peak liquid length varies over 50 cycles for each SOI case. In order to obtain these curves only 5 of the 10 spray plumes were used in order to have reliable and consistent data. The laser light used for

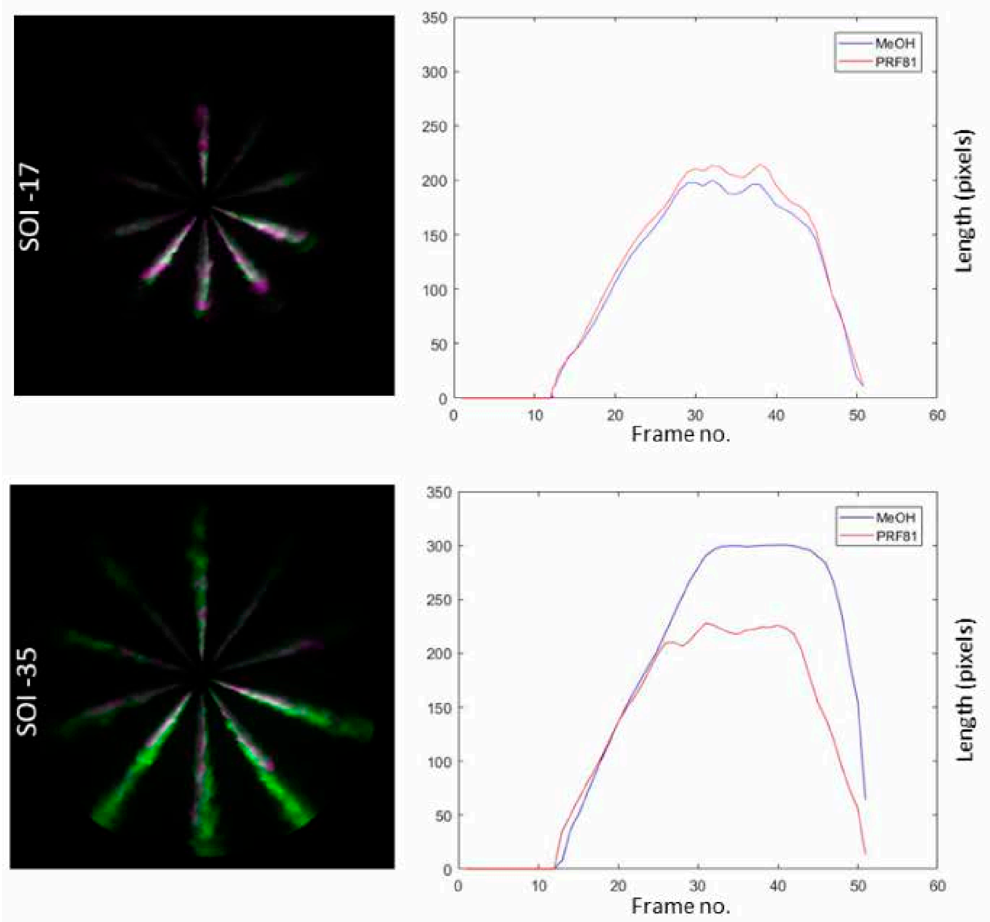


Figure 1
(Left) Snapshots of the two fuels at the same frame number for the two SOI timings are overlaid in false-colour (green for methanol, purple is PRF81).
(Right) Liquid length plotted over one cycle. While in SOI -17 liquid lengths are very similar, in the case of SOI -35 methanol has larger liquid length.

Mie-scattering enters from one side-window of the optical engine and gets scattered from the liquid spray droplets of the fore spray plumes. Thus, less light propagates towards the aft sprays, resulting in less reliable information as the signal-to-noise ratio drops significantly making the liquid part edges less discernible for the algorithm to detect.

Ignition location and combustion behaviour

A dual-camera setup was used, consisting of a high-speed camera to record combustion chemiluminescence and an intensified-CCD (ICCD) camera was used to capture fuel distribution via acetone fuel-tracer Planar Laser Induced Fluorescence (ft-PLIF). The 266nm laser pulse was formed to a sheet and provided a cross-section view of the fuel distribution inside the cylinder. The pulse was fired right before the onset of combustion and the high-speed camera started recording 200µs earlier. This timing setup was selected as the laser light source was capable of 10Hz repetition rate, thus only one laser pulse was available for each combustion event. Nevertheless, the high-speed camera operated at 30000fps, temporally resolving the combustion event. By using calibration targets the two different camera views were registered and the chemiluminescence images could be overlaid with the fuel distribution images. By doing so, the combustion behaviour relative to fuel distribution can be monitored within individual cycles despite lack of time-resolved fuel distribution data. This technique was benchmarked by checking the overlap ratio of combustion over fuel distribution. Depending on SOI case, the fuel distribution image remains relevant for a significant amount of time corresponding to multiple CAD's duration.

Due to cyclic variations, combustion occurs at different timings with respect to the start of image acquisition. In order to study combustion location and behaviour over many cycles, first the image sequences from the high-speed camera need to be phased to the start of combustion. This is achieved by finding the first frame where combustion occurs and labelling that frame as the first of the sequence. An illustration of this can be seen in Figure 3. Then, all cycles are phase-locked

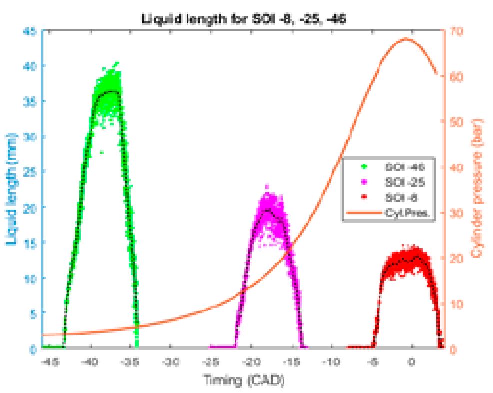


Figure 2
The graph summarises all measured liquid lengths for the 5 sprays. The liquid length of each spray is plotted for the full cycle, for all 50 cycles, along with the average indicated by the dotted black lines. The in-cylinder pressure is also plotted to better demonstrate the effect on liquid length.

and combustion progress can be studied, over multiple combustion events, in terms of average spatial location and growth rates. Once the image sequences are synced to start of combustion the average combustion images can be overlaid on the average fuel distribution images for all cycles studied and for SOI's of -7, -10, -17 and -25. In Figure 4, two indicative cases are shown, -7 as indicative of spray-driven combustion and -17 as indicative of PPC combustion. The other cases behave similarly, as -10 is also spray-driven and -25 is PPC type of combustion. The average combusting area in each frame is used as a mask over the fuel distribution image and the average intensity of those pixels is used as an estimation of fuel concentration. In the next time step, the previously combusting region is subtracted from the current combusting region and only the new combusting regions are used as mask to probe fuel concentration. The same procedure is carried out for the subsequent frames and thus a trend is derived of where combustion occurs and which fuel regions are preferred for propagation. The graph of Figure 4 summarises the results for all SOI's and it becomes apparent that for spray-driven combustion ignition occurs on fuel rich regions and propagates towards fuel-lean areas. The opposite is true for the PPC cases where on average, ignition occurs at fuel-lean regions and propagates towards more fuel-rich areas. The fact that combustion propagates differently in reality isn't a physical phenomenon but rather that fuel concentration alone is a poor metric for predicting combustion. Ignition sites for all SOI cases are usually very close to the centre of the bore, regardless of where most of the fuel is located. Thus an underlying mechanism exists that enables ignition in those regions.

Conclusions

Methanol injection and combustion during compression-ignition have been optically investigated. We have developed tools in order to evaluate the liquid length for various engine operating conditions and obtained valuable spray data. A high dependence of methanol on initial temperature and pressure conditions is observed compared to a commonly used PPC fuel. The liquid length dependence on SOI has also been studied and this data can be used in order to validate CFD models. Additionally, the combustion behaviour of methanol combustion in spray-driven and PPC modes has been analysed. A method has been developed in order to phase the combustion images to a common start in order to minimize the influence of cyclic variations on flame shape and ignition location. Methanol combustion, particularly in spray-driven cases is vastly different to what is commonly observed in other diesel-type fuels. All this data has been submitted to academic journals and is awaiting publication.

Figure 3

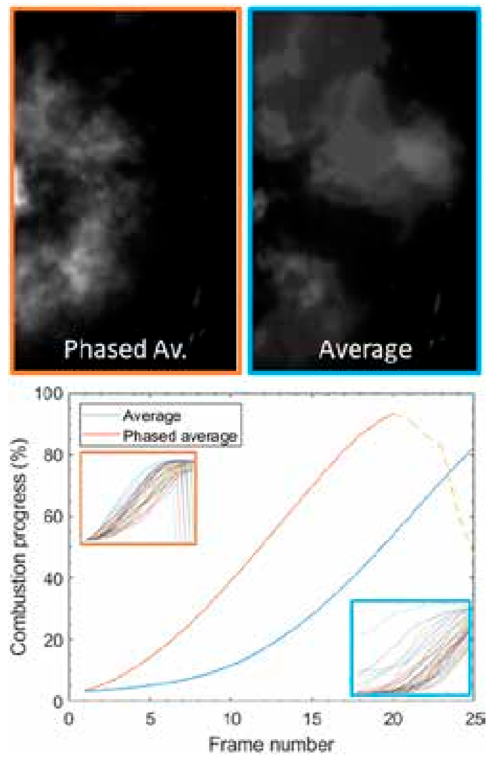


Figure 4

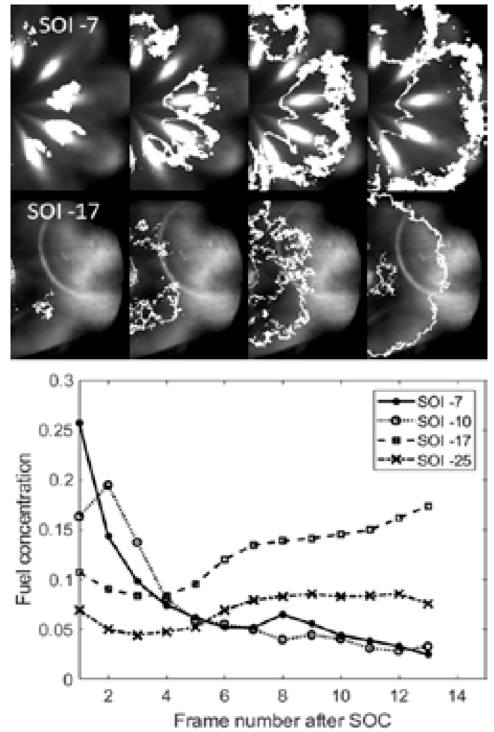


Figure 3
Phased vs plain averaging of combustion images and the resulting progress curves. In the insets of the figure the combustion progress curves of all 50 cycles can be seen for the two different processing methods.

Figure 4
Average combusting area overlaid on average fuel distribution for SOI -7 and -17. In both cases the ignition location is radially close to the centre of the bore. (Below) The graph summarises the combustion propagation tendency for the different SOI's.

OPTICAL TECHNIQUES FOR STUDIES OF PARTIALLY PREMIXED COMBUSTION (PPC)

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Supervisor:
Mattias Richter

Objectives

Different injection strategies and their effects are investigated in an optically-accessible engine. The low-temperature combustion mode in use here is partially premixed combustion (PPC) for which the mixing process is of great importance. Different optical techniques were utilized, first the high-speed imaging of natural luminosity in the combustion chamber, which was followed by Mie scattering to capture the fuel sprays.

Introduction

Partially premixed combustion (PPC) as a combustion mode for internal combustion engines, has shown potentials for achieving high thermal efficiency and low emissions. This concept is usually achieved by using multiple injection strategies. The reasons behind this better performance of engines are yet to be understood fully and during this research campaign we aimed at shedding light on these underlying mechanisms.

Methods

Experimental SetupAn optical engine based on Volvo MD13 heavy-duty engine is run in skip-fire mode at 1200 rpm for this campaign. Different injection strategies and timings, including early and late single, double, and triple injection are investigated and the results are compared to the engine parameters. The setup and its schematic, together with injection strategy profiles are shown in figure 1.

The diagnostic techniques that have been utilized are high-speed imaging of natural luminosity following by Mie scattering to capture fuel sprays. The high-speed camera was a CMOS Photron SA-X2 camera which was recording at 27000 fps, sufficiently fast to capture combustion development in the combustion chamber. For Mie scattering section, a CW diode laser at 452 nm was used to create to horizontal laser sheet for illuminating the fuel particles.

Furthermore, computational fluid dynamics (CFD) simulation of these cases has been carried out and added to the publication.

In this setup, bowl-shape design of the piston distorted the images, and this distortion needed to be removed. This is achieved by recording a target image and removing the distortion in Matlab. The same procedure then is performed on each image to get a proper flat projection of the combustion chamber. This procedure can be seen in the figure below, where the top left image is a distorted target image, and the bottom right one is the result after post-processing in which the distortion is accounted for and resolved.

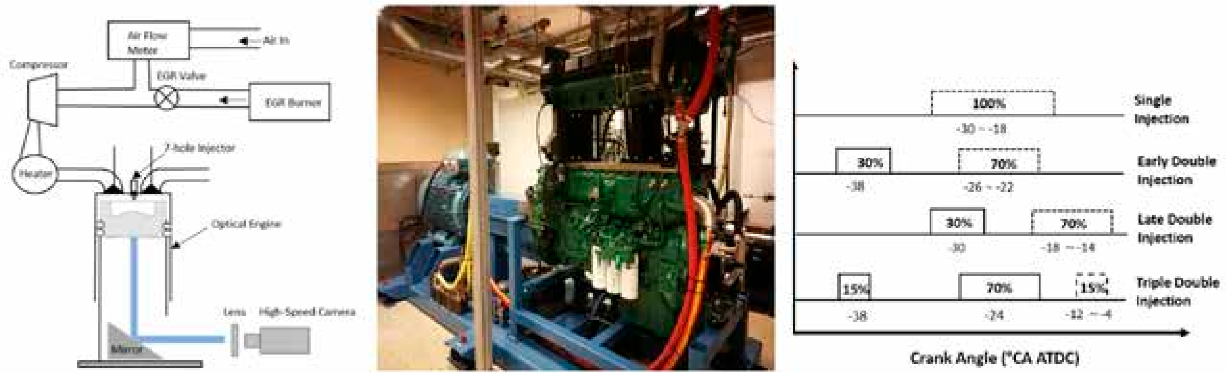

Figure 1
Schematic setup (left), Volvo heavy-duty optical engine (middle), and injection strategy profiles (right)

Results

After post-processing, the results of captured images together with other engine data were used to shed light on PPC combustion concept and the effect of different injection strategies in optimizing the efficiency and emission. A few exemplary results are shown here and of course more results and discussions can be found in the 3 papers that are published within this research campaign.

First, the average natural luminosity of 50 cycles for different injection strategies, single, double, and triple injection are compared for ignition, middle (CA50), and late combustion phase (CA90) in figure 3. We observed that in the triple injection (third row) the combustion is more homogenous and less fuel-rich bright areas exists which is an indication of low soot emissions. These observations along with other results, helped us understand how a more advanced injection strategy can benefit engine output parameters.

The imaging of combustion in optical engines usually suffers from injector dribble, which is essentially locally-rich burned and might saturate the imaging sensor. To mitigate this effect, a small circular area in the middle of the piston was covered with graphite painting, which eventually allowed us to capture dimmer, more homogenous chemiluminescence in PPC engine.

Furthermore, in figure 4 the comparison within double injection cases for early and late injection shows that the combustion in early injection cases (first and second row) spreads more toward the center while in late injection cases (third and fourth row) it stays closer to the recirculation zone, closer to the bowl area, which can lead to different heat loss for these cases. These images were further used as a validation tool for CFD analysis which is discussed in detail in "Analysis of engine efficiency in an optical PPC engine" report.

Mie scattering of the fuel sprays were the following part of the research, in order to see how these different injection strategies change the fuel sprays. These spray images are valuable to see how the fuel sprays develop and they were further used in combination with natural luminosity images to address various effects of the aforementioned injection strategies.

A set of Mie scattering images As it is clearly captured here, earlier injections lead to more liquid penetration length (left column), while in late injections, higher temperature and pressure shortens the liquid penetration length (right column).

Conclusion

By using two optical techniques, natural luminosity and fuel sprays are captured at high-speed rates by high-speed imaging of combustion natural luminosity and high-speed Mie scattering measurements. and the extracted data were used together with the engine data to show how different injection strategies, can affect the engine performance in a PPC engine.

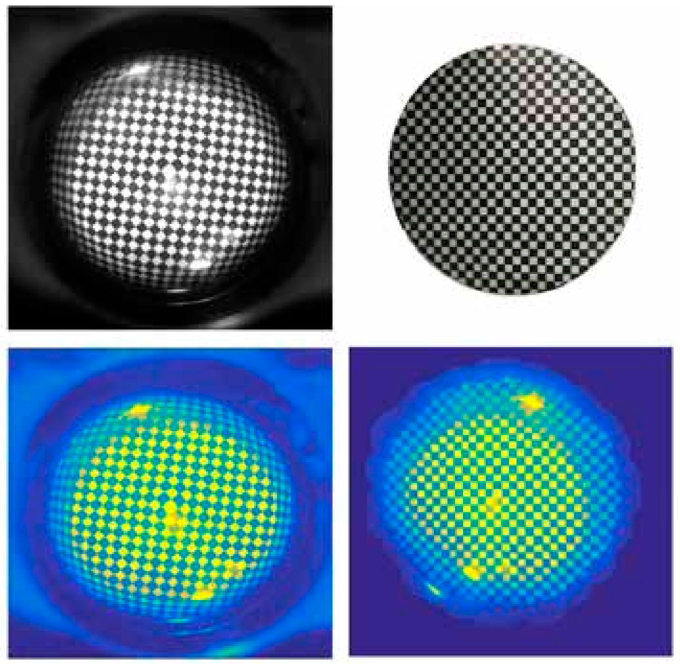

Figure 2
Distortion correction, top left is distorted image, top right is the target image, bottom left is image in post-processing, and bottom right is the resulted image after post-processing.

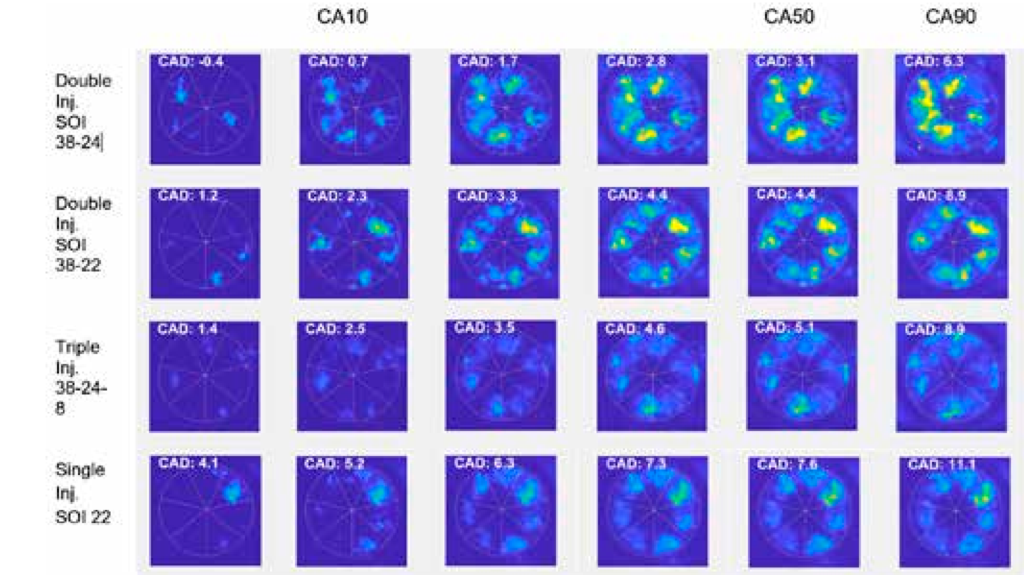

Figure 3
Natural luminosity of Single, double, and triple injection strategies

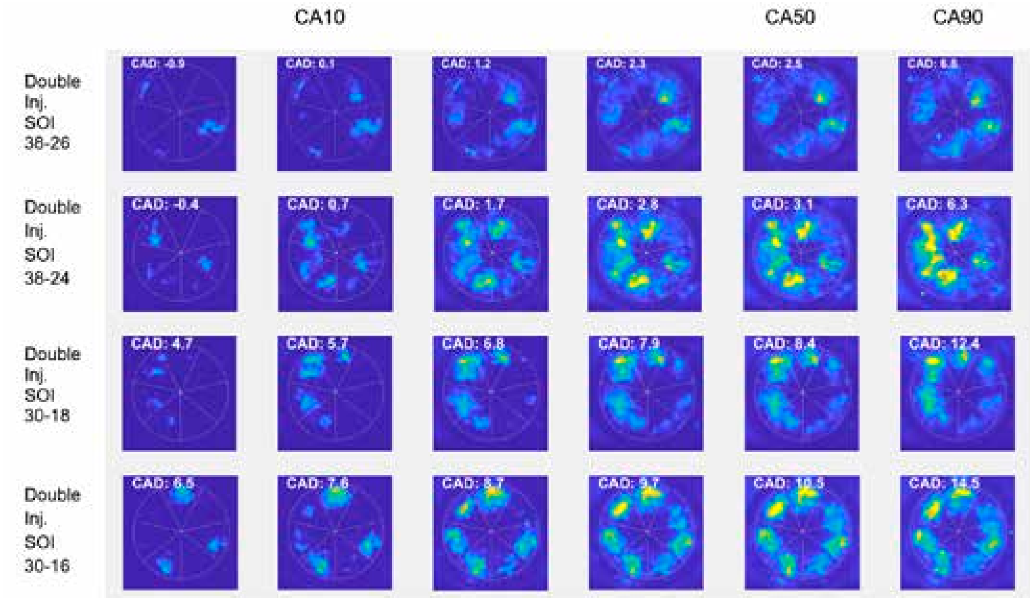

Figure 4
Natural luminosity of early and late double injection

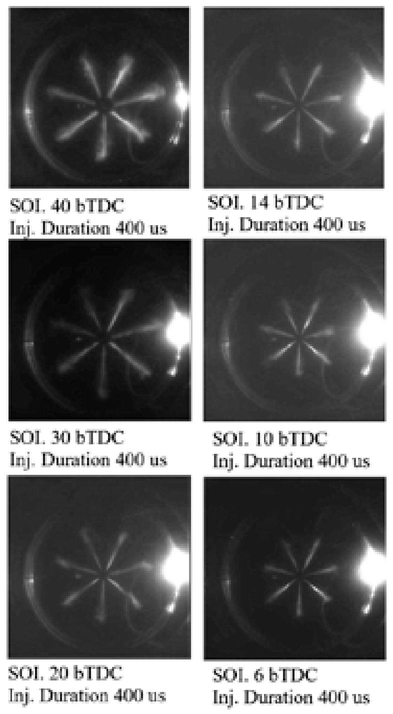

Figure 5
Mie scattering of fuel sprays for 6 different start of injection time



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WAVE PISTON FLOW FIELD VISUALIZATION

Introduction

Lots of efforts have been put to increase the efficiency of combustion and reduce the engine emissions and optimizing the geometry of the piston bowl shape and design is of great importance for this goal. A novel design for the piston bowl has been introduced recently, which is called wave piston as it has wave-shape protuberances on the peripheral of the piston bowl. This design is attributed to a better mixing of fuel and air, which in turn increase the fuel efficiency and less emissions.

To look further into this design, a similar optical piston, has been designed to use in research optical engines, and better understand these positive effects. The following picture shows this optical wave piston. It is worth noticing that the waves in the optical piston (in contrast to the metal design) are only on one side so that the incoming light source (laser light), does not get distorted in the entrance.

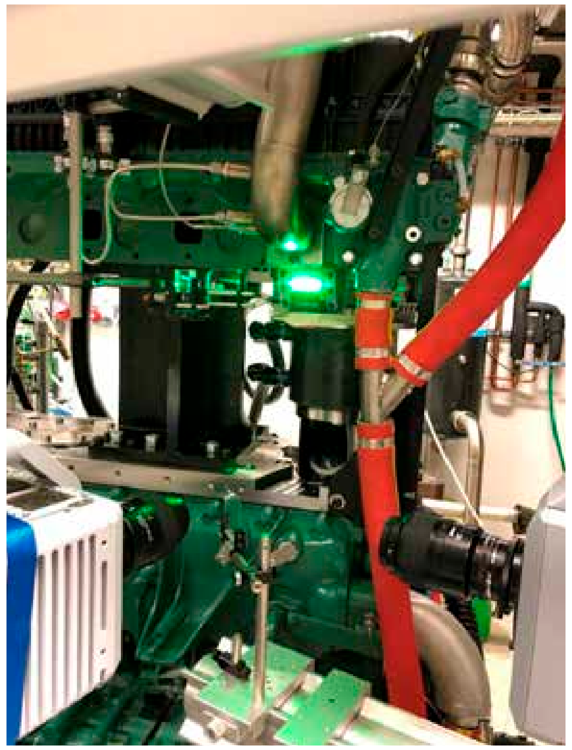
Optical Diagnostics

To visualize the flow field inside the combustion chamber, particle image velocimetry (PIV) is the main optical technique. A dual-cavity Nd:YLF laser creates double-pulsed laser light sheets, and the scattered light from the TiO_2 particles that are added to the mixture through the ports, is recorded with a high-speed CMOS camera (Photron SA-X2). Additionally, combustion natural luminosity is recorded at the same time with a 90-degree mirror located in front of the Bowditch design's mirror. Natural luminosity is also recorded with a similar high-speed camera (Photron SA-Z), and not only helps to record different combustion phases during the cycle, but also provides the opportunity to compare the flow fields derived by PIV to the flow fields that can be derived by treating the natural luminosity images with the same type of analysis as PIV (that the displacement between two frames, divided by the time difference between them, gives us the flow field). Due to its similarity to PIV, this technique is sometimes referred to as CIV (combustion image velocimetry). **Outlook**

This campaign holds a high value both from engine point of view and the diagnostics, and it has the highest priority, even though there have been some challenges with the equipment/setup. When receiving the laser from the manufacturer after some critical repair, experiments will continue.

Figure 9
Optical wave-piston

Figure 10
Experimental Setup, Wave-piston PIV and CIV



Detailed combustion modelling

THE USE OF CFD SIMULATIONS TO CHARACTERIZE PPC COMBUSTION

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PhD students sponsored by KCFP[1], MOT2030[2] and CSC[3]

Objectives

The goal of the CFD modelling project is to improve the understanding of the ignition and combustion process in advanced engine combustion concepts, i.e., partially premixed combustion (PPC) in the current project phase. PPC engine exhibits superior engine performance with high engine efficiency and best tradeoff between NOx emission and CO/unburned hydrocarbon (UHC) emissions. This has been demonstrated in single cylinder Scania metal engine experiments using different fuels, e.g., gasoline surrogate primary reference fuels (PRF) and alcohols (methanol). The main objectives of the CFD project are to provide detailed information about the flow, the fuel/air mixing in the cylinder, temperature and the species composition, to understand effect of charge stratification on the combustion process and emissions.

Introduction

Heavy-duty internal combustion engines are commonly based on Diesel cycle, as it consumes less fuel compared with its gasoline rivals. Diesel engines have better work characteristics suited to carry heavy loads. The challenge is the high emission output of NOx, soot and particular matter (PM). During the last two decades combustion engine research community has been focusing on the development of alternative combustion systems to diesel engines. Advanced concepts such as homogeneous charge compression ignition (HCCI), reactivity controlled charge ignition (RCCI) and partially premixed combustion (PPC) were developed based on the general idea of low temperature combustion (LTC), which results in cleaner emissions already in the combustion chamber. LTC engine concepts are promising and work excellent in the engine laboratory cell, however they barley exists on the global commercial scale due to the technical challenges regarding robustness of the combustion process, which is needed in the commercial applications. A number of different challenges are, for example, a limited operation load range due to the mechanical constraints, cold start issues or sensitivity to the inlet conditions. LTC engines are also characterized by a low exchange gas efficiency in comparison to Diesel engines, which can result in a similar brake thermal efficiency, despite an improved in-cylinder combustion process.

In the present project phase, PPC engine combustion in diesel-engine type piston geometries has been investigated in both engine experiments and in CFD simulations. It has been shown that while PPC combustion can reach outstanding efficiencies and low emissions the combustion process is sensitive to parameters like injection timing, fuel air mixing and intake gas temperatures. In 2019 the following CFD studies have been carried out, and the results are published in seven articles:

- CFD study of the effect of injection timing on the ignition and mode of combustion in an optical engine with a modified piston bowl geometry based on Scania D13 heavy duty engine [1].
- CFD study of the effects of in-cylinder flow on turbulent mixing in a Volvo D5 light duty engine at different injection timing [2].
- Large eddy simulation of the ignition front in an optical Scania D13 heavy-duty diesel engine [3].
- CFD study of combustion characteristics in a single cylinder Scania D13 (metal) engine in the transition from HCCI to PPC combustion [4].
- CFD study of emission characteristics and engine performance in a single cylinder Scania D13 (metal) engine in the transition from HCCI to PPC combustion [5].
- CFD study of methanol chemical kinetic mechanisms applied to heavy duty DICI engines [6].
- CFD study of methanol PPC combustion in a modified single cylinder Scania D13 engine with optical access and multiple injection strategies [7].

Methods

Computational Fluid Dynamics (CFD) simulations are used to study fuel injection, spatial and temporal evolution of mixture composition, chemical kinetics and the spatial and temporal distribution of onset of ignition and reaction front propagation. While metal engine experiments report the performance of the engine in terms of its efficiencies and emissions and the optical experiments provide direct measurements of physical quantities in two-dimensional physical space, CFD simulations provide further information about the three dimensional and temporal evolving physical quantities that cannot be measured experimentally. In the PPC engine context, CFD simulation is particularly important since the fuel/air mixing is dominated by turbulent transport that is a three dimensional and unsteady phenomenon.

The CFD tools used to model turbulent flow and combustion in the PPC engine modelling are dependent on the case which is studied, but since most simulations are calculated in engine-like geometries the relatively cost-effective Reynolds-average formulation of the Navier-Stokes equations (RANS) is used. This means that the resulting modeled turbulence (and quantities transported by turbulence) is an ensemble average of engine cycles. When studying small-scale flow details or cycle-to-cycle variations RANS model is insufficient and Large Eddy Simulation (LES) is employed instead. The liquid droplets of fuel spray are studied using Lagrangian Particle Tracking (LPT) with suitable evaporation and breakup modelling. Because PPC ignition is sensitive to the chemical kinetics, fully coupling of the finite rate chemistry is needed. Methods of coupling the turbulence to the chemistry are investigated and used based on what is deemed necessary to answer the posed scientific questions. Typical methods include the well-stirred reactor model, partially stirred reactor model, Eulerian stochastic fields and various flamelet based models.

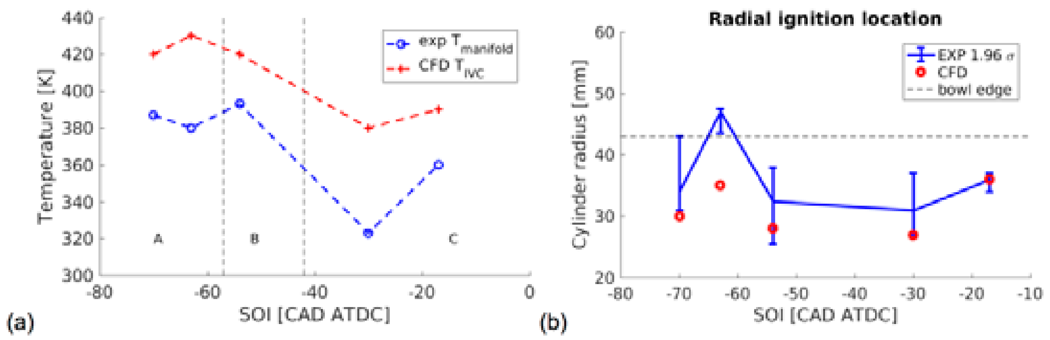
Results

Required intake temperature and ignition location

The effect of start-of-injection (SOI) on the ignition of a primary reference fuel (PRF81) and the subsequent combustion process in an optical Scania D13 heavy duty engine running at low load conditions are studied using CFD employing a detailed chemical kinetic mechanism. Five cases with injection timings ranging from SOI at -70 crank angle degrees (CAD) to -17 CAD after top dead center (aTDC) have been studied using RANS models and the results are compared with engine experiments. In both the engine experiments and CFD simulations the intake temperature was adjusted to keep the combustion phasing constant. Figure 1 shows that the required intake temperature in the experiments to maintain a constant crank-angle at which 50% of the chemical energy is released (CA50) varies with SOI. The ignition location varies with SOI as well. In the early injection case, i.e., the SOI-63 case (with SOI at -63 CAD aTDC), the required intake temperature is higher than the later injection cases, and the onset of ignition in the SOI-63 case is in the squish region, whereas the ignition takes place first in the bowl region in the later SOI cases. When the SOI is retarded further from SOI-30 to SOI-17 (SOI at -17 CAD aTDC), the required intake temperature increases with SOI and the ignition location moves towards the bowl edge. This 'spoon-shaped' intake temperature profile was also observed in Scania D13 metal engine experiments (with the production engine bowl geometry), cf. Ref. [4], and the underlining physics was investigated using CFD simulations, employing both RANS models [1], [4], and [5], and large eddy simulation [3]. The RANS simulations were performed in a closed cycle sector domain using the k-ϵ turbulence closure and direct coupling of finite rate chemistry with a Well-Stirred Reactor (WSR) model. The predicted trends in required intake temperature and auto-ignition location for a constant combustion phasing are consistent with experiments, cf. Figure 1. The predicted incylinder pressure trace agrees with the experiments reasonably well, with the model slightly over-predicting the peak pressure and heat release rate for the later injection cases (details of model validation, including spray model validation, are given in Ref. [1]). The simulations show that the auto-ignition is dependent

Figure 1
(a) A comparison between the required temperature at intake valve close, TIVC, for constant CA50 in simulations and experiments. The regions A, B and C indicate that the spray hits outside the bowl, partially outside the bowl or entirely inside the bowl. The experimental trend is replicated but with an offset. This could be explained in part by the difference in the time and location of the intake thermal sensor measurement was done and TIVC was determined in the simulations.

(b) A comparison of radial ignition location of the first ignition site from chemical luminosity and from CFD simulations based on heat release rate. The horizontal dashed line indicates the location of piston bowl edge. Details of the results and discussion of the figures are referred to Ref. [1]



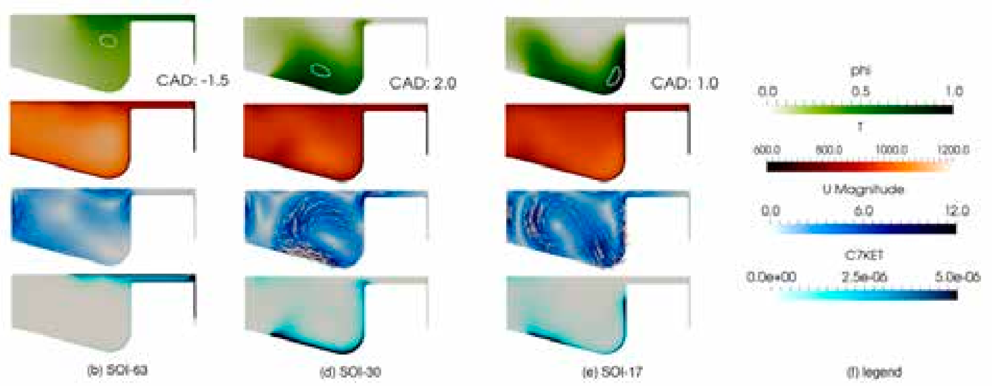


Figure 2
The equivalence ratio, temperature, velocity vectors and ketohydroperoxide (C7KET) mass fraction over a central cross section at the instance of time of onset of ignition for three SOI cases. The white rings in the equivalence ratio field indicate the region at which the volumetric heat release rate is $5 \cdot 10^9$ J/($m^3 \cdot s$). Details of the results and discussion are referred to Ref. [1].

on both fuel and temperature stratification. A higher heat release rate is observed in the later injection cases, which is attributed to the higher equivalence ratio of the mixture inside the bowl. Negative temperature coefficient (NTC) heat release behaviour of the studied fuel plays a role in shortening the ignition wave propagation but the impact of the effect varies with SOI.

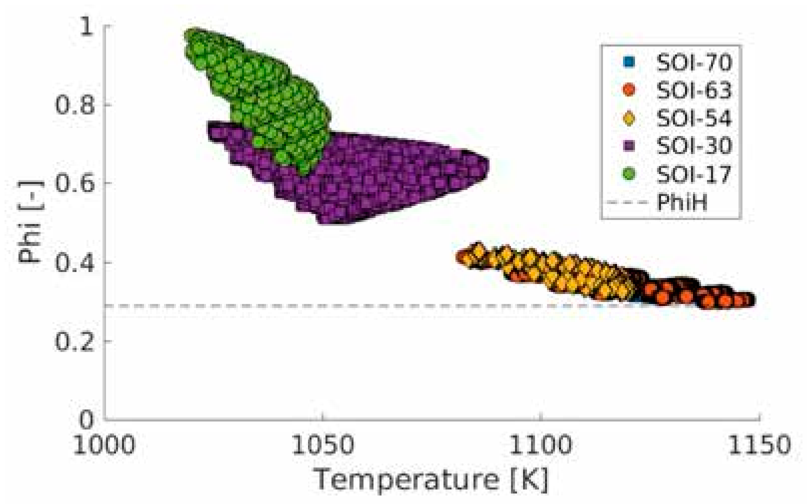
Mixing field, flow structure and first ignition site

Figure 2 shows the fuel/air mixing (i.e., the equivalence ratio, Phi), the flow structures, and the first ignition sites in the cylinder. An earlier injection (SOI-63) leads to the injection site shifting to the squish region and the fuel is located mainly in the squish region and the boundary layer of the cylinder head. Thus, the onset of ignition occurs in the region near the squish room and cylinder head. This region is cooled by the walls prior to the onset of ignition, which explains the higher required intake temperature in the earlier ignition case. On the other hand, in the later injection cases, e.g., SOI-30 and SOI-17, the fuel is directly injected in the bowl, which results in the onset of ignition in the region close to the bottom of the bowl. Furthermore, the first ignition sites are found in the regions close to the (low speed) center of recirculation zone, and during the onset of ignition a significant amount of ketohydroperoxide (C7KET) is found in the near wall region where the mixture is relatively fuel richer. The ignition process is sensitive to both the temperature and equivalence ratio (Phi) of the mixture.

Dependence of ignition on temperature and equivalence ratio

Figure 3 shows values of equivalence ratio (Phi) and temperature of the mixtures in the region of the first ignition sites. In the earlier ignition cases, e.g., SOI-63, the mixture is more homogeneous and fuel-lean (due to longer mixing time). The ignition delay time for fuel-lean mixture at a given temperature increases with decreasing equivalence ratio (Phi) [4]; thus, a higher temperature is needed for the fuel-leaner mixture to maintain the same ignition delay time. This is another reason that is behind the required higher intake temperature in the earlier injection cases. For the later injection cases, i.e., SOI-30 and SOI-17, the mixtures around the first ignition sites have an increasing equivalence ratio while SOI is retarded. Although the temperature of the first ignition sites decreases with retarding SOI, the required intake temperature increases with retarding SOI, since the mean temperature of these fuel-richer mixture decreases rapidly with retarding SOI.

Figure 3
Equivalence ratio and temperature of the mixtures with heat release rates higher than $5 \cdot 10^9$ J/(m^3s) at the instance of time of onset of ignition. The dotted line is the equivalence ratio of a fully homogeneous mixture. Details of the results are referred to Ref. [1].



Propagation of reaction fronts

To examine the spatial distribution of the reactive scalars and their temporal evolution, LES was carried out for the later injection cases, SOI-30 and SOI-17 [3]. Figure 4 shows spatial distribution of CO mass fraction and an iso-contour of OH mass fraction in a cross section through an injection hole plane. OH radicals are indicators of the second-stage (high temperature) ignition of the PRF fuel. As seen at 2.5 CAD aTDC, the OH contour encloses only a small region of the domain in both cases, indicating that the process is in the earlier ignition stage. At this stage CO is shown to be distributed in a large region of the domain. It appears that CO is already formed during the first-stage (low temperature) ignition, before the onset of second-stage ignition. The fuel is converted to CO in the first-stage ignition, and CO is convertedto CO2 in the second stage ignition by reaction of CO + OH = CO2 + H2. Since this reaction is very fast CO and OH are hardly seen to co-exist in the domain, cf. Figure 4. By comparing the CO field and the OH iso-contour it is evident that the reaction front of CO and OH propagate through a large region of domain within just 2.5 CAD, which is only possible by virtue of ignition wave propagation.

LES of methanol PPC engine combustion

Methanol is a genuine candidate on the alternative fuel market for internal combustion engines, especiallywithin the heavy-duty transportation sector. Partially premixed combustion (PPC) engine concept, known for its high efficiency and low emission rates, can be promoted further with methanol fuel due to its unique thermo-physical properties. The low stoichiometric air to fuel ratio allows to utilize late injection timings, which reduces the wall-wetting effects, and thus can lead to less unburned hydrocarbons. Moreover, combustion of methanol as an alcohol fuel, is free from soot emissions, which allows to extend the operation range of the engine. However, due to the high latent heat of vaporization, the ignition event requires a high inlet temperature to achieve ignition event. In the work published in Ref. [7], LES was used, together with experimental measurements on a heavy-duty optical engine, to study methanol PPC engine. After a successful calibration of the pressure trace in terms of required intake temperature and combustion model, the natural luminosity data is used to validate the prediction of ignition kernel and vapor penetration length. It is shown that the required inlet temperature is reduced by 47 K when applying multiple injection strategy. Changing the injection strategy also affects the average temperature of combustion and thus the emissions rates. Additionally, an ignition sequence analysis is performed to identify the mode of combustion and the heat release (HR) distribution depending on the local equivalence ratio, recognizing characteristics of PPC regime. Based on this analysis, a conceptual heat distribution model for PPC engine and other low temperature combustion (LTC) engine concepts is proposed. More details of the results and discussion are referred to Ref. [7].5.

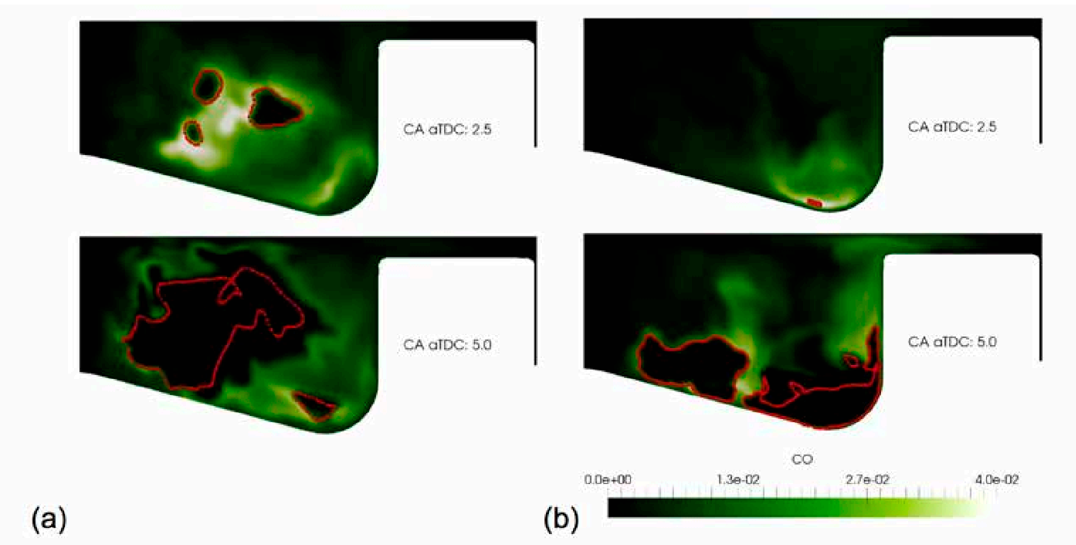


Figure 4
Mass fraction of CO for the SOI-30 case (a) and SOI-17 case (b) at the onset of high temperature ignition (2.5 CAD aTDC) and during the propagation of the ignition front (5 CAD aTDC). An iso-line of OH mass fraction shows the high temperature ignition front that encloses the burned gas (the low CO region). The results are from LES [3].

Conclusions

The combustion process, in particular, the impact of SOI on the engine performance (thermal efficiency, and emissions of CO, UHC and NOx) in the Scania D13 engine has been studied using CFD simulations for both PRF fuels and methanol fuels. The main conclusions from these investigations can be summarized as follows:

- The combustion process in the engine can exhibit three different modes, HCCI combustion (with earlier SOI), PPC (with later SOI) and transition between HCCI and PPC (moderate SOI). As the SOI is retarded, two distinctive classes of in-cylinder temperature can be found; the first is for the SOI range from −100 to −48 CAD aTDC, where the maximum mean effective in-cylinder temperature (T_{max}) is lower than 1700 K. This may be referred to as the HCCI combustion class, in which the emissions of NOx is generally low. The second is for the SOI range from −44 to −20 CAD aTDC, where T_{max} is higher than 1850 K. This may be referred to as the PPC combustion class. In this class, the emissions of CO and UHC decreases with retarding SOI.

- The NOx emissions is not only affected by the mean temperature but also by the stratification of temperature in the cylinder. NOx emissions in the low temperature class of SOI (in the HCCI class) is relatively low owing to the low in-cylinder temperature, although it increases with the increase of T_{max} and σT (stratification of the incylinder temperature). In the PPC class of SOI (later than −44 CAD aTDC), NOx is relatively higher, and it is more closely correlated with σT than with T_{max}, due to the relatively slower variation of T_{max} with SOI. In the transition range of SOI, NOx is highly correlated with T_{max}.
- The main source of UHC emissions in the studied engine is the fuel trapped in the crevice region where the oxidation process cannot function properly.

- For the HCCI combustion class (with earlier SOI), the controlling factor for CO emissions is the in-cylinder temperature. CO is formed rapidly along with oxygen consumption and thereafter CO is oxidized rapidly. For the PPC combustion class (with late SOI), CO formed in the fuel-rich zones requires the mixing of ambient oxygen to the CO zone, which slows down the oxidation process. During the transition from HCCI to PPC, the CO emission shows two peaks in the bowl and squish region, respectively, owing to the distribution of the fuel and oxygen in the cylinder.

- The maximum peak pressure rise rate (MPRR) is affected by the stratification of composition and temperature of the mixture. In this study, the MPRR is closely correlated with ratio of the mass of fuel in the bowl to the ignition delay time of the mixture.

- The operating point in the PPC regime has a higher MPRR than that in the HCCI regime. The reason is that the ignition delay time of the fuel-lean mixture with different temperatures varies drastically, while the ignition delay time of the fuel-rich mixture is less sensitive to the temperature stratification.

- The highest engine efficiency is achieved with the SOI at −44 to −31 CAD aTDC. The lower engine efficiency for the SOI range of −80 to −48 CAD aTDC is due to the low combustion efficiency. With SOI later than −31 CAD aTDC, the engine efficiency decreases with further retarding SOI due to the increasing heat loss to the piston wall.

- The engine heat transfer is an extremely unsteady and spatially varying process, and it strongly depends on the combustion mode.

Associated projects

GLYCEROL DERIVATIVES AS MOTOR FUEL OXYGENATES: EFFECT ON ENGINE PERFORMANCE AND EMISSIONS

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Supervisor:
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Introduction

In order to comply with mandates for the use of green energy, there has been an increasing worldwide demand for renewable fuels, which has led to an overall surge in biodiesel production. The production of glycerol (also known as glycerin), an unavoidable byproduct of the biodiesel industry, has increased accordingly, as it represents around 10 wt% of the biodiesel output, resulting in an oversupply of low-value glycerol on the market.

Due to this glycerol "glut", the sustainability of the biodiesel industry has become increasingly dependent on finding novel ways to enhance the value of this waste glycerol and turn it into useful chemicals. One of the several ways glycerol can be transformed into value-added products is by converting it into fuel additives that can be blended in either gasoline or diesel fuels.

This research is mainly related to "BioRen" **(www.bioren.be)**, an EU-funded Horizon 2020 project which aims to convert municipal solid waste (MSW) into transportation fuels, such as ethanol and isobutanol, through fermentation of the lignocellulosic biomass present in the MSW. Most importantly, BioRen also seeks to valorize the surplus glycerol from the biodiesel industry by converting it into glycerol tertiary butyl ether (GTBE), a compound that can be used as an oxygenated fuel additive in both gasoline and diesel engines.

Besides GTBE (an ether), several other glycerol derivatives of different types have potential as fuel oxygenates, including glycerol esters (e.g. acetates), acetals, ketals, and glycerol carbonate.

Objectives

The overall goal of the current research is thus to evaluate the performance of different types of glycerol derivatives as fuels oxygenates—on both diesel (CI) and gasoline (SI) engines. Emphasis will be put on the effect of the oxygenates on engine performance (e.g. fuel consumption) and emissions, with a special focus on particulate emissions.

Method

In this initial phase, the main aim was to get a first impression of the potential of isobutanol and GTBE as diesel fuel oxygenates, that is, their ability to decrease soot emissions was investigated. The preliminary tests were performed on a 4-cylinder light-duty Volvo D4 diesel engine. To evaluate the performance of the fuels, start-of-injection (SOI) sweeps were done at 2000 rpm and at three different loads: 70, 140, and 280 N·m.
The fuels tested were as follows:

- 100% fossil diesel (i.e. no biodiesel added),
- 5,0 vol% GTBE in diesel
- 6,5 vol% isobutanol in diesel

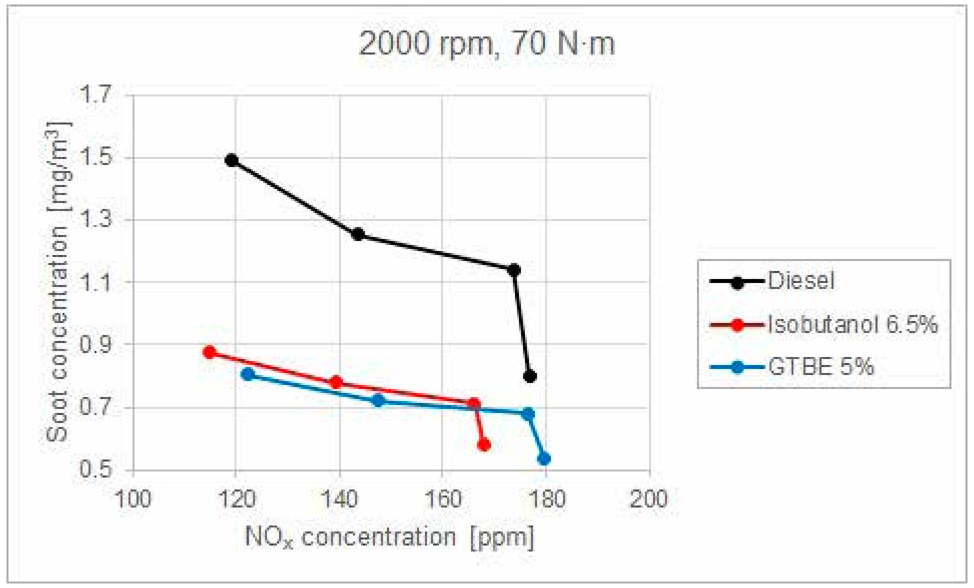
(The latter two having the same oxygen content.)

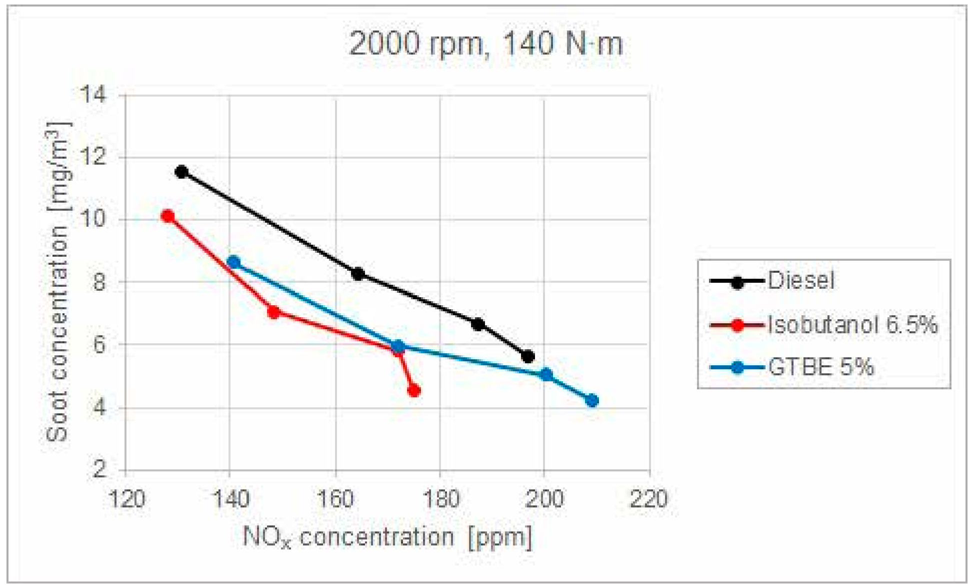
Results

Based on the preliminary engine tests, it can be concluded that the diesel-isobutanol and the diesel-GTBE blends, as expected, inhibited soot formation without increasing NOx emissions at the low and medium engine loads. However, the high-load results (Figure 3) were dubious.

Conclusions and future work

The diesel-isobutanol and diesel-GTBE blends behaved as expected for oxygenated fuels and the results are encouraging. However, further engine testing has to be done for a more thorough assessment, especially regarding the soot-NOx trade-off, fuel consumption, and combustion characteristics. Moreover, the particulate emissions are going to be characterized in deeper detail. Besides GTBE, other glycerol derivatives are going to be investigated as fuel oxygenates and, further ahead, engine tests will be performed on a gasoline engine as well.





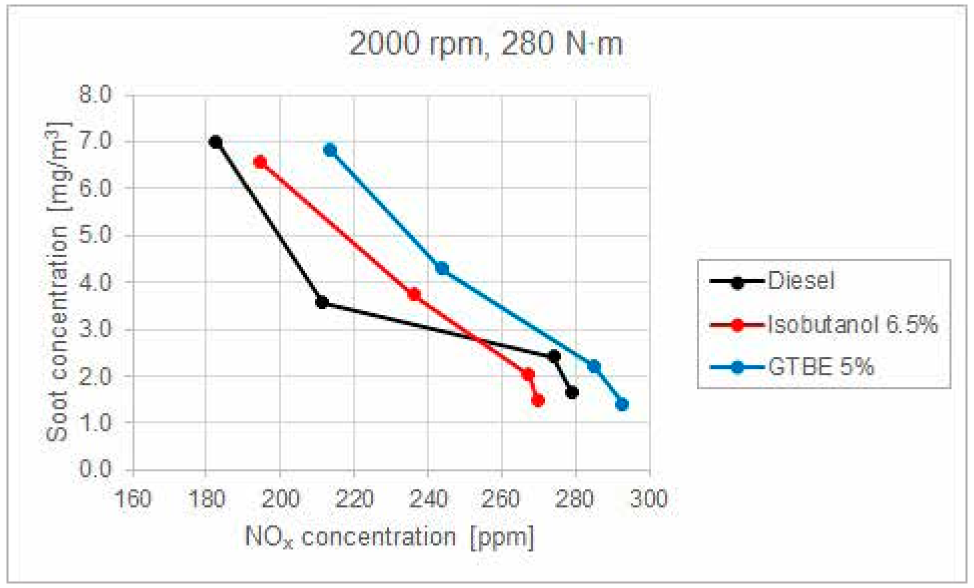


Figure 3
Soot-NOx trade-off
at 280 N·m

FUTURE ALTERNATIVE FUELS FOR TRANSPORTATION

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Supervisor:
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Background

Many researches have been conducted on renewable substitute to replace fossil fuels where various aspects of renewable fuels have been investigated. There are several international research projects on-going to introduce fuels which can be used in conventional combustion engines without a significant need of modification. These new fuels are not always properly assessable using conventional test methods. For example, the Research and Motor Octane Numbers (RON & MON) are mainly designed based on fossil fuels while on the other hand many researchers claim that RON and MON are not proper indicator of fuel behavior or antiknock quality in modern engines.

Objectives

The focus of the project is the characterization of renewable fuels in connection with both advanced and conventional combustion concepts using experimental approaches. Two intermediate goals are to research new robust test methods to complement exciting fuel metering indexes. These have been defined as:

- A standard φ-sensitivity test method to provide more information for selecting proper fuels for better controlling of LTC engines and also a better understanding of how load-adaptive fuels can be designed.
- A boosted SI test method to provide a better understanding of alternative fuel's knock propensity in modern SI engines.

Methods

In this project a modified CFR engine for HCCI combustion is the experimental apparatus. The experimental campaign for the φ-sensitivity test method has been performed to investigate the effect of variation in equivalence ratio (φ), on the different combustion, performance and emissions properties using toluene, ethanol reference fuels (TERFs) as the extreme blends to span the ranges of the method. The detailed study of the low temperature heat release (LTHR) was one of the main consideration during the design and post processing of this campaign. To test the method, 12 different blends were prepared to cover a wide range of RON, MON, aromatic contents and oxygenate contents. Blends were prepared in three different levels of RON numbers, (63, 84, and 105). In each RON group four blends with different composition but similar RON and approximately the same MON number were prepared. Table 1 shows the one of the groups. These blends were evaluated in lean HCCI combustion within a φ range of 0.37- 0.32, three intake temperature of (50, 100, and 150 °C) and an engine speed of 900 rpm. The results are now being prepared for publications. Designing a GTPOWER model of the CFR engine and perform kinetic simulation with Cantera are other ongoing activities to improve the understanding of the behavior of these different blends under stoichiometric to rich condition during HCCI operation. Table 1Example of fuel blending strategy for φ-sensitivity test method.

	Fuel	n-heptane, vol.%	Ethanol, vol%	Toluene, vol.%	RON	MON	S=RON-MON
1	$T_{25}E_{30}RF_{N40}$	40	30	25	85.4	77.6	6.9
2	$E_{38}RF_{N43}$	43	38	0	84.4	78.7	5.4
3	$T_{50}RF_{N30}$	30	0	50	83.8	76.6	8.5
4	PRF84	26	0	0	84	84	0

A preliminary study was performed to gain more practical knowledge and experiences about HCCI combustion and specifically the LTHR. In this campaign gasoline blended with ethanol (10% v/v) was used as the base fuel. Different percentages of 2-EHN (0.25%, 0.50%, 1%, and 2.5 %) were added to the base fuel as an ignition improver. The blends were tested at operating points defined for the Lund HCCI number at two different engine speeds (600 and 900 rpm) and three different intake temperatures (50, 100, and 150 °C) to investigate the effect of 2-EHN on the auto-ignition behavior of the fuel. Combustion, emissions, and performance parameters of HCCI combustion of the blends were measured.

Results

ϕ-sensitivity test method:

More than 150 operating points were evaluated. Many different parameters are evaluated in this study as an example, with some results showing that a higher level of toluene increases the HC emissions while the HC level for the highest ethanol content is still low. This effect is more noticeable at the leanest condition (φ= 0.32+ 0.005) with figure 1 illustrating this effect. The hypothesis is that the effect is due to the shorter ignition delay of toluene compared to ethanol and that toluene therefore cannot tolerate a compression ratio as high as ethanol. Ethanol has high HOV and was more effective in the increasing of RON and MON compared to toluene. Therefore, it was not possible to have the same volumetric percentage of ethanol or toluene in the blends of a group with the same RON number.

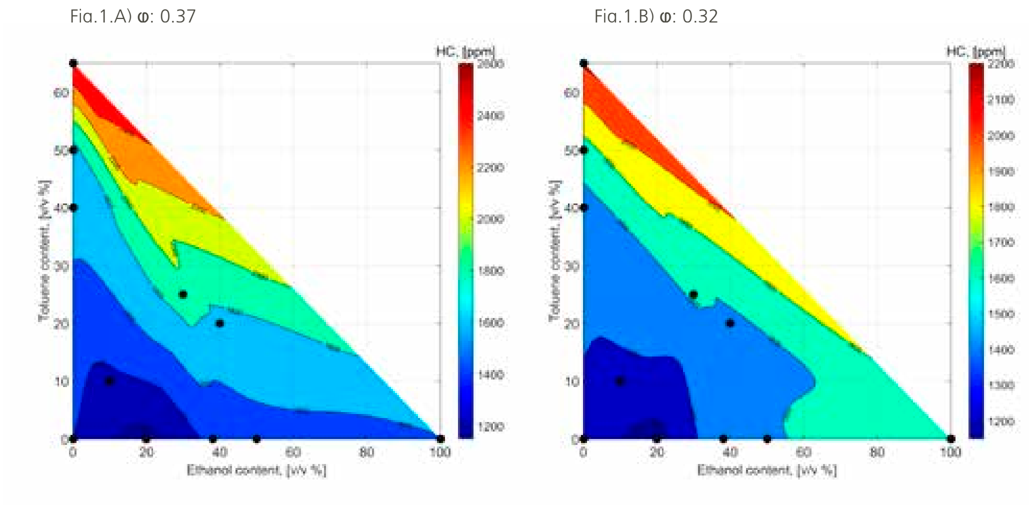

Figure 1
The effect of equivalence ratio on the HC emissions of different blends at Tin:100 °C.

2-EHN study:

The presence of 2-EHN in the blends improves the auto-ignitability of the blends in a nonlinear manner. It was also found that 0.25 % of 2-EHN can compensate for the effect of ethanol on the required compression ratio and remove the quenching effect of ethanol on LTHR. The results show that for the same fuel, a higher compression ratio is needed to maintain the combustion phasing constant at a higher engine speed. The results of this campaign can be found in the *Fuel* journal: *The effect of 2-Ethyl-hexyl nitrate on HCCI combustion properties to compensate ethanol addition to gasoline*.

Conclusions

The φ-campaign shows that the oxygenated fuels in all operating conditions of this study emit less HC and CO compared to other fuels and increase the combustion efficiency. Aromatics increase the combustion stability. Aromatics contents also increase the HC emissions especially in leaner conditions.

Adding 2-EHN to E10 gasoline can compensate for the effect of ethanol content in gasoline. The study shows that using high octane fuel with fractions of renewables to lower the green-house-gasses, can be an option to maintain combustion phasing during HCCI operation if those fuels are tailored by adding ignition improvers.

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